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Welcome to Gothenburg

It is a pleasure to welcome you to Gothenburg and the Swedish west coast for the 36th Nordic Geological Winter Meeting! The Geological Society of Sweden is very proud to be able to continue this strong tradition among geologists in our Nordic countries, and we look forward to an exciting scientific program with over 450 abstracts in six parallel sessions. We hope that all of you will have a fulfilling three days of high-level scientific discussions, making new connections, and meeting old and new friends.

The organisation of a meeting like this requires more than a year of preparation, a task that many people have been involved in. We would like to thank the Scientific Committee for putting together an ambitious program, the conveners for promoting exciting sessions, the plenary speakers for their contribution, and not least the sponsors and exhibitors who have made this event possible.

We hope that the 36th Nordic Geological Winter Meeting will be fruitful and lead to better and deeper insight into the different fields of geosciences, and stimulate further Nordic collaboration.

Sincerely,
The Organising Committee

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Critical Raw Materials for the Energy Transition

Kathryn M. Goodenough

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The global objective of achieving net zero greenhouse gas emissions is driving significant decarbonisation of energy and transport, with a shift towards renewable energy sources and electric vehicles. It is now widely recognised that this will lead to significant increases in demand for a range of minerals and metals, including lithium, graphite, manganese, nickel and cobalt (used in batteries), the rare earth elements (used in magnets in motors) and the platinum group elements (for electrolysis to produce green hydrogen). There are concerns about the security of supply of some of these raw materials, and the increasing demand cannot be met solely by recycling; mining of primary resources will be essential. In this talk I will summarise current issues around supply of critical raw materials, with a focus on our recent research on lithium resources and supply chains. Whilst there is popular concern around the availability of lithium for batteries, in reality there is no geological scarcity of lithium – a variety of resources are known, and ongoing exploration continues to grow the resource base. The bottlenecks in the lithium supply chain are related to mineral processing and infrastructure development, and geopolitics is an important control on availability. I will discuss the role that geologists can play in all aspects of critical raw material supply chains, to ensure security of supply for a greener future.

Ancient DNA reveals patterns of postglacial plant and animal colonization of N Fennoscandia

Inger Greve Alsos and co-workers

UiT – The Arctic University of Tromsø

Sedimentary ancient DNA (sedaDNA) is revolutionizing our comprehension of long-term ecosystem transformations, shedding light on megafauna extinctions and enabling the reconstruction of ecosystems dating back two million years. This DNA allows for precise identification of plant species, facilitating the reconstruction of past environments based on plant traits indicative of abiotic factors like moisture, temperature, and pH, as well as biotic interactions with pollinators and mycorrhizal fungi. While consistently detecting mammals has been difficult, methodological advancements now permit regional-scale analyses, and we are increasingly able to identify other organisms, including fish, birds, and worms. For N Fennoscandia, we recovered several thousand-year lags in post-glacial plant colonization and that millennial timescales are required to establish stable and resilient diversity and ecosystem functions. Reindeer was the earliest postglacial terrestrial mammal to arrive. Boreal species such as the beaver coincided with the arrival of tree species like pine, mountain ash, and poplar. The elk emerged around 8,700 years ago, after which the diversity of traits and ecosystem functions stabilized and became resilient to new species arrivals. We show how it is possible to integrate the DNA time-series data with process-based ecosystem models and inverse modeling techniques to decipher the biotic and abiotic processes driving these ecosystem dynamics. The ultimate goal is to leverage these refined models to predict ecosystem responses to future climate scenarios with greater accuracy.

Session 1
Hydrogeology

Session Chairs:
Roland Barthel,
Department of Earth Sciences, University of Gothenburg
Charlotte Sparrenbom,
Department of Geology, Lund University

Where does the pollution go? Conceptual understanding of interaction between groundwater and stream

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Background and purpose

At a location in the Capital Region, a pollution investigation was previously carried out, which concluded that significant pollution with chlorinated solvents flows into a sand aquifer and into a nearby stream. It was therefore assessed that there was no risk to the groundwater resource in the area. Subsequently, an initial surface water survey was carried out, which showed that no significant amounts of pollution flow from the site into the stream.

WSP was therefore tasked with confirming or denying whether the pollution from the location flows in or under the stream, to reassess the risk to the groundwater resource.

The purpose of this (hopefully) oral presentation is to emphasize that a groundwater and/or surface water investigation cannot stand alone if there is contamination in an aquifer close to a recipient. The interaction is complex, and one therefore must use several methods and lines of evidence to understand what is going on.

Methods and data

It has been a long winding road in the attempt to reach the goal of the investigations. We have tested many methods, e.g. traditional boreholes, geoprobe soundings, geophysical surveys (MEP), water flow measurements in the stream, etc.

The research methods will briefly be reviewed, which are relevant for either/or groundwater and surface water surveys? What are the strengths and weaknesses, why some methods do not apply. The point is to show the series of surveys that together help to provide the necessary "line of evidence".

Result

Initially, conventional boreholes were carried out, but the plume was not located. But there were challenges in finding a plume in a mighty sand aquifer with traditional boreholes. Subsequently, geoprobe soundings were carried out. Especially level-specific water samples proved to give good results and a good understanding of the distribution, composition, and strength of the plume.

To investigate whether there was a separating cover layer between the sand aquifer and the primary aquifer (limestone) at the site, a deep borehole was carried out to the maximum possible depth, according to the capabilities of the equipment. As the borehole did not provide the final answer, geophysical investigations were carried out.

During water level measurements between boreholes close to the streambank and measurements in the stream, it turned out that there is a gradient difference of 2 m from the aquifer down towards the stream, a few meters away. There were no signs of a continuous hydraulic barrier or of a spring at the streambank. The geophysical investigations could not clarify whether there was a hydraulic barrier between.

It was assessed that it was necessary to remeasure waterflow in the stream. The result can indicate whether the stream receives or loses water to the aquifer on the section past the site and in what quantities.

The investigations are expected to be concluded ultimo 2023.

Drillers mapping and groundwater monitoring in the context of arsenic risk reduction in Bangladesh: policy, implementation and sustainability

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Bangladesh's drinking water supply primarily depends on privately drilled tube wells. Groundwater provides microbial-safe water but increases the risk of long-term exposure to arsenic as the shallow groundwater in most of Bangladesh contains elevated concentrations of arsenic. More than 17 million people in Bangladesh are still exposed to high arsenic concentrations in drinking water exceeding the Bangladesh drinking water standard of 50 µg/L. Groundwater arsenic contamination is not uniform and has various scales of spatial heterogeneity across the country. Besides, it is not yet well understood whether an arsenic-safe section of an aquifer will remain arsenic-safe in the long run. Therefore, a comprehensive groundwater monitoring network with a central protocol for quality-ensured data capturing, along with the finding that groundwater arsenic concentration correlates with the colour of the aquifer sediments, may ensure and lay the foundation to help reduce arsenic exposure if properly implemented nationally at grassroot level. More than 80% of drinking water wells in Bangladesh are drilled and installed by local drillers without formal training or education in drilling, geology or hydrogeology. Since identifying sediment colour does not require much expertise and training, engaging the local drillers can be vital in scaling up safe water coverage in Bangladesh. Drillers engagement requires for identifying, assessing their knowledge base, and training them on selecting arsenic-safe aquifer layers based on sediment colour. In this study, we determined that the local hardware shops and service providers at the Upazila/union level can be considered drillers hubs because all drillers in a community are connected to these shops. Nevertheless, the Department of Public Health Engineering (DPHE), the government agency tasked with ensuring safe drinking water, is currently constructing monitoring wells to understand variations in groundwater levels and water quality. This study also provides a structure for prioritisation, siting and planning for installation of monitoring wells. It is identified that the land ownership, preferably a union headquarters (the lowest administrative entity), participation of the local government institutions, modification of the current institutional framework of the Department of Public Health Engineering, capacity building of the local drillers for selection of the appropriate depth (preferably shallow, intermediate and deep aquifers) and layer for monitoring, as well as a centralised system for storing and analysis of monitoring data are the key requirements for a sustainable monitoring system. In this connection, a digital platform - ASMITAS- has been developed to acquire digital data from the piezometers and support decision-making by different water supply actors. Hence the monitoring well installation and trained, certified drillers in conjunction were found to be performing much better in installing arsenic-safe wells and eventually will help to reduce arsenic exposure along with long-term sustainability for safe drinking water resources in Bangladesh.

Has the hydro(geo)logy changed after drainage in restored lowlands?

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Many countries aspire to expand the amount of restored carbon-rich lowlands, as part of their efforts to reduce greenhouse gas emissions, while also promoting desired ecosystem services. The practise has received increasing attention, yet there is limited information available on how restored agricultural fields' hydro(geo)logical and hydrogeochemical functioning has changed due to previous drainage and nutrient load, and in turn, how that could influence the intended outcomes. To decrease the knowledge gap, we have sampled precipitation, surface waters, shallow (<1 mbgl) groundwater from 61 wells, and deep (4-8 mbgl) groundwater from 10 wells in 12 riparian wetlands in Denmark, during one year. Six of the sampling sites are restored, while the other six sites are near-natural. They have also been classified based on management (grazed or ungrazed). The wetlands are located along three separate stream valleys, with subsurface geologies consisting of carbonate rock, glacial till or glacial outwash sand. Six sediment cores of the top 30 cm soil were collected from each wetland, 72 in total, and analyzed for organic and inorganic carbon content, mineral content and bulk density. Shallow groundwater of restored wetlands had strongly elevated concentrations of iron(II) (median 15.2 mg/L) and phosphate (median 1.8 mg/L), compared to their near-natural counterparts (medians 0.1 and 0.1 mg/L, respectively), despite the fact that restoration took place 13-18 years ago. In comparison to the near-natural sites, the restored sites displayed lower dissolved oxygen concentrations, along with enriched mean and range of water δ^2H- and δ^{18}O-values that indicated younger water ages. The combined oxygen depletion and isotopic indication of younger water suggest that restored sites have abundant reactive organic carbon, while near-natural sites are limitied in reactive organic carbon. Furthermore, analysis of the sediment cores shows that restored sites have a higher bulk density (mean 1.3 g/cm^3), and lower soil organic carbon content (mean 14%) than near-natural sites (means 0.7 g/cm^3 and 33%, respectively). This indicates that both physical (compaction) and chemical (peat degradation) processes during previous drainage have caused long-term changes to the wetlands' soil properties, and thus, the hydrological conditions. With changing climate, wetland areas will probably increase in the landscape. This study aims to increase the knowledge of wetlands' response to past drainage and nutrient loading, and thereby facilitate the increased success of on-going and future restoration programs.

Interpretation of hydraulic responses to borehole drilling and flow logging as planning tools for hydraulic tests

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SKB (Swedish Nuclear Fuel and Waste Management Company) is conducting site investigations and monitoring in Forsmark in mid-eastern Sweden, as part of preparations for an extension of the existing final repository (SFR) for short-lived radioactive waste (SKB 2013). As part of the site investigations, boreholes are drilled and used to establish physical and hydraulic properties of the bedrock volume in which the extension will be constructed. Geophysical investigations are typically used as guidelines to determine borehole placements and orientations, while hydraulic borehole tests are used to assess the hydraulic connectivity and properties of the fracture network of the bedrock.

This study describes SKB's approach for hydraulic monitoring during borehole drilling as a tool for planning of subsequent hydraulic tests. Two recent boreholes (KFR90 and -91) were drilled horizontally from the existing SFR construction tunnel, at 100 m depth below the sea level and with lengths of 450 and 340 m, respectively. The boreholes were drilled roughly perpendicular to each other, with the aim to intersect previously modelled deformation zones of relevance for the site understanding. Borehole KFR91 was drilled first, followed by temporary installation of a pressure sensor in the borehole for continuous monitoring during drilling of the second borehole (KFR90). Pressure in KFR90 was monitored during daily pauses in active drilling, through a temporary pressure sensor mounted at the borehead.

Pressure monitoring in KFR91 showed almost no hydraulic response to the drilling of KFR90, despite both boreholes intersecting deformation zones that should provide hydraulic connectivity between them. This lack of identifiable hydraulic interference response could be due to several reasons, but one main drawback is probably the sparse instrumentation used in KFR91 (a single pressure sensor) and the length of the borehole (340 m) that damped potential local pressure changes associated to daily cycles of borehole drilling and closing of KFR90.

However, other boreholes in the SFR bedrock volume, sectioned by packers and instrumented with pressure sensors for continuous pressure monitoring, demonstrated hydraulic responses to the KFR90 and -91 drilling activities, suggesting hydraulic connectivity across the fracture network. For instance, pressure responses within one borehole (KFR105) indicate a strong hydraulic coupling with borehole KFR90. Moreover, although less clear, one borehole section (KFR27:2) demonstrate pressure variations that are consistent with impacts from drilling. However, responses were unclear in some other boreholes (KFR102A, KFR102B, and KFR104) that intersect deformation zones that should be hydraulically connected to borehole KFR90.

Difference flow-logging (PFL method) tests are planned in both KFR90 and -91. These tests will provide detailed information on hydraulic transmissivity along each borehole. The results of the PFL tests and associated hydraulic responses will be used to define a plan for placement of borehole packers and for execution of upcoming interference tests. The interference tests will use packed-off sections of borehole KFR90 as sinks, and aim to assess hydraulic connections across the fracture network of the SFR extension volume. An integrated analysis of all tests and hydraulic responses related to KFR90 and -91 will be used to plan placements of permanent borehole packers and installation of pressure sensors, for continuous pressure monitoring of the boreholes prior to and during the SFR extension.

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Digital groundwater and geoscience data supports the green transition and UN Sustainable Development Goals

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Societies are profoundly dependent on resources from beneath the Earth's surface. It's crucial to have unrestricted access to accurate, consistent and coherent digital scientific data detailing the subsurface's geological features including the extent of regional and local aquifers down to five kilometers (Hinsby et al. 2023). Such information is pivotal in evaluating and mitigating climate change effects and spearheading the shift towards environmental sustainability. Digital maps and integrated 3D/4D surface and subsurface models are vital for exploring and tackling challenges related to groundwater quantity and quality, impacts of floods and droughts, renewable geo-energy alternatives, availability of essential raw materials supporting the green transition, resilient urban planning carbon storage and capture, natural disaster risk evaluation and adaptation, and safeguarding groundwater dependent ecosystems and biodiversity.

For over ten years, EuroGeoSurveys, representing Europe's Geological Surveys, has dedicated itself to offering harmonized digital data of Europe's subsurface via the European Geological Data Infrastructure (EGDI). These datasets are an unmatched asset for informed decision-making and green transition policy enactment, aligning with UN Sustainable Development Goals and the forthcoming Digital Twins in Earth sciences. The database is continuously refined and expanded with pertinent stakeholders to address societal demands and ensure a balanced, robust, and holistic management of surface and subsurface resources, which sometimes have conflicting uses.' Here, we present selected examples of groundwater quantity and quality data and knowledge with open access in EGDI at European and regional scales.

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Assimilating hydraulic response data from in-situ bioremediation injection treatment for improved decision-support modelling

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In-situ remediation through the injection of bioremediation fluids is becoming increasingly common for treating contaminated sites. Contaminants are targeted for treatment either directly at the source zone or through injections that form a permeable reactive barrier to prevent further transport of the contaminants. Commonly, multiple injections are performed in a grid covering an area of strategic importance. These injections, essentially serving as high-frequency inverse pumping tests, present an opportunity to capture rich information regarding the hydraulic response (changes in head during injection) in the aquifer at multiple locations. This information, which is often overlooked, can add valuable insight into the site, improve site characterization, aiding in predictions of future management actions and enhancing future monitoring efforts. However, due to the high pressures during injections, hydraulic fracturing often occurs at the time the injections are made. These events, representing temporary or permanent changes in aquifer properties depending on the treatment strategy, must be considered when assimilating hydraulic response data into a decision-support model to reduce the risk of introducing parametric biases. We have developed four groundwater numerical models for a PCE-contaminated site in Alingsås, Sweden, that was treated with in-situ remediation injections in 2017. Each model, although structurally identical, is calibrated using different parameterization and weighting approaches applied to the hydraulic response data. Preliminary results showed that by employing time-varying parameters at the location and time of injection, the model achieved a better fit with measured data and a lower parameter variance compared to other models. On the other hand, traditionally configured models (i.e., models that do not employ the use of time-varying parameters) show signs of parameter compensation, potentially biasing any predictions based upon their use.

Managing complexity: Local groundwater management in Sweden

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Common pool resources (CPRs) are resources which are sufficiently large to make them difficult or costly to exclude users from and where the use of others depletes the resource pool (Ostrom 1990). Groundwater resources are an example of a CPR, which is used globally, but often with local governments being responsible for water resource management and service delivery (OECD 2011). Groundwater is the largest body of unfrozen freshwater and accounts for one-quarter of all water used by humans (Alley et al. 2016; KC et al. 2022; Kinzelbach et al. 2003; United Nations 2022). However, globally groundwater resources are in a crisis but remain highly underrepresented on the political agenda (Guppy et al. 2018). In this interdisciplinary study, we were interested in studying groundwater systems and the interactions with the surrounding governance systems, using the framing by Huggins et al. (2023) of *groundwater-connected systems* which are *"formed by social, economic, ecological and earth system interactions with physical groundwater systems"* (Huggins et al. 2023). From this definition we investigated the complexity of governing groundwater resources and how complexity affects management of groundwater resources within local governments in Sweden. The empirical data used in this study consists of interviews with municipal water managers depending on groundwater and legislative documents directly or indirectly affecting the governance of groundwater resources. Based on the collected data we have 1) developed a novel theoretical concept of *drivers of complexity*, which we define as factors in CPR-connected systems that contributes to and/or increase complexity, 2) we have used the concept *drivers of complexity* to assess complexity in groundwater governance systems in in local governments in Sweden. The empirical concept is not limited to groundwater-connected systems and can be used in any CPR setting. The drivers of complexity we identified in Swedish local groundwater governance so far, include the following: fragmented responsibility for groundwater resources, absence of national recognition of the importance of groundwater resources and incompatible management timeframes between groundwater bodies and governing institutions. This study elucidates why it is complex to manage groundwater resources and how this relates to the rules and systems in place to govern groundwater using Swedish groundwater management as a case study. Complexity is inherent in all groundwater systems and therefore affects all groundwater connected systems. In the Swedish governance context systems are to some degree geared towards complexity but this could be improved by making clear responsibility for groundwater resources, nationally recognizing the value of groundwater bodies, and improving systems so they to a higher degree can respond to feedbacks from the environment.

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Upscaling of bedrock fracture network models for use with porous media groundwater flow modelling tools

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SKB (Swedish Nuclear Fuel and Waste Management Company) is conducting site investigations and monitoring at the Forsmark site in mid-eastern Sweden. The investigations and monitoring form the basis for integrated site descriptive modelling (SKB 2008). As part of this modelling, regional-scale groundwater flow through fractured crystalline bedrock is simulated using ECPM (Equivalent Continuous Porous Media) models as representations of the fracture network in the bedrock. In SKB's work an ECPM is typically an upscaled representation of a DFN (Discrete Fracture Network) model realization. A DFN is a discrete, stochastic model of the geometric and hydraulic properties of a fracture network.

The hydraulic properties of an ECPM model and the ability of an associated porous media groundwater flow model to represent groundwater flow in fractured bedrock depend on many factors. For instance, such factors include the geometric-hydraulic properties of the fractured network, methodology and data availability for DFN modelling and for selection among DFN realizations for ECPM upscaling, upscaling methodology, and ECPM grid resolution.

This study is focused on the impacts of DFN-to-ECPM upscaling methodology and ECPM grid resolution on the results from porous media groundwater flow models. The impacts of these factors are investigated in a case study, comparing flow modelling results to field measurements from a selected pumping (interference) test in bedrock at the Forsmark site. Specifically, three DFN model realizations for a bedrock volume at Forsmark were upscaled using three different upscaling methodologies; two geometrical (Oda (1985) and GEHYCO (Ferry 2020)), and one hydraulic (here denoted Linear Darcy).

The DFN model realizations are produced using the FracMan software. In order to select DFN realizations to be used in the case study, pumping well inflow and groundwater level drawdown were first modelled using the PFLOTRAN software, simulating groundwater flow through each realization-specific network of discrete fractures. Subsequent to ECPM upscaling of the selected DFN realizations, the same interference test was modelled using the MIKE SHE software, using structured grids of different resolutions, and the DarcyTools software that can also handle unstructured grids. Relatively simple model domain geometries and boundary conditions were used in all flow model setups in order to facilitate inter model comparisons.

Compared to some other ECPM upscaling methodologies, such as hydraulic upscaling using a so-called guard zone (Jackson 2000), the upscaling methodologies of the current study can be expected to overestimate the connectivity of the underlying fracture network. For the scale of the model, flow regime and fracture network characteristics of the case study, the results show that the ECPM grid resolution is more important than the choice of upscaling methodology for the ability of an ECPM to reproduce the geometric-hydraulic properties of the underlying DFN model. This is a potentially important finding of relevance for the groundwater flow modelling community, specifically related to hydrogeological studies of e.g. construction and operation of facilities in fractured crystalline bedrock.

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Predicting the impact of climate change to groundwater and its implications for the built environment

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Climate change is expected to have a significant impact on groundwater- and pore pressure conditions and as a result, on stability of natural slopes, geotechnical structures that support buildings, infrastructure and other facilities. Predictive models for groundwater and pore pressure are therefore of importance to planners, developers, owners of infrastructure and property etc. to assess the need for climate change related mitigation. To meet this societal need, an ongoing research project (PIGALL) is developing tools and strategies to predict groundwater levels and pore pressure in both site specific and regional scales.

The research project combines predictive climate models, conceptual Hydrogeological Reference Conditions (see i.e. Surendran et al., 2020) and specific geological and hydrogeological data and interpretations as input data for regional and site specific hydrogeological predictive models.

Regional scale

A parallel ongoing project is developing predictive groundwater models for climate change in unconfined aquifers with a four-by-four km resolution for Sweden using the SGU-HYPE model. The regional scale model is used to provide groundwater recharge input to site-specific models. Within PIGALL, a further development of the SGU-HYPE model to produce groundwater predictive models also for confined conditions is planned.

Site-specific scale

The site-specific models are developed to exemplify groundwater predictive models for e.g. a specific location as for the design of geotechnical constructions, assessing the impact to existing constructions and infrastrucutre or as input to municipal physical planning. Within PIGALL, site-specific models are developed with MODFLOW 6 for selected case studies (in different types of location) based on geological and hydrogeological data and conceptual Hydrogeological Reference Conditions.

The first site-specific model is being developed for a case study in Kolmården, located approximately 15 km northeast of Norrköping, Sweden. This case study includes complex hydrogeological conditions including cohesive sediments (prone to subsidence) as well as hydrogeologically relatively conductive sediments.

Use of output data

The output from the predictive groundwater models is to be used as input data for further assessment of impact to geotechnical structures.

Furthermore, the output from the regional scale models provides a foundation for the planning of infrastructure projects, planning of communal water resources as well as for municipal and regional spatial planning.

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Finnish-Nepalese cooperation to develop a conceptual hydrogeological model of arsenic transport in groundwater (Terai, Nepal)

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Arsenic contamination in groundwater is a major challenge in the water supply of the Terai region of Nepal, and especially in the most affected Nawalparasi district (2162 km^2) where 12% of the tubewells have arsenic concentration >50 µg/L, exceeding the WHO provisional guideline in drinking water of 10 µg/L (Panthi et al. 2006). Arsenic in groundwater in Terai is of geological origin (Guillot et al. 2015).

Since the 1980s, Finland and Nepal have been partners in development cooperation in the water sector. In this context, the NeAs project (www.syke.fi/projects/neas) was launched in 2020, jointly with the Geological Survey of Finland (GTK), the Finnish Environment Institute (SYKE) and the Department of Water Supply and Sewerage Management (DWSSM). The project is funded by the Ministry of Foreign Affairs of Finland (MFA) with the ICI-instrument. The objectives of the project are to 1) determine the occurrence and distribution of arsenic in groundwater of Nawalparasi, 2) develop a conceptual hydrogeological model of the pilot area, using chemical, hydrogeological and geological data, 3) make recommendations on the groundwater management and mitigation options, 4) provide training to the Nepalese partners including field operations, laboratory quality and procedures, Geographic Information System (GIS) and communication.

Three groundwater sampling campaigns were carried out between June 2022 and June 2023, in contrasting conditions (monsoon, dry season and pre-monsoon). A total of 96 water samples were collected from deep and shallow tubewells, irrigation wells and observation wells. Physico-chemical parameters and arsenic concentration (using Digital Arsenator), were determined in the field and major ions, TOC, DOC, arsenic, iron and manganese were analyzed in the laboratory. Arsenic concentration was 0-960 µg/L, with 44% of samples exceeding the WHO guideline value of 10 µg/L. No correlation between well depth and arsenic levels was observed. The groundwater type defined with major ions was predominantly Ca-HCO3, while some deep tubewells showed Na-HCO3 type, suggesting more evolved groundwater. Further studies and sampling tours in September and November 2023 will support the development of the conceptual model of the study site.

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Impacts of climate on long-term variation in the abundance of different chemical fractions of phosphorus in Finnish archipelago sea sediments

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Phosphorus is a factor that controls the growth of organisms in marine systems. However, excessive phosphorus input triggers eutrophication and hypoxia (Schindler 1977), which have deteriorated especially the environmental status of inner Finnish Archipelago Sea (Jokinen et al. 2018). Though external phosphorus load has diminished, the problems caused by eutrophication have not been conquered (Andersen et al. 2009, HELCOM 2011, McCrackin et al. 2018). Previous studies have also shown the significance of internal load of phosphorus that hinders the recovery of Archipelago Sea (Puttonen et al. 2014, 2016). However, the accumulation, preservation, and long-term variations in the burial of phosphorus within the sediment is not fully known. Thus, we trace long-term variations in chemical forms and contents of sediment phosphorus in detail to reveal the importance of different processes on phosphorus deposition, burial, and release.

We investigate variations in the abundance of different chemical fractions of phosphorus (i.e. different binding and solubility forms of phosphorus) during the last 60 years with seasonal resolution from varved sediments of Halikonlahti Bay sediments in inner Finnish Archipelago Sea. We compare abundances of phosphorus fractions to hydro-climate parameters to study how variations in the conditions, such as occurrence and timing of precipitation or snow and ice cover, control the washout of phosphorus from the catchment. In addition, we investigate if the changes in enhanced leaching of phosphorus are directly mediated to sediment deposits. According to our knowledge, varved marine sediments have not been earlier used to study long-term variations in chemical phosphorus fractions with sub-annual resolution. The importance of this study lies within high temporal resolution allowing to assess the response of phosphorus burial to past hydro-climate conditions. This can further improve our understanding on internal loading and hence the use of rehabilitation actions and target them better spatially and temporally.

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Chemical changes in groundwater associated with earthquakes in northern Iceland

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Samples of Ice Age meteoric groundwater have been collected from a flowing artesian well at Hafralækur in northern Iceland on a weekly basis for 14 years. These samples have been analyzed for stable isotopes values (δ^2H and δ^{18}O) and element concentrations (Na, Si, Ca and K).

During our study, five M > 5 earthquakes occurred in a region within which previous empirical estimates imply that groundwater responses might be expected.

Our results show that changes of δ^2H, which can be shown to be statistical anomalies, coincided with 3 of 5 earthquakes and that changes of Na concentration, which can also be shown to be statistical anomalies, coincided with 2 of 5 earthquakes. Anomalous behavior of δ^2H started 3–5 months before each earthquake occurred.

Comparison with the global meteoric water line (GMWL) implies that anomalous behavior of δ^2H is largely due to mixing between meteoric groundwater sources. Petrographic analysis of well cuttings imply that anomalous behavior of Na concentration is largely due to release of Na caused by microfracturing of analcime that replaces plagioclase in the basaltic host rock.

Because onsets of anomalous chemical behavior occur before earthquakes, we propose to test the hypothesis that a future earthquake could be forecast based on groundwater chemical changes and if so, with what sensitivity.

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Using qanat (karez) geography and geological setting for estimating groundwater resources

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Since their origin during the drought periods of the Persian Empire, 3000 years ago, more than 200,000 qanat (also called “karez”) groundwater tunnels have been constructed in the Middle East and south-central Asia. In addition to their cultural-heritage value and their continued importance for water supply in rural areas, qanat infrastructures can often be mapped using satellite imagery and they offer a valuable insight into groundwater depths and basin hydrology when these proxy data are combined with modern geomorphologic and stratigraphic models. The overall aim of this research is to assist sustainable water-resource management by utilizing the qanat “archive” of basin-specific conditions in regions with poor data control for modelling basin hydrology.

Our more specific objective is to demonstrate the combined use of several information sources in order to estimate local groundwater resources. Of central importance for this approach is the geographic distribution of qanats, which allows elevation mapping of the groundwater table. Combining sedimentological documentation or models can suggest constrains on the hydraulic properties, such as conductivity and aquifer stratification and dimensions. Although this approach is independent of climatic data, qanat discharge measurements or indigenous knowledge, there are obvious benefits in terms of verification, scenario predictions and scaling when these information types are also used. We demonstrate the methodology using qanats (karezes) north of Kandahar, Afghanistan.

Application of self-affine fractal methods for generating fractures with internal aperture heterogeneity and impacts on flow

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Understanding fluid flow through fractured crystalline rocks is important in many areas, including subsurface infrastructure and storage of nuclear waste. Aperture variability exhibits significant control of the flow field through single fracture and fracture networks within sparsely fractured crystalline rock. Inclusion of aperture heterogeneity however is often hampered due to lack adequate numerical representations and field measurements. Self-affine fractal methods, which use two key parameters, the Hurst exponent and scaling parameter, are used to develop a model for aperture generation which accounts for relative anisotropy and correlation between the upper and lower surfaces creating the aperture. Surface scans of a natural rock fracture are used and a methodology for analysing and extracting relevant parameters is developed. Analysis of the natural fracture surfaces displays a range in Hurst exponent and scaling parameters across parameter space, and pairwise combinations following a linear upper bound can be used to generate aperture fields that accurately reproduce measurements. It is shown that correlation between the upper and lower surfaces is less sensitive than the Hurst and scaling parameters. The model is an improvement on previous methods and produces aperture ensembles that closely correspond with the natural aperture obtained from surface scans. A sub section of the sample is also taken and analysed, and input parameters based off restricted measurements were successfully used to generate up-scaled apertures. The model can generate apertures that are representative of natural fracture apertures and can be implemented in larger scale fracture network models allowing for numerical simulations to include representations of aperture internal heterogeneity. Impacts of the Hurst and scaling parameters on flow through the resulting aperture fields are also discussed.

Site investigation of the natural geological barrier of a rock quarry as a potentially new landfill site

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In Norway, landfill sites are often established in old rock quarries. To assess the quality of the surrounding bedrock as a natural barrier it is vital to understand the fracture network and their inter connectivity as these can provide routes for groundwater flow towards the interior of the quarry and pathways for contaminants out of the site. Different sources of information can be considered. Aerial photos can be used to map major and minor lineaments as well as their continuity. Borehole logs and time series of groundwater level, and pumping data collected from the quarry drain system can also be analysed. Water collected from specific fractures, and analysis of isotope ratios can also provide valuable information about sources of groundwater recharge.

We will present the interpretation of aerial photos, and data from 8 observation wells drilled in the circumference of the Rekefjord rock quarry in southwestern Norway. The geology of the quarry consists of Norite, a mafic intrusive igneous rock composed of a mixture of massive medium sized Monsonorite (1-5mm), dominated by plagioclase and the dark mineral orthopyroxene (NGU, 2016). Structural interpretation indicates randomly distributed orientation of the fractures. The bore hole logs indicate that there could be several vertical fractures, these are not well captured in vertical boreholes, therefore a Terzaghi correction was applied (Sanderson & Nixon, 2015; Terzaghi, 1965). Most of the fractures appear wide with an aperture size between 2 mm and 10 mm. Fracture connectivity and various topological parameters were also investigated. The average degree of connection (D) varies between 3.09 to 1.92, indicating that some parts of fracture networks are better connected than others. Well-connected fractures will have the largest potential for groundwater flow. Previous Lugeon tests (Slinde, 2021) for different sections of the boreholes, range from 1.6×10^{-10} ms^{-1} to 1.2×10^{-6} ms^{-1}. No relationship between hydraulic conductivity and fracture frequency was observed. Based on the different datasets, we will present a preliminary conceptual groundwater model for the rock quarry and its surroundings.

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Use of UN framework for classification (UNFC) for groundwater resources

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There is an urgent need to support sustainable development of groundwater resources, which are under increasing pressure from competing uses of subsurface geo-resources, compounded by land-use and climate change impacts. Management of groundwater resources is crucial for enabling the green transition and attainment of the Sustainable Development Goals. The United Nations Framework Classification for Resources (UNFC) is a project-based classification system for defining the environmental-socio-economic viability and technical feasibility of projects to develop resources and has been recently extended for groundwater. UNFC provides a consistent framework to describe the level of confidence of groundwater resources by the project and has been designed to meet the needs of applications pertaining to: (i) Policy formulation based on geo-resource studies; (ii) Geo-resource-management functions; (iii) Corporate business processes; and (iv) Financial capital allocation. To extend use in groundwater resources management, supplemental specifications have been developed for the UNFC that provide technical guidance to the community of groundwater professionals to enhance sustainable resource management based on improved decision making. This includes addressing barriers to sustainably exploiting groundwater resources, avoiding lack of access to water and also related to 'common pool resources' in which multiple allocations are competing with domestic water supply (e.g. geo-energy, minerals, agriculture and ecosystems, and transboundary allocation of natural resources). UNFC for groundwater resources is designed to enhance governance to protect the environment and traditional users while ensuring socio-economic benefits to society. Consequently, it is a valid and promising tool for assessing both sustainability and feasibility of groundwater management at local, national and international levels

Compound-specific isotope analysis (CSIA) – A reliable method to assess chlorinated solvent degradation in groundwater systems

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The long-term persistence of chlorinated solvents poses a major challenge for the remediation of contaminated sites. To determine the best remediation strategy for sites contaminated by chlorinated solvents, it is of major importance to determine whether chlorinated solvents are subject to degradation. If degradation is absent the sites need to be remediated by active remedial measures such as excavation, which is time-consuming and often related to high costs. In contrast, if chlorinated solvents degradation occurs such that the contamination concentrations are expected to decrease below the remediation goal within reasonable time frames, a monitored natural attenuation approach (MNA) can be applied. MNA is a much cheaper remediation option compared to more active remedial approaches. Thus, the costs of a site remediation heavily depend on whether chlorinated solvents are subject to degradation.

Despite its high importance for applying the best remediation strategy and for its costs, determination of chlorinated solvent degradation is challenging based on concentration measurements only. Often, it remains unclear if chlorinated solvent concentrations decrease due to dilution or degradation. To overcome the shortcoming of concentration analysis only, compound-specific isotope analysis (CSIA) has emerged in the last two decades as an effective tool to determine chlorinated solvent degradation. The method makes use of the preferential cleavage of bonds between light compared to heavy isotopes during degradation, leading to a progressive enrichment of heavy isotopes in the parent compared to the daughter compound. Hence, an enrichment of heavy carbon isotopes in the parent compound over time provides unequivocal evidence for chlorinated solvent degradation.

This study aimed to assess the degradation of chlorinated solvents in the groundwater at the Räven site in Helsingborg, Sweden using CSIA. The Räven site was contaminated by chlorinated solvents, predominately tetrachloroethene (PCE), during dry cleaner activities between 1929 and the end of the 1970's. To obtain detailed insight into the degradation of the chlorinated solvents and its implications for remediating the site, high-resolution carbon CSIA profiles were determined from 9 multilevel wells located in the contamination source zone and farther downstream. In the source zone, the CSIA profiles revealed that the degradation activities are generally low and that trichloroethene (TCE), previously considered as a degradation product of PCE, likely originates from the contamination source. Moreover, the CSIA combined with the concentration profiles in the source zone showed that chlorinated solvent degradation stalled at cis-dichloroethene (cDCE) and did not proceed further to vinyl chloride (VC). In the downstream multilevel wells, the chlorinated solvent concentrations decreased by more than two orders of magnitude, and the degradation activities were higher as opposed to the source zone, which also proceeded to some extent to VC. However, despite the higher degradation activities in the downstream wells, the concentration decrease compared to the source zone could be attributed to a higher extent to dilution in comparison to degradation. This demonstrates that MNA might be not a suitable remediation approach for the Räven site and that other remedial measures might be more effective for fulfilling the site remediation goals.

Groundwater flow in crystalline rock: flow-log data evolution and predictive modeling

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Prediction of groundwater flow in crystalline rock remains a challenging task, which is important for many geoengineering applications, such as geological disposal of high-level radioactive waste, rock tunnelling, and geo-energy extraction and underground storage (e.g., Zou & Cvetkovic 2023). At present, many flow-logs and computational models have been developed to characterize and analyze hydraulic properties and groundwater flow processes in crystalline rocks. It is realized that groundwater flow pathways in crystalline rocks are dominated by the complex rock fracture networks, which essentially contains multiscale hydraulic heterogeneity, such as the network scale heterogeneity, fracture-to-fracture scale heterogeneity and internal heterogeneity due to fracture surface roughness. We analyzed the impact of multiscale heterogeneity on inference of fracture transmissivity based on flow-log measurements and prediction of groundwater flow in crystalline rocks using three-dimensional discrete fracture network and channel network models in our recent studies (i.e., Zou and Cvetkovic 2020, 2021; Zou et al., 2023; Frampton et al., 2019). The results generally show that the internal heterogeneity has relatively small impact on the inferred transmissivity distributions compared to the fracture-to-fracture scale heterogeneity. Comparison between the inferred and underlying input transmissivity distributions shows that interpreting hydraulic tests in crystalline rock using flow logs and the Thiem equation may underestimate the variation range of the underlying transmissivity. The ambient hydraulic gradient has limited impact on pumping test because the pumping flow is dominant compared to the ambient flow during pumping. The channel conductance can be statistically parameterized based on available hydrogeological characterization data. It is possible to compensate for the neglected heterogeneity in the channel network model by enhancing the variability of assigned channel conductance. The findings are useful for improvement of hydraulic characterization and simplification of predictive models for simulating groundwater flow in crystalline rock relevant to various applications.

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Session 2
Applied geology as an engineering tool: enhancing collaboration and reducing risks for infrastructure and urban construction

Session Chairs:
Magnus Hellqvist,
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Martin Persson,
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Arsenic rich metasedimentary belts in the Mälardalen region – a primary source of contamination

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Arsenic (As) is a toxic and carcinogen element that locally occurs at high background levels in the bedrock from which it may be mobilized and spread to the environment. At present, this is an acute problem in parts of the Mälardalen region with extensive demands for exploitation of the bedrock. The lack of knowledge on the geological setting, petrography, and mineralogy of the As-rocks is hampering safe production and use of rock masses.

To address this problem, a field campaign targeting high-As rocks was carried out in the Arlanda-Rosersberg and the Mariefred-Södertälje area. Documentation of the field context, petrography, mineralogy, and bulk rock geochemistry is used to pin down where and in what form As is sitting in the rocks.

In the Arlanda-Rosersberg area, high-As rocks (>10 ppm As) occur along a NNE trending steeply dipping ca 5-10 km wide metasupracrustal belt. Geothermobarometry coupled with phase equilibrium modelling indicate amphibolite facies metamorphism at pressures of 3.0–5.5 kbar and temperatures of 490–640 °C (Skoog, 2022). Elevated levels of As are preferentially found in rocks of a sedimentary origin, pegmatites and in mafic meta-intrusions. Associated rhyodacitic to andesitic volcanic rocks are low in As. Highly elevated levels of arsenic at 100 ppm to near 1 wt.% occur in a ca 1 km wide zone in the central-eastern part of the supracrustal belt. Here, arsenic rich lithologies include epiclastic metasedimentary rocks, structurally concordant sills and dykes of metagabbro, metagranitoids with As-rich xenoliths, and fractionated pegmatites and aplites. There is no clear correlation between high-As and enrichment of sulphur in the rocks. Arsenopyrite (FeAsS) is the most common As-mineral but Löllingite ($FeAs_2$) is also common. It occurs as a single phase (in places euhedral) or as overgrown with a rim of arsenopyrite, in places followed by an outer rim of pyrrhotite which is the dominating sulphide. Pyrite is less common but often present in late micro-shear zones together with albite, K-feldspar, and chlorite.

The bedrock in the Mariefred-Södertälje area is dominated by upper-amphibolite to granulite facies metatexitic to diatexitic ±garnet±cordierite±sillimanite paragneiss with abundant disrupted dykes and lenses of metamafic rocks and late kinematic granitoids. The metamorphic complex is cut by unmetamorphosed NNW to WNW trending, less than 1 dm to several meter wide dolerite dykes that crosscut the migmatite structures. The gneisses, the late kinematic granitoids and the dolerites are with few exceptions low in As (≤ 10 ppm). As contents at 300-400 ppm have only been encountered in mafic granulite (opx+hbl+plag) and in 1-3 dm wide disrupted garnet-rich dykes and lenses of intermediate chemical composition. Reconnaissance petrographic work in the metagabbro shows that arsenopyrite and löllingite occur as 100-200µm large crystals in the matrix or as <10 µm minute crystals at the grain boundaries of hornblende or inside hornblende. Minute grains of löllingite and probably also cobaltite occur inside pyrrhotite but has not been observed in orthopyroxene. Arsenopyrite is the dominating As-mineral and pyrrhotite is the dominating sulphide, pyrite is absent.

Acknowledgements

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Theory, model, and method for coupling and interpreting hydromechanical investigations in the laboratory and in the field – Focus on low rock stress, initial results

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Introduction

Large fractures with low effective stress are of central importance for stability and inflow, in rock construction and when extracting or storing natural resources and energy. Fractures, especially large ones, affect geometry and technical execution related to reinforcement and grouting. Superficial, large fractures can be significantly affected if the grout pressure is chosen too high.

Given this, it is of great importance to be able to identify and hydromechanically describe fractures both in the laboratory and in the field. The difficulty of investigating (hydro)mechanical properties in the field makes a field-laboratory coupling particularly relevant.

Aim and hypothesis

The aim of this work is therefore to develop theory, model, and method to describe, couple and interpret hydromechanical investigations, in the laboratory and in the field, for different scales, focusing on fractures with low effective rock stress.

The hypothesis is that this can be done via modelling and hydraulic tests, focusing on stiffness, k, fracture aperture, b, contact point distance, ω, number of contact points and mechanical properties of the rock mass (E, ν). Key references for modeling and coupling of hydromechanical investigations in the laboratory and in the field are Hertz (1896), Witherspoon et al. (1980), Olsson & Barton (2001), Cooper & Jacob (1946) and Doe & Geier (1990).

Initial results

A basic analytical model has been developed and so far tested against a laboratory experiment with known geometry and low rock stress (Thörn & Fransson 2015, Thörn et al. 2015). There is good consistency. Values of stiffness, k, and width, b, for the specific laboratory experiment also coincide with a semi-empirical relation for k and b that has previously been developed based on data from Äspö and Laxemar (Fransson 2014).

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Norwegian National Database for Geophysics (NADAG geophysics)

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Ground investigations have gained attention and importance for infrastructure development in recent years. They are crucial for safe and secure planning, including the assessment of geohazards and realization of new roads, tunnels and other infrastructure projects.

While a national database for geotechnical drillings (NADAG) was established a decade ago, a new database for geophysics has only recently been launched (NADAG geophysics). It is an improved and modernized expansion of the database for borehole and ground geophysical data collected by the Geological Survey of Norway over the past 70 year. The new database is now supplemented with data from public agencies and contractors, including the public road administration, railway authority and municipalities.

An automated workflow allows the user to register geophysical data and surveys via a user-friendly web interface as well as a modern programmatic interface (API). The surveys are then archived in a database from which metadata and data are available for visualization and download via NGU’s map services. This workflow is designed to receive and store all types of geophysical metadata and data, regardless of format, size or source. It has proven crucial to involve public agencies and contractors in the design and testing from an early stage on.

Currently, data registration in the database is voluntary, but the public agencies aim to make it mandatory for surveys financed with public resources. In some cases, it may be beneficial to only register metadata without enclosing the actual data and results.

This project, as the first of its kind, has so far focused on the registration of new data and migration of existing metadata. In the coming years, more focus will be given to data accessibility, offering a range of options for visualization and download.

Hyperspectral imaging of drill cores from Heggdal (E39, Møre-Romsdal, Norway) for mineral characterisation and mapping of expansive clays

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Drill cores providing essential information for planning of infrastructure projects and innovative methods are desired for efficient analysis of these core materials. Mineral composition controlling geotechnical properties should be carefully evaluated during the planning stage in infrastructure projects. Specific clay minerals, in particularly smectites, which can also occur with chlorite as mixed-layered clay, can expand due to water absorption, and generate significant swelling pressure. Extra measures might be required for tunnel constructions and should be addressed during planning when expansive clays with critical swelling pressure occur. It is therefore crucial to analyse the presence of expansive mineral composition in the planning stage of infrastructure projects.

Hyperspectral imaging is a non-destructive, non-contact method to identify and map mineralogical composition utilising the reflectance properties of minerals within the visible and the infrared spectral range of light and is increasingly used in rock laboratories for drill core analysis. Many minerals, among others, different clay types can be differentiated by reflectance spectrometry and can be therefore mapped with hyperspectral imaging.

In this study, the potential of hyperspectral imaging is evaluated to detect, map, and quantify expansive clays in the Heggdal cores, drilled for the infrastructure project E39 Vik–Julbøen (Vestnes, Møre og Romsdal, Norway), which is aiming to cross the Romsdalsfjord with a 14.5 km long underwater tunnel from Vik to Nautneset and a 2 km long suspension bridge from Nautneset to Julbøen. The project is a part of the infrastructure program led by the state highways authority intending a ferry-free coastal highway in Southern Norway.

A selection of core boxes from the Heggdal core have been scanned with the core hyperspectral imaging system at NGU using a SisuRock scanning system equipped with two hyperspectral image cameras measuring within the visible near-infrared (VNIR, 400-1000nm) and short-wave infrared (SWIR, 1000-2500nm) spectral range. The evaluation of the hyperspectral image data shows that image spectra with smectite and chlorite signatures have been found. The spectra and spectral maps indicate that the clay composition in these cores is dominated by smectite and chlorite and both minerals are found in all analysed core boxes. The spectral mapping results can guide in-depth sampling, and swelling pressure should be tested at locations with high smectite and chlorite concentrations.

XRD analysis confirms that spectra interpreted to be representative for smectite and chlorite in these data showing highest concentrations of this minerals and that the clay composition in these cores are dominated by smectite and chlorite. The XRD analysis also indicates that the spectral maps provide representative mineral distribution and mineral concentration maps. This study confirms the potential of core hyperspectral imaging for mineral characterisation and to map minerals of particular interest such as swelling clays or other hazardous material over the entire core lengths. Further work is required for more comprehensive validation studies, to determine limitations and to adjust the method for the need in infrastructure projects.

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Unexpected weak zone at the Bergåstunnel construction site – hypotheses about the age and formation

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During the construction of the 2015 m long Bergåstunnel, which comprises a part of the new E6 in Nordland County near Trofors in Grane municipality, an unexpected zone of weak material was encountered beneath the Bergdalen valley. The construction work had to be halted to complete additional investigations to constrain the thickness and composition of the weak zone. From 5 boreholes drilled from the tunnelface and one borehole drilled from the surface down to the level of the tunnel, it was identified that the zone was about 70 m wide and composed of two main layers: a lower unit of light brown, heavily altered bedrock, and an overlying layer of grey, overconsolidated moraine. This weak sone is located at or close to the border between two bedrock units: metasedimentary rocks comprising amongst other limestones and sandstones, and granite to granodiorite. After adjusting the excavation and reinforcement method, the weak zone was successfully excavated from around mid-April to mid-July of this year.

The Norwegian Road authority hired an interdisciplinary group from the Geological Survey of Norway to characterize the mineralogical and geochemical composition of the different layers comprising the weak zone, and to constrain the formation process and age of the weak zone. These analyses were complemented by geophysical investigations of the extend of the weak zone using electrical resistivity and refraction seismic. The geophysical investigations could clearly identify the extent of the weak zone, although the results of the electrical resistivity analysis are strongly influenced by the underground construction work. The structural framework as well as mineralogical and geochemical composition suggest that the lower light brown unit was formed by hydrothermal alteration of the bedrock related to a regional set of east-west striking mineralized fracture zones. Palynological analyses of the overconsolidated moraine identified marine palynomorphs from

Costs and benefits of reducing groundwater drawdown risks in tunnelling

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With increasing global urbanization follows a land-use conflict which results in a higher demand for locating infrastructure such as roads and rails below the ground surface. However, construction below the ground surface and the groundwater table is often associated with groundwater leakage and decline in groundwater levels in surrounding aquifers. This subsequently results in a wide variety of risks to e.g., human health, buildings, infrastructure, and the environment and thus potential loss of services for human wellbeing. To reduce these risks, risk-mitigation measures can be implemented. There are both costs and benefits of internal (project owner) and external (all other affected stakeholders in society) character associated with implementing measures; benefits constitute the reduced risks of implementing the measure and costs constitute the implementation cost. To use society's limited resources in an efficient manner when implementing measures to reduce hydrogeological risks, these costs and benefits must be balanced. Cost-benefit analysis (CBA) is a widely used method for balancing risks by accounting for positive (i.e., benefits) and negative (i.e., costs) effects on human well-being on a societal level, including present and future generations. A CBA should include all internal and external costs and benefits for all affected stakeholders of implementing a measure. This implies that a thorough and comprehensive identification of cost and benefit items are of importance for the CBA to provide robust decision support. The aim of this contribution is to present two gross-lists of costs and benefit items associated with reducing groundwater drawdown risks in tunnelling. The applicability of the catalogues for identifying cost and benefit items are also exemplified with a case study constituting a railroad tunnel in Sweden.

Geological approach to Lined Rock Cavern (LRC) design in green transition

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This study reviews holistic approach for both geological and rock engineering applications for Lined Rock Cavern (LRC) design in Finland. LRC refers to underground caverns used for the storage of gas under high pressures (20-25 MPa). This storage technique has been developed in Sweden during the last 30 years.

This study investigates the possibilities to construct an underground hydrogen storage in crystalline bedrock in Finland. The need for a large storage capacity is linked to the development of the green hydrogen economy and green transition. Several industrial processes require large volumes of hydrogen to lower greenhouse gas emissions. Green hydrogen is produced by renewable energy and is therefore weather dependent. Large storage facilities are needed to ensure continuous feed for industrial processes. Such large quantities of pressurized gas are safely stored only deep underground.

The implementation of the LRC must be safe, but also economically sound. The work considers the geological site selection for the underground storage, rock engineering planning, technological solutions like lining materials, excavation, construction, and operating processes, among others.

An LRC site requires certain geological properties to ensure its stability throughout its use. The Finnish bedrock (mainly Precambrian crystalline rocks) provides very favorable conditions to meet the strict geological and rock mechanical requirements.

At first, we need to define recommendations for adequate geological and rock mechanical site criteria. This means defining geological setting and rock mass quality parameters or boundary conditions.

After the site criteria have been defined, the next task is to execute the site selection and site characterization phase. This desktop study comprehends lineament and rock block analysis, investigating existing geological and geophysical data and evaluating hydrogeological and rock mechanical conditions. After the screening, one of the pre-selected sites will be investigated in detail in a case study phase by drilling and completing field measurements. Field methods will cover field mapping, drilling, drill core logging, geophysics, in-situ stress measurements, groundwater and flow measurements, rock mechanical tests, geochemistry and petrophysics.

Geological approach is complemented by defining also rock engineering design parameters by using rock mechanical modelling and numerical simulation tools for different rock types and rock mass qualities. Design parameters consider e.g. preferred depth, rock stability, cavern size and shape, cavern spacing, rock deformations, in-situ stress and uplift failure.

The aim of this two-year research project is to produce geological, hydrogeological and geomechanical 2D/3D models and numerical analyses from one potential LRC construction site. Case study is also an essential part of the techno-economic feasibility study, which is one of the outcomes of this research. The aim is also to produce guidelines for both site selection and site characterization with road map for LRC production and cost estimates. This project is a collaboration between Finnish public and private companies and experts covering wide range of relevant industries.

Rational and efficient ground investigations for industrialised construction of new railways

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To complete a new Swedish railway line in a much shorter timeframe than today, alternatives to the traditional methods need to be explored. One option is the use of prefabricated concrete slabs elevated on piers, analogous to the concept used in China for building new railways in record time (He et al., 2017). The method has the advantage of directly tackling the barrier effects exhibited by traditional methods and can be built following an industrialized production process. But the pre-investigation process for such a method needs to be put into a Nordic perspective.

A new methodology is being developed to localize optimal pier locations, determine the foundation type in each location and to provide estimated uncertainties. The method relies on archived data migrated to a database within a GIS and Python environment with high potential for automation. A combination of machine learning techniques and analytical hierarchical process are used to get a first estimate of pillar locations, foundation types and uncertainty. If the database is insufficient, new data is gained and incorporated by the use of self-piloted UAV:s equipped with radar and piloted UAV:s equipped with an inductive EM device. The database can then be updated and further refined by ground-based geophysics. With this stepwise implementation, a drastic decrease in geotechnical ground surveys can be achieved (Baynes & Parry 2022) and decisions can be made continuously.

The predictive machine learning models of ground uncertainty and archaeological sites complements the method by providing a risk-based approach to the final decision-making process on pier locations prior to the geotechnical field campaign.

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Session 3
Geothermal energy and geological storage

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A first stress field assessment for geothermal exploration in Gothenburg (borehole GE-1)

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This study contributes to early phases site investigations for geothermal exploration of radioactive granites in Gothenburg, southwest Sweden. The main objective of this study is to assess the orientation of horizontal stresses from borehole stress indicators, and to discuss the implications for geothermal exploration. Analyses of high-resolution acoustic televiewer (HiRAT) image data from the near-vertical, 1 km deep borehole GE-1 provide information on metamorphic features, natural fractures, and three types of stress indicators: borehole breakouts (BOs), drilling induced fractures (DIFs), and petal-centerline fractures (PCFs).

Removal of rock during drilling generates local elastic circumferential stress concentrations. For a borehole drilled parallel with the in-situ vertical principal stress, the circumferential stress magnitude varies with respect to the far-field in-situ maximum and minimum horizontal principal stresses. BOs are formed in the minimum horizontal stress direction if the circumferential stress overcomes the compressional rock strength, and DIFs are formed in the maximum horizontal stress direction if the circumferential stress exceeds the tensional rock strength (e.g. Zoback et al. 2003). PCFs represent a less well-known type of drilling-induced fracture that develop parallel with the maximum horizontal stress direction some meters below the drill bit, that subsequently is penetrated by the borehole (e.g. Kulander *et al.* 1990). As a result, PCFs may be present in both drill cores and in the borehole wall.We observed about 135 stress indicators in borehole GE-1, from 0.2 to 1.0 km depth. The results suggest that the stress field is uniformly oriented in the NNW-SSE mean maximum stress orientation. About 135 stress indicators are observed from 0.2-1.0 km depth. We further observed co-occurrence of BOs and DIFs in several sections, which is unusual for crystalline rocks.

It is not possible to fully distinguish open natural fractures from those that are sealed (filled or closed) using HiRAT data alone, but the classification of Massiot *et al.* (2018) offers a first interpretation on separating open and sealed fractures. Over 1500 pre-existing structures (natural fractures, foliation) were mapped in the borehole. The prevailing stress regime controls if natural fractures and foliation are well-oriented for stimulation. For strike-slip and normal faulting stress regimes, fractures steeply dipping towards WSW are well-oriented for stimulation, whereas shallow dipping fractures are well-oriented for simulation in a reverse faulting stress regime. Our results tentatively suggest that a strike-slip stress regime in GE-1, but additional stress measurements are needed to constrain the complete stress field at study depth and towards greater depths.

The secondary objective of this study is to test different strategies for interactive stress analysis through visual inspection of acoustic images, and to highlight the need to develop better guidelines for data interpretation. We have tested and compared three methods of data interpretation. Our results suggest that BO orientations, especially in fractured formations, increases the risk of misinterpreted data. In contrast, DIF data appear to produce similar results, regardless of analysis method.

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Storage of carbon dioxide and hydrogen; geological capacity and risk

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To limit global warming to 1.5–2 °C, the Intergovernmental Panel on Climate Change predicts the need for carbon capture and storage (CCS). For CCS to work, CO_2 storage capacity on a global scale is crucial. It is estimated that the required storage capacity for 2050 (3–10 Gton CO_2 per year) will probably not be achieved for most of the IPCC scenarios (Krevor et al. 2023). Geologically, there is potential for onshore/offshore storage, but reservoirs need to be investigated and verified for capacity. The storage rate of today is the bottleneck for the CCS value chain as less than 0.1% of the global CO_2 emissions are captured and stored in the subsurface (Zhang et al. 2022).

Presently, CO_2 storage focuses on marine subseafloor reservoirs. However, there are a few noteworthy onshore examples such as the Icelandic Carbfix site. These sites utilize the reactivity of the volcanic bedrock with CO_2 and take advantage of natural or induced bedrock permeability to facilitate the injected CO_2 for subsequent mineral carbonation. During mineral carbonation, CO_2 is naturally converted into stable carbonate minerals, which is a potentially safer way of permanently storing the CO_2 in the subsurface compared to marine storage (Snæbjörnsdóttir et al. 2020). In the pioneering INSURANCE and TAILOR-MADE projects, the potential for onshore storage in the Swedish bedrock and in mining waste materials is investigated, respectively, together with the utilization of industrial waste streams from paper/pulp and mining to optimize the CO_2 capturing efficiency. Compared to Iceland, the Swedish bedrock is metamorphosed, deformed, and altered. The geological conditions for mineral carbonation will be different but, as the storage capacity is the bottleneck, lithologies other than the ones in Iceland also need to be investigated for their storage potential. Sampled lithologies throughout Sweden will be subjected to carbonation experiments covering suitable mineralogy, reactive surface areas, porosity and permeability, fluid pH, pressure, and temperature. The suitability of the reservoir rock is dependent of all these parameters (Snæbjörnsdóttir et al. 2020).

Since the global scale-up of storage capacity is uncertain, global CO_2 emissions need to be strongly reduced by phasing out fossil fuels to meet the projected storage capacity. Reductions in emissions through electrification of industry sectors is likely required. CCS should then be used in industries that are hard to abate, i.e. cement and paper/pulp where the carbon enters the industrial processes through the raw materials used. In northern Sweden, the steel industry will shift to renewable energy sources coupled with hydrogen storage (for battery capacity) and thereby reduce the CO_2 emissions by an estimated 90% from point emitters through electrification (the HYBRIT technology). When scaling this technique from present pilot- to industry implementation, the potential for geological storage of hydrogen and potential subsurface reservoir leakage into the surrounding environment is addressed in the HYDROTRANS project. Here, flow modelling of hydrogen (and also CO_2) through the bedrock down to the nanoscale is analytically investigated at LUMIA (Luleå Material Imaging and Analysis) and the MAX IV synchrotron laboratory.

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Novel CO_2-based electrothermal energy and geological storage system

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Rising energy demand is pushing electricity prices and emissions to unprecedented levels, with serious implications for the economy and the energy transition. The EU's long-term climate strategy and the European Green Deal emphasise the key role of renewables in the continent's decarbonisation goals and the implementation of large-scale energy storage to continuously power the entire electricity system.

The CEEGS (CO_2-based Electrothermal Energy and Geological Storage Systems) research project is a three-year project funded by Horizon Europe EU programme. The project aims to implement a new transcritical CO_2 cycle concept, based on underground energy storage and simultaneous CO_2 sequestration in the geological reservoirs. Due to the thermodynamic properties of CO_2, this gas will act as a working fluid in the energy storage system. Under favourable geological environments, an added value may result from geothermal heat recovery.

The main challenge of this project is to solve the difficulties related to the interface between the surface and underground parts. This includes aspects related to CO_2 flow composition, well design, turbomachinery properties and overall integration. To achieve this, a conceptual integration design is to be developed and adapted to operate in different scenarios and modes of operation based on: Energy storage from renewable energy sources or energy storage for CO_2 capture.

Preliminary results show that these cycles are promising energy storage technologies, highly competitive in terms of electricity-to-electricity storage efficiency (42-56%) and cost (70-120 USD/MWh) for energy storage capacities ranging from 500 kW and limitless. Furthermore, the results indicate that more than 1 Mt/year of additional CO_2 can be stored [2,3]. The energy storage system is composed both of surface thermal storage and of underground storage through CO2 injection and production wells, thus decreasing environmental and visual impacts at surface. The CEEGS concept has great potential to be replicated worldwide in a range of realistic geological environments.

The project is expected to increase the CEEGS current TRL 2 to TRL 4, through overcoming obstacles such as the interfacial gap between the surface transcritical cycle and the CO_2 reservoir, improving the technological economics of the technology and to prove its feasibility. An analysis of the social, economic and sustainability impact is to be conducted to clarify the contribution of the technology for the climate change mitigation, its economic viability and possible business models, while identifying the social acceptance challenges that it may face.

By coupling energy storage with direct CO_2 emissions reductions, CEEGS supports the ambition of the Paris Climate Agreement and Europe's green objectives to explore new smart energy systems. This will improve the efficiency and cost-effectiveness of CO_2 capture, utilisation and storage (CCUS), enabling cost-effective and environmentally friendly renewable energy storage technology.

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Hydrothermally altered shear zones: a new reservoir play for the expansion of deep geothermal exploration in crystalline settings

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Context

This abstract introduces an innovative approach to deep geothermal exploration in crystalline settings. Traditionally, geothermal energy production has relied on the exploitation of permeable reservoirs, which are rarely found in crystalline settings. However, recent research has unveiled a promising reservoir play—brittle shear zones that have undergone hydrothermal alteration—that could leverage the expansion of deep geothermal exploration in crystalline settings.

Scientific challenges

Exploring deep geothermal resources in crystalline settings offers a promising solution for direct space heating, industrial applications, and electricity generation. However, the typically low porosity and low permeability of crystalline rocks remain a key obstacle in deep geothermal exploration. Faults and fractures are understood to play a substantial role in defining permeable zones that facilitate efficient heat extraction from crystalline reservoirs. Nevertheless, fractures constitute just a part of the potential void space in crystalline rocks. Besides fracturing, the effects of other equally important processes such as brecciation, cataclasis, and mineral dissolution have received limited attention as potential contributors to creating prolific crystalline reservoirs.

Methodology

Our study involves a comprehensive geological and petrophysical investigation of granitic reservoirs formed within a brittle shear zone in central Finland, evaluating their feasibility as deep geothermal targets. This investigation combines petrography, hyperspectral imaging, CT scans, micro-XRF spectrometry, and a suit of laboratory-based experiments (i.e. porosity, permeability, density, elastic wave velocity, and thermal conductivity) to characterize the reservoir performance of these granites.

Discoveries

Optimum reservoir properties were observed in granites affected by cataclasis and mineral dissolution, leading to a notable porosity of ~20%. Reservoir quality is largely controlled by the pore network morphology. Alongside fractures, interconnected moldic, sieve, and interparticle pores contribute to substantial permeability of $\sim 5 \times 10^{-14}$ m^2 (50 mD), even under high confining pressures of 50 MPa (~2 km deep). These processes are typical of brittle shear zones that have undergone high-temperature (200–300°C) propylitic alteration, which have the potential to create extensive (>100 m) interconnected crystalline reservoirs. Additionally, we find that granites dominated by fractures only have high permeability ($\sim 10^{-12}$ m^2) at relatively shallow depths, which sharply decreases to $\sim 10^{-21}$ m^2 as the confining pressure increases. Conversely, granites that have undergone alteration and brittle shearing exhibit comparatively milder permeability reductions as confining pressure increases.

Implications for geothermal exploration

The discovery of hydrothermally altered shear zones as viable geothermal reservoirs may represent a paradigm shift in deep geothermal exploration in crystalline settings. Highlighted is the pivotal role of pore-network morphology in altered and brecciated granites, bearing great significance for identifying prolific permeable zones in crystalline settings. This observation is of paramount importance not only for finding prolific permeable zones within crystalline settings but also for advancing Enhanced Geothermal Systems (EGS), which could mimic natural reservoirs by prioritizing the development of intricate fracture networks through thermal and chemical enhancements.

Evaluating the potential for onshore carbon storage through mineral carbonation: Insights from the INSURANCE project

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The 2015 Paris Agreement seeks to limit global temperature increase below 2°C, demanding substantial CO_2 emissions reduction. To achieve this, negative emissions, endorsed by international bodies such as the International Panel on Climate Change (IPCC) and the International Energy Agency (IEA), are crucial. Negative emissions encompass for instance Bioenergy with Carbon Capture and Storage (BECCS). BECCS combines bioenergy production with CO_2 capture and permanent storage, offering the dual benefit of emissions reduction and sustainable energy generation. In the BECCS project INSURANCE, we are exploring the feasibility of onshore CO_2 storage for BECCS in Sweden and researching methods for CO_2 capture using enzymes and industrial waste streams. The need to explore local storage alternatives becomes increasingly crucial, especially in regions marked by notable emissions at a distance from existing storage reservoirs. Additionally, diversifying mineral carbonation research beyond young basaltic rock formations is essential, ensuring adaptability in more diverse geological settings, and fostering a versatile approach to carbon sequestration.

Through three extensive geological mapping and sampling campaigns across Sweden, close to major point emitters, we have investigated more than 30 lithological units, including various mafic rock types, both volcanic and plutonic. Utilizing microanalytical tools, including scanning electron microscopy, X-ray diffraction, and micro-X-ray fluorescence, we have characterized the samples. Our investigation emphasizes five potential study areas, which include two mafic plutonic massifs of gabbroic composition, an olivine dolerite dyke, and two areas of partially metamorphosed extrusive rocks of basaltic composition. Notably, even among samples that display varying degrees of alteration, their potential remains significant due to the presence of a high molar fraction of reactive silicate minerals e.g., olivine, augite, and Ca-rich plagioclase (Heřmanská et al. 2022) with high content of Ca, Mg and Fe.

The collected parameters are used in a geochemical model that aims to further investigate the reactivity of the studied rock types upon interaction with injected CO_2-charged water as well as the rate and extent of CO_2 sequestration as a function of injected CO_2. The mineralization in the selected rocks has been simulated using the PHREEQC software (Parkhurst and Appelo, 2013). Similar to Marieni et al. (2021), reaction calculations were used to estimate the expected geochemical reactions and mineralization rate efficiency in the absence of a detailed system description. The mineralization was approximated using CO_2-charged rainwater injected around 50°C into the 1D column of the selected rock types. The results from the model are used to understand the impact of the injection on the geochemistry of selected rocks as well as associated volume changes that may occur during mineralization.

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The origin and fate of trace metals during CO_2-charged water injection into basaltic geothermal reservoir, Nesjavellir SW Iceland

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The Nesjavellir geothermal power plant is located within Hengill volcanic system (SW Iceland) where bedrock consists of successions of hyaloclastites and lava sequences formed during glacial and interglacial periods, respectively. The common alteration minerals include smectites, zeolites, quartz, calcite, prehnite, sulfides, feldspars, epidote, chlorite, wairakite and wollastonite (e.g., Franzson, 1998). The hydrothermal fluids in the geothermal system are meteoric in origin and dilute with chloride concentrations <250 ppm. Among the major solutes are CO_2 and H_2S which are emitted during geothermal utilization in quantities of 15 and 8 kt/yr, respectively. Based on carbon and sulfur isotope systematics, the main sources of CO_2 and H_2S in these hydrothermal fluids are magmatic gas input and host rock leaching (Stefánsson et al., 2017). To limit the power plant emissions, a pilot project using Carbfix technology has been conducted in Nesjavellir, where CO_2 and H_2S are separated from the power plant exhaust stream, dissolved in condensed steam, and injected together with separated geothermal water into the injection reservoir (Gunnarsson et al., 2018). Here this mixture reacts with basaltic host rock resulting in mineralization of these gases and therefore providing their safe and permanent underground storage. One of the main concerns related to a subsurface injection of acidic CO_2-H_2S fluids is enhanced mobilization of trace metals which constitute the reservoir rocks. This increased metal mobility has been observed during laboratory experiments mimicking water-CO_2-basalt interaction (e.g., Galeczka et al., 2013). To assess the possibility of toxic metals plume forming during the injection of CO_2-H_2S charged water, we investigate sources and sinks of trace metals in the storage reservoir. We take into account the chemical composition of Nesjavellir boreholes' drill cuttings and the geothermal fluid at depth and on the surface after depressurization. We demonstrate that quantification of metal fluxes in such conditions is crucial for predicting long-term environmental impact of such gas injections especially when considering scaling up of the operations.

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Maturation for potential CO_2 storage in Denmark – The Stenlille and Havnsø structures

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Geological storage of CO_2 has become important in relation to capture and thus to reduce emission of large quantities of greenhouse gases affecting the climate. Subsurface storage of CO_2 is part of the Danish political 2021 CCS-strategy. Eight geological structures are investigated and matured with seismic acquisition (e.g. Papadopoulou et al. 2023) and mapping (Gregersen et al. 2023). Two of these structures investigated are the Stenlille and Havnsø structures in western Zealand, Denmark, not far from the cities of Kalundborg and Holbæk. Results of the mapping of this project are presented with focus on the main reservoir sandstones of the Gassum Formation and the thick overlying Fjerritslev Formation mudstone seal. The Gassum Formation of the Stenlille structure has been used for safe storage of natural gas to consumers for more than 30 years. The Stenlille area has the most extensive data base onshore Denmark with 20 wells, a 3D seismic survey and 2D seismic surveys. It is therefore a key area for understanding the nearby Havnsø structure with less data coverage. The areas can be connected using seismic correlation and both structures are structural 4-way closure traps at the reservoir levels and are formed by the growth of an underlying salt pillow during mainly the Jurassic time (Gregersen et al. 2023). The Gassum Formation and deeper sandstone successions could potentially provide reservoirs for storage of CO_2, and key horizons and successions are mapped and the storage potential of the Gassum Formation has been estimated for both structures.

The regional mapping shows that the Gassum and Fjerritslev formations are widely distributed across the region. In the Stenlille structure, details of the Gassum Formation sedimentary systems with channels and progradation are revealed in 2D and 3D seismic data and wells. Such features are also observed in 2D seismic data at the Havnsø structure, where these also support the presence of sand-prone sedimentary systems.

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CCNS: Evaluating CO_2-storage potential offshore southern Norway

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The recent focus on the development of sustainable and low-carbon energy infrastructure in the North Sea region has sparked renewed interest in the Norwegian-Danish Basin (NDB) and its potential for CO2 storage. Stretching from the Southern Norwegian North Sea into the Danish sector and below onshore Denmark, the NDB is characterised by a thick sedimentary package of late Palaeozoic to Cenozoic age. Large volumes of Zechstein salt occur throughout the basin, and salt tectonism significantly influenced Mesozoic stratigraphic development. Earlier exploration for oil and gas has proven successful in only small parts of the area due to the absence of mature source rocks and hydrocarbon migration routes. However, the existence of several clastic storage units overlain by low-permeable lithologies indicate promising conditions for CO2 storage. This has not gone unnoticed: as of October 2023, the Danish Greensand Project has completed test injections into depleted Paleocene oil reservoirs, while two CO2-storage licenses have been awarded in the Norwegian portion of the basin. Previous investigations of the western, offshore part of the NDB have sought to evaluate its overall storage potential (e.g. Halland et al., 2013). Still, the capacities of key units remain largely unquantified, and there is a significant lack of stratigraphic correlation across the NO-DK sector border.

Here, we present preliminary results from the new UiO:Energy & Environment project, *CCNS*. CCNS aims to evaluate the general potential for CO2 storage in the western, offshore part of the NDB, and provide a baseline for further research in the area. This includes updated analyses of the basin's structural development and "CO2-storage plays" from seismic and well data, as well an updated cross-border stratigraphic scheme. Furthermore, the stratigraphy and structures of the NDB provide a great opportunity for investigating the general conditions for CO2-storage in basins affected by salt tectonism, e.g. regarding reservoir/seal distribution and seal integrity.

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Rönnskär repository: Site-descriptive model with photogrammetric verification

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Boliden Mineral AB has recently established a deep rock repository for the deposition of hazardous waste at 350 m below the ground surface. Environmental permitting required assurance from ground investigations and research that the repository system can limit leakage from the repository to a maximum of 10 kg of cadmium and 10 g of mercury per year. An investigation strategy and site-descriptive model was developed in the years 2008 – 2018 as a basis for an integrated assessment of Rönnskär's suitability for a deep rock repository for the waste. The strategy was based on thorough borehole investigations from the surface supplemented with extensive borehole investigations and tunnel mapping during the construction phase of the ramp down to the storage level. Through active design, the supplementary investigations during the construction phase were used to guide the ramp towards a rock volume for the repository with suitable geological, hydrogeological and rock mechanical properties. Guiding the establishment was the deterministic structural model of deformation zones that was established successively during the investigations. This work, as well as all other investigations, were summarized in a site descriptive model before the repository area was chosen.

Before the storage area was built, a photogrammetric mapping methodology was developed to verify that the rock conditions were in line with the models developed. The methodology utilized the contractor's presence on site, which enabled engineering geologists to remotely map all tunnels and mine halls, which reduced production time while documenting them in very high resolution for future relational documents. The use of photogrammetry also had the advantage that the location descriptive model of deformation zones could be verified with high accuracy. The results from the mapping were also used as a basis for updated hydrogeological calculations to verify the site's suitability as a storage volume.

The methodology utilized the contractor's on-site presence, enabling engineering geologists to remotely map all tunnels and rock storage chambers, reducing production time while documenting them in high resolution for future reference. The use of photogrammetry also had the advantage that the site descriptive model of deformation zones could be verified with high accuracy. The mapping results were also used as a basis for updated hydrogeological calculations to verify the site's suitability as a storage.

The relationship of fractures and hydrothermal alteration in fault damage zones in crystalline bedrock

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Understanding fluid flow characteristics within the crystalline bedrock is important for several societally significant applications, including long-term safety of nuclear waste repositories or utilizing geothermal energy. In regions characterized by low-porosity crystalline bedrocks, such as the Fennoscandian Shield, fluid flow is primarily controlled by brittle deformation structures such as faults and fractures. The development of the resulting fracture networks and their properties (including topology, type and extent) are relatively well understood in 2D (e.g. Kim et al. 2004). However, less is known about their 3D-character, with specific reference to the relationship between the fractures and alteration, and their relevance on permeability. As brittle deformation is typically associated with fluid-mediated mineral alteration, which can cause porosity and increase permeability of crystalline bedrock, it is essential to understand the relationships between the different types of fault-associated fractures and alteration patterns. We do know that healing and recrystallization may occur within the core of fault zones, or cores can host impermeable clays, for which reason fluid migration occurs preferentially along the fracture network within the damage zones (Caine et al. 2010). Some recent works (e.g. Bischoff et al. submitted) have improved the understanding about mineral alteration and the resulting porosity in crystalline rocks, but the relationship between the fracture networks and mineral alteration in crystalline bedrock have received even less attention.

This investigation is part of a larger project that aims to provide improved understanding of the 3D-architecture of faults and fault-associated fractures networks, thus the fluid flow pathways within these. This study will contribute to the background information for the project through characterizing the relationships between fault-associated fractures and hydrothermal alteration. In specific, we aim to define: i) the relationship between different types of alteration minerals and fractures, and ii) the spatial distribution of alteration in 3 dimensions. New constraints on the above will reveal whether specific zoning of alteration - associated with the distance from faults or fractures, or occurrence in a specific type of damage zone - can be recognized. Furthermore, our study will provide insight into the similarities and differences between the mechanical and hydrothermal influence of faults, which eventually contributes to the understanding of fluid flow mode and localization within the faults and their damage zones.

In this study, we used data and samples collected from five representative faults occurring in various types of crystalline bedrock (mafic to felsic). The data includes high-resolution drone-derived orthophotos, digitized fracture traces, maps of alteration domains, fracture orientation data with detailed field photos, and ca. 1 m * 14 cm *14 cm triangular samples collected across the faults. The modelling workflow involved standard 2D-characterization of fracture network data, from which we progressed to 3D-characterization of the samples, which allowed making correlations between the fracture network and alteration properties of the rocks.

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CRM-geothermal: Raw materials from geothermal fluids

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The energy and digital transitions require a large amount of mineral raw materials, some of which are considered 'critical' by the European Union. These Critical Raw Materials (CRM) are predominantly imported from non-European countries where environmental and ethical standards may be less strict than in the EU. However, the EU has largely untapped resources at its disposal in geothermal fluids, some of which contain significant amounts of CRMs.

The EU-funded CRM-geothermal project therefore proposes to combine the extraction of mineral raw materials and geothermal heat, a renewable energy resource from the ground that is available 24 hours per day. The technology solution developed by CRM-geothermal will thus help Europe fulfil the strategic objectives of the EU Green Deal and the Agenda for Sustainable Development while reducing dependency on imported CRM.

Although Critical Raw Materials are known to occur in geothermal fluids, there are still many uncertainties concerning their occurrence in different geological settings and the sustainability of their extraction. The actual extraction process is also a major challenge, requiring technology development. The Horizon Europe-funded CRM-geothermal project therefore aims to:

- establish an overview of the potential for raw materials in geothermal fluids for a large range of elements across the EU and third countries;
- determine the source of selected CRM, their mobility and potential for sustained extraction from geothermal brines;
- develop and optimise innovative extraction technologies for selected CRM from geothermal brines that can form a business case for European SMEs;
- assess the environmental-social-economic viability, create transparent and traceable value chains, and foster ethical sourcing of CRM;
- demonstrate at a pilot site the extraction technology for at least one CRM at the scale of a mini-plant and evaluate the system's sustainability.

The combined extraction technology will support the European Union in developing a more resilient and ethical CRM supply-chain from domestic sources, reducing its dependency on imports, which are exposed to market and political risks. The proposed solution will also help to bridge the gap between societal resistance to domestic raw materials extraction and increasing demand for raw materials that are critical for the Twin Transition. Finally, the combined extraction of minerals and heat will also increase the number of viable geothermal projects, fostering the green transition and diversifying Europe's energy portfolio.

CRM-geothermal is coordinated by the Helmholtz Zentrum Potsdam Deutsches Geoforschungszentrum (GFZ) based in Potsdam, Germany. The research consortium consists of 20 partners, involving 14 EU-based and 6 associated partners from UK, Switzerland and Kenya, covering academic and industry backgrounds.

CRM-geothermal is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

Low potential for deep geothermal heat under Gothenburg

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District heating powered by geothermal energy is an attractive idea. Contrary to a conventional heat plant, a geothermal heat plant requires no fuel logistics and no chimneys in the city. Thus, the viability for geothermal district heating in Gothenburg was investigated, initiated by Göteborg Energi. The municipal district heating system in Gothenburg operates at a temperature of 120 °C during winter, which we set as the minimum requirement for a geothermal reservoir temperature.

To investigate the potential for extraction of geothermal heat from the bedrock for district heating in Gothenburg, we conducted a desktop study of the local lithosphere during 2020. The bedrock is dominated by two suites of 1.6 and 1.56 Ga metamorphic granitoid gneisses as well as a 1.3 Ga suite of granites that includes the actinide-rich RA Granite ("radioactive granite").

The corrected heat flow density, measured in a 550-m-deep drillhole in the city, is 58.6 mW/m^2 (Balling 1995). The calculated heat conductivity, based on average modal mineralogy, spans a range of 2.47–3.62 W/mK. Assuming a mean conductivity of the upper crust between 2.7 and 3.3 W/mK results in a mean calculated geothermal gradient between 17.2 and 21.3 °C/km (Angelbratt 2020). Thus, we expected that the target temperature of 120 °C could be found at a depth of 5.3–6.6 km, similar to St1's Otaniemi geothermal pilot project in Finland, which at the time was still ongoing.

We chose the RA Granite as the focus of geothermal research since we expected it to have the highest geothermal gradient with its mean heat production of 7 $\mu W/m^3$. To model the geothermal gradient more reliably, we had to acquire new data on the temperature of the bedrock. Thus, we decided to drill to 1 km depth, to minimise the influence of recent climate on the temperatures measured at depth.

In 2021, the deepest drillhole in Västra Götaland, GE-1, was drilled vertically down into RA Granite to a depth of 1 km. After resting, the temperature was logged down to the bottom of hole, resulting in a mean geothermal gradient of 15 °C/km between 100–1000 m (Hogmalm et al. 2021). The temperature curve could alternatively be interpreted to first stabilise on 17 °C/km at 100 m depth before decreasing to 14.66 °C/km 500–1000 m (Sjöqvist & Tillberg 2023).

A second hole, GE-2, was drilled in 2022 to 986.45 m depth with a -70° dip (vertical depth ≈ 860 m), to study fracture zones and to make a second measurement of the geothermal gradient, above the RA Granite. The geothermal gradient is stable from 200 m depth and is on average 16.94 °C/km between 200–856.7 m. The rock quality was good in both drillholes. Fractures occur localised in narrow zones separated by wider intersections of mostly unfractured crystalline rocks (Sjöqvist & Tillberg 2023).

We conclude that the RA Granite is not voluminous enough to raise the heat flow density significantly above average conditions in the Nordic crust. According to our investigations, the Gothenburg area is not prospective for high geothermal gradients (Hogmalm et al. 2021, Sjöqvist & Tillberg 2023). Extrapolating the measured geothermal gradients, a geothermal reservoir with 120 °C would be found at around 6.6 km depth, which is deeper than the failed Otaniemi geothermal pilot project. Therefore, the idea of an economically viable enhanced geothermal system in Gothenburg has been suspended.

Research about geothermal district heating in Gothenburg has been discontinued since 2023.

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Hydrogeological field investigations to assess the potential for large-scale utilization of groundwater for cooling at Gardermoen, Norway

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Oslo Airport City AS is planning a sustainable business park at Gardermoen, Norway, with energy solutions delivered by Statkraft Varme AS. The business park is situated on Norway's largest aquifer, the ice-marginal Hauerseter delta deposit (~9700 years BP) (Longva & Thoresen 1989). Statkraft Varme AS has engaged Norconsult AS to assess the local groundwater's applicability as a heat sink. The business park will be built stepwise, with an estimated peak cooling demand of ~5 MW in year 2036 (i.e., planned completion year of the business park).

The Gardermoen aquifer has been the subject of numerous hydrogeological studies, especially in the periods immediately before, during and after the opening of Oslo Airport Gardermoen (OSL) in 1998. Groundwater from the aquifer is already being utilized at numerous locations for heating and cooling of buildings (e.g., the aquifer thermal energy storage (ATES) scheme at OSL). Previous studies have shown that groundwater with high iron and manganese concentrations (i.e., high clogging risk) can be expected at greater depths in the aquifer.

Therefore, the focus of Norconsult's assignment was to find suitable well locations within the designated study area, with regards to…

(1) well capacity (i.e., to cover the estimated high cooling demand)
(2) groundwater quality (i.e., low iron and manganese concentrations), and

Hydrogeological field investigations were carried out in May-June 2023, comprising test drillings with sediment sampling for grain-size distributions, water quality field measurements and sampling, and pumping tests of test wells. Based on results from these investigations, the location, design and dimensioning of two full-scale wells and a test infiltration basin were carried out. The full-scale wells and infiltration basin were established in September-October 2023, and subsequently test-pumped.

The investigations have revealed…

(1) groundwater with low iron and manganese concentrations in shallow parts of the aquifer within the study area, and
(2) considerable variations in (expected) well capacities due to variations in the aquifer's sediment composition horizontally and vertically.

This has led to recommendations of establishing production wells with well screens located in the shallower part of the aquifer. This means groundwater drawdown (s), which should not be below the top of the pumping well screen, will be a limiting factor for the groundwater extraction capacity (Q). Thus, production wells should be established in the coarse-grained parts of the aquifer, where the specific well capacity (Q/s) will be higher.

Further work will comprise testing of infiltration capacity by means of basin vs. injection well(s), possible hydraulic advantages of placing intake below the top of the well screen. This will lead to recommendations for future design and development of Statkraft Varme AS' groundwater cooling scheme at Oslo Airport City, Gardermoen.

The authors would also like to underscore that the project's duration and its step-by-step approach to developing the area, lends itself to incremental improvements in methodology and energy solutions.

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Session 4

Slope stability, landslides/avalanches and their secondary effects

Session Chairs:
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Mass movements in Svalbard: A study of impact on infrastructure in the Longyear Valley

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Abstract

Geomorphological mass movements are projected to increase as the local climate changes in the Arctic, following global climate change. This poses a threat to Arctic settlements, as these movements may disturb and threaten infrastructure and people. Longyearbyen, Svalbard, has experienced these changes firsthand, as three major mass movement events occurred in close succession following a change in climate and environmental conditions. These events were previously unprecedented at this scale, and previous studies on mass movement events in the Longyear Valley have been sparse. This study aims to fill in some of the existing knowledge gaps by identifying what geomorphological activities exist within the valley and how the society of Longyearbyen has adapted in response to current and future projections. This is done by comparing aerial images from 1936, 2008, and 2014, digital elevation models from 2008 and 2018, NIR data from 2008, and ground truth imagery during an excursion in May 2023. These comparisons enable observation and analysis regarding geomorphological activities, changes to infrastructure, and the ability to assess avalanche conditions in connection to infrastructure. The results indicate that several measures have been taken within the town in response to previous and future projected events, as it is continuously densifying as a recreational town. Several geomorphological activities have additionally been identified within the valley, with a strong presence of colluvial fans caused by cornice falls.

The destabilizing effect of glacial unloading, Svínafellsjökull, SE Iceland

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The destabilization of alpine rock walls in the light of ongoing climate change has been linked to processes such as permafrost thaw (Penna et al., 2022), extreme precipitation (Stoffel and Huggel, 2012), and effects tied to deglaciation (McColl, 2012). Glacial retreat and thinning expose rock walls to atmospheric erosional factors, affect the surrounding ground water and reduce the load and buttressing from the slope. We quantify the destabilizing effect of glacial thinning on an unstable mountain slope in SE Iceland, where an extensive fracture network has appeared in the 2000s during a period of rapid glacial thinning (Ben-Yehoshua et al. 2023). In our model, we consider the glacial changes since the Little Ice Age and future scenarios resulting in complete removal of the currently 500 m thick glacier. The resulting reduced factor of safety is a function of ice volume loss and bed topography over time between scenarios. Even though the effects of deglaciation alone might not be sufficient to lead to slope failure, they increase shear stresses within the slope which can affect inherent structural weaknesses, as well as increase the vulnerability to seismic triggering, extreme precipitation, and other destabilizing processes.

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Large rock slopes failures in Iceland – why and when?

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Large Rock slopes failures (Landslides) are common in the oldest part of the Icelandic bedrock, particularly in the Central North, East and Northwest Iceland, which is dominated by relative homogenous Tertiary flood basalts and occasional extinct central volcanoes. The central volcanoes cause regional disturbance and irregularities in the regular Icelandic flood basalt pile due to volcanic and tectonic activity during their eruption time. They have also been the source of fine-grained acidic tuffs and tephras in sedimentary horizons within the flood basalt pile. The acidic tuffs have been chemically altered into material rich in clay minerals. Some of these minerals have the capabilities to expanded and become slippery when in contact with water. During Quaternary glaciations these parts of Iceland have been deeply eroded with high and steep valley sides, exposing relatively weak and irregular bedrocks of extinct Tertiary central volcanos. Consequently, rock slope failures are by far more widespread in these parts of Iceland, with *e.g.* several hundreds of them occurring in Central North Iceland but also the largest landslides in Iceland, some of them measuring tens of millions m^3.

Large rock slopes failures have yet only been briefly studied in Iceland, but in general the theory is that many of these features have formed shortly after deglaciation and withdrawal of glacier debuttressing of the slopes. Despite this assumption, morphology of landslides and their vegetation cover varies greatly from from one landslide to another. Incomplete studies of soil formation and tephrochronology suggest that most large rock slope failures are of Early Holocene age, while quite a number of them are thought to be of Middle Holocene age. Some landslides, particularly the smaller ones, are known to be of Late Holocene age.

Common for all previously glaciated parts of Iceland, is a combination of post-glacial debuttressing and erosional undercutting which closely links the large rock slopes failures with the last deglaciation. Furthermore, it is hypothesized that crustal deformation, related to glacio-isostatic adjustment, which was particularly vigorous in Iceland at that time, may also have played an important role in triggering these large rock slope failures, as well as the weak clay rich horizons in the bedrock. Ground thermal conditions and changes in ground water conditions are also believed to be an important aspect of rock slope stability in areas of Alpine settings. Thus, the degradation of permafrost during the Holocene thermal optimum may also have contributed to a phase of widespread landslides in Iceland. It is unknown how many of these slope failures can be classified a result of a deep seated gravitational slope deformation. Additionally, seismic activity in some parts of Iceland may also have led to large rock slope failure. A combination of all these aspects is likely to have played a role in triggering large rock slope failures in Iceland. Improved chronology with more direct dating of these features is very much needed for a better understanding of the mechanism behind their failure and age.

The "Permolards" project – investigating the factors leading to permafrost landslides and their mobility

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Discontinuous permafrost is prevalent in most mountainous regions around the globe (e.g., Obu et al., 2019). In periglacial territories, ice provides the "cement" that holds many mountain slopes in place. In the context of the increase of global mean temperatures, permafrost environments are experiencing unprecedented warming that is resulting in failures of mountain slopes (e.g., Draebing et al., 2014). These failures often mobilise permafrost materials, which can manifest as frozen blocks of loose debris or poorly lithified bedrock. These blocks come to rest within or proximal to the landslide deposits and degrade into permafrost molards, which are conical mounds of loose debris (e.g., Morino et al., 2019). In addition, such landslides can have unexpected complex behaviours and long runout due to the inclusion of ice and water into the sliding mass (e.g., Morino et al., 2021; Roberti et al., 2017). In a project funded by the French Scientific Research Council (ANR), we have been investigating the formation of molards via field observation and analogue laboratory experiments (Philippe et al., 2023) to gain insight into the range of materials that can produce molards and the factors that control their final shape. In parallel, we have been using topographic data in combination with temperature logger data (from field deployments) as inputs into a thermal model to understand the permafrost conditions preceding such mass wasting events. This is giving us insights into the conditioning factors that lead to such events. Using satellite data, we have compiled a database of 39 landslides with candidate permafrost molards from around the world, which is giving us insights into the types of terrain, lithologies and permafrost conditions that favour these types of mass movement. As a final strand to this project, we have begun to investigate how the distribution of molards in the landslide deposits can provide additional information on the landslide dynamics, which in turn helps us to better understand the role of ice and water in the mobility of these landslides. In this presentation, we will summarise the key results of this project, showing examples from Nordic countries and outline key avenues for future research.

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Landslide inventory around Torfajökull volcano, South Iceland, 1958–2022

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A comprehensive GIS-based slope processes inventory was conducted along the caldera rim of the central volcano Torfajökull using aerial photographs ranging from 1958 to 2022. This volcanic complex, situated at an elevation of 1200 m above sea level, is the largest silicic formation in Iceland, spanning an approximate area of 450 km². Given the absence of prior landslides investigations in this Icelandic region, this study has crucial significance. The context of changing climate conditions and the resultant extreme weather patterns in Iceland have been increasingly instigating slope failures. Addressing this concern, the study documents landslides events around Torfajökull, a region of ecological significance and a tourist destination featuring the Laugavegur hiking route and other visitor facilities. This study examines the distinct slope processes categories as delineated by Varnes (1978), and later by Hungr et al. (2014), alongside the exploration of Torfajökull's geological and seismic dynamics. The thesis presents an exhaustive analysis of sixteen slope deformations within the caldera vicinity where the diverse failure types, their triggering mechanisms, and intriguing patterns are presented within the context of geological dynamics. The observed slope processes encompass nine slow-moving slides, three retrogressive slides, five rock avalanches, one rockslide, five rotational slides, four block slides, and three slump patterns. The analysis suggests that two events were triggered in 1958, one in 1973, seven in 1979, three in 1999, two in 2013 and one in 2020. The failures progressed over time from 7 to 62 years, but none seem to be ongoing since 2020. This inventory aims to discover pattern in the development of landslides which could help for future studies around similar volcanic regions.

Subaqueous landslides associated with shoreline infrastructure in steep glaciated terrain, Loch Lomond, western Scotland

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Shorelines in steep glaciated terrain are focal points for development and can provide important natural corridors for transport (e.g., road, rail). However, the steep subaqueous slopes at nearshore sites present challenging ground conditions, and it is only in recent decades that acquisition of continuous high-resolution bathymetric datasets has become available to inform investigations. This work investigates a site in Loch Lomond, Scotland, where a reported displacement of 15,000 m^3 of rock fill occurred during the construction of a shoreline embankment as part of improvement work on a strategic road in the 1980s. We revisit the area using recently collected multibeam swath bathymetry, shallow sub-bottom seismic data and geomorphological mapping, as well borehole logs from the original ground investigation. These data suggest that the displacement of rockfill initiated a sequence of subaqueous landslides incorporating a total volume of up to 95,000m^3. The bathymetric and seismic data also provide strong evidence for older subaqueous landslide activity across the area, suggesting a pre-existing susceptibility. The research demonstrates the value of nearshore geophysical datasets in steep glaciated terrain, both for understanding geomorphological response to past shoreline modifications and as part of investigations where future developments (e.g., transport, energy infrastructure) are planned.

Episodic and jerky landslide movements at the Tungnakvíslarjökull outlet glacier, south Iceland

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In general, landslides show various characteristics of spatio-temporal distribution of movement. Episodic movements are often connected to seasonal changes in precipitation. The Tungnakvíslarjökull landslide is located above the Tungnakvíslarjökull outlet glacier on the west flank of the Katla Volcano, which again is overlain by the Mýrdalsjökull ice cap in South Iceland. The landslide is a deep-seated gravitational slope deformation with a rotational movement. It has an approximately 1.5 km long head scarp. The downward deformation has been approximately 200 m in the past 70 years. The landslide is buttressed by the Tungnakvíslarjökull outlet glacier, which retreat promotes failure of the hillslope. Active volcanic structures, such as a growing cryptodome, have also been proposed to affect the landslide movement. The landslide subsided fastest in the early 2000s. Here we constrain further the temporal history of landslide motion using Synthetic Aperture Radar (SAR) data pixel tracking. The SAR pixel tracking shows a clear slow-down in 2011, coinciding with a decrease in seismicity. Two continuously recording GNSS instruments were installed in 2019 and 2020 in the landslide. The GNSS stations show movements of several decimeters per year, with most movement confined to late summer and fall each year. The lower GNSS station of the two has recorded several distinct instantaneous offsets of 5-15 cm each time. These "jerk-like" offsets are sometimes accompanied by regionally located seismic events occurring within seconds of the offsets. The upper station, however, moves more continuously. The landslide region experiences heavy rain in the fall season, however, there are also periods of intense rainfall in the spring when little movement is observed. One possibility explaining the lack of motion in the spring time that frozen surface layers in spring to mid-summer may hinder precipitation from entering the landslide mass. The continuous low-cost GNSS observations complement spatially dense deformation techniques, such as using InSAR, differential DEM, and feature/SAR pixel tracking.

Traces of major landslides in marine clay and a possible Mid Holocene tsunami at Alta, northern Norway

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A combined morphological and sedimentological study of the Alta area reveals a fjord-valley landscape affected by several landslide events and a possible tsunami. The investigations presented here are part of an ongoing Quaternary mapping project, combined with a research project on acid sulfate soils. The work involves the study of landforms from fieldwork and LiDAR data, and of sediments through logging of sections and cores, and the collection of samples for radiocarbon dating. Subsurface structures are studied through geophysical techniques, including GPR and marine seismics (TOPAS). Large landslide pits in fjord-marine clays (possibly up to more than 25 million m^3) and associated landslide deposits testify to dramatic, pre-historic failures along the Altaelva and Tverrelva rivers. Radiocarbon dating of organic material from one major pit at Alta prestegård gave a minimum age for the landslide event of around 2000 cal. years BP. A landslide scar in fjord-marine deposits with a backscarp up to 15 m high and a volume of at least 250.000 m^3 is also present along the shoreline at the UNESCO World Heritage rock art site at Hjemmeluft. In addition, a few landslide-like pits with smooth and gently curved backscarps facing Altafjorden have been identified at Bossekop. The associated debris have been mapped on the adjacent sea floor at both locations. Considering the widespread landslide activity and estimated ages of the landslide events, they must have affected people living in the area during the Holocene. In addition, sedimentological and morphological evidence of a possible Mid Holocene tsunami has been discovered. Radiocarbon dating of wood fragments in sandy deposits suggest that the event occurred close to 5 ka cal. years BP.

Is the Skutshorn rockslide held back from failure by its foot and could it be eaten up by rock falls prior to a failure event?

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The unstable rock slope Skutshorn is a slow-moving rockslide with a volume of at least 7 million m^3. It is situated above lake Vangsmjøse in Innlandet county, Norway. The lithology of the rockslide is characterised by arkose and quartzite of the Valdres sparagmite nappe. The rockslide is positioned at the lower limit of this nappe. In the lower part of the mountain are these competent rocks underlain by more ductile phyllite rocks of the Vangs nappe. The back scarp is well developed along subvertical joint sets with very high persistence. This back scarp limits the slide to the top but also to much less defined rocks to the NW. The SW lateral flank is free as it is truncated by a tributary valley to the main valley that hosts lake Vangsmjøse. The upper sliding surface coincides with the schistosity that is in this part of the slope less folded and acts as a planar sliding surface or it can act in combination with several joint sets as one of the surfaces of a wedge slide. The foliation is folded towards the front of the slide body where average dip angles of the foliation are on average steeper than in the upper part of the rockslide. The foliation is vertical at the foot of the slide body. Here the basal sliding surface is interpreted to be the thrust separating the Valdres sparagmite nappe from the Vangs nappe, however outcrops of a daylighting structure or the thrust fold do not exist on that slope section that is covered in scree.

We have dGNSS data of installed measurement bolts (installed in 2018 and 2020 and last measured in 2022), satellite based InSAR for the past 8 years and GB-InSAR deformation data (collected in 2019 and 2020) for this slope. While the dGNSS data, and satellite based InSAR data are from the upper rockslide body that are accessible by helicopter or are in line of sight from the satellite do the GB-InSAR data better cover the frontal part. The deformation rates vary between 1 and 4 cm/yr and data mimic the structural conditions; in the upper parts of the rockslide, the movement vector is parallel to the dip of the foliation plane, while in the folded lower parts, the movement vector is steeper, corresponding to the dip of the foliation. The velocities are in general highest in the upper parts, decreasing down slope. In areas where the sliding surface in the upper part of the rockslide is exposed by rock fall do the GB InSAR data suggest that indeed no deformation takes place below that surface.

The underlying phyllites along lake Vangsmjøse also show deformation. This is slower than in the rockslide body and more diffusive, however also more difficult to measure as the foot is covered by extensive scree deposits. It is possible that this deformation is part of the upper rockslide, however electric resistivity tomography analysis in the lower part did not reveal any sliding surface within the phyllite. This is supported by the lack of geomorphological features showing deformation below the lake level on the newly collected bathymetric. Thus, we favour the interpretation that the deformation in the phyllite is local and detached from the main rockslide body.

The scree deposit at the foot of the instability is morphologically connected to a pronounced niche within the slide body at its SE flank exposing the basal slide surface parallel to schistosity. Today, most rock falls source from that niche; it stretches up in the slide body towards the upper part with the highest deformation rates. Be-10 surface exposure ages from multiple boulders from the scree vary strongly laterally and in time, suggesting that the scree was build up by continuous rock fall activity over a long time span rather than as one sudden failure from the niche. Rock fall activity is thus battling against rock strength in the foot of the instability to “eat up” the unstable rock slope.

The unstable rock slope has a high likelihood of failure following the Norwegian hazard and risk classification (Hermanns et al. 2012) and the population exposed to a displacement wave in lake

Rock slope instability along the Isfjorden coastline and the impact of climate warming

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The archipelago of Svalbard is one of the fastest warming arctic regions. The mean annual temperature at Svalbard Airport increased by 3.7 °C during the last 118 years, which is about three times the estimated global warming during the same period. This rapid rise in temperature, combined with negligible human influence, makes Svalbard an ideal laboratory to study the relationship between mass movements and climate warming.
For this purpose, two study areas, the west-facing Forkastningsfjellet and the east-facing slopes of Garmaksla were selected, both characterized by postglacial landslide activity but differing in terms of litho-structural setting, deformation history and slope exposition.
Field mapping, GPS- and temperature measurements and bathymetrical surveys were performed to reveal the controlling factors and deformation mechanisms that drive the rock slope instabilities. Successive UAV surveys acquired between 2019 and 2023 document the spatio-temporal development of the landscape.

A 175.000 m³ rockslide affected the coastal cliff of Forkastningsfjellet in August 2016 and concluded an 80-year period of relative stability along this coastline. A back-analysis of the rock slide revealed that slope instability initiated along a pre-existing listric block fault that was inherited from the postglacial Forkastningsfjellet rock slide. Slope failure was attributed to a strength decrease of weak Jurassic shales, permafrost degradation and increasing water pressures. Since then, rapid surface alterations could be documented.

Thermokarst settlements, sinkhole and subsurface channel formation in combination with redirection of surface water runoff finally lead to a second rock slide event (volume ~500.000 m³) in November 2022. dGPS data revealed the highest displacement velocities on the block that failed and acceleration was detected on that block the year before. Drone-based visual observation of the main scarp documents the cryogenic-structural setting and evidences thermo-erosional gullying and permafrost thaw governing rock mass dilation and slope failure.

The east-facing slope of Garmaksla at the western margin of Billefjorden is also characterized by a huge postglacial rock mass instability, which affected a strong sandstone/mudstone and overlying limestone/dolomite sequence of Devonian-Permian age.
The rock slide is delimited to the west by the Balliolbreen Fault, an important pre-existing fault that accommodated multi-phase deformation since Devonian time and served as the main rupture surface. It is explained by a compound rock slide model in which displacement is governed along shallow out-of-slope dipping bedding planes and weakness zones.
During the observation period, the area showed no signs of reactivation processes of large slide blocks, surface runoff or seepage spilling out of the coastal cliff was not observed. However, thermokarst structures and ALDs were first noticed on the water-saturated northern slopes of the rockslide area in summer 2023, demonstrating permafrost thaw and an increase in the active layer thickness as well.
The findings in both landslide areas show that unfavourable litho-structural settings and climate warming correlated permafrost thaw and increasing water availability are likely first order controls on the stability of the rock slopes. With regard to Forkastningsfjellet, it can be predicted that the coastal blocks will be affected by accelerating rock slide activity.

For future research and to better understand the effects of climate warming on landslide activity, it would be helpful to initiate a long-term monitoring project that collects and evaluates future landslide activity along the Isfjorden.

A novel dragon-king approach to forecasting catastrophic rock slope failures at Preonzo (Switzerland) and Veslemannen (Norway)

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Catastrophic rock slope failures pose great threats to life and property, but remain difficult to predict. Over the past decades, great efforts have been devoted to develop and deploy high-precision monitoring technologies to observe unstable rock slope movements. However, only a limited number of large rock slope failures have been so far successfully mitigated. Here, we present a novel predictive framework that can quantitatively assess the slope failure potential in real time (Lei et al. 2023). Our method builds upon the physics of extreme events in natural systems: the extremes so-called “dragon-kings” (e.g. slope tertiary creeps prior to failure) exhibit statistically different properties than other less intense deformations (e.g. slope secondary creeps) (Lei & Sornette 2023). We develop robust statistical tools to detect the emergence of dragon-kings during rockslide evolution, with the secondary-to-tertiary creep transition quantitatively captured. We also construct a phase diagram characterising the detectability of dragon-kings against “black-swans” and informing on whether the slope evolves towards a catastrophic or slow landslide. We test our method on real datasets, demonstrating how it might have been used to forecast the catastrophic rockslide events at Preonzo (Switzerland) and Veslemannen (Norway). Our method, superior to the conventional velocity threshold approach, can considerably reduce the number of false alarms and identify with high confidence the presence of true hazards of catastrophic rock slope failures. Our work adds a new conceptual framework and operational methodology with a significant potential to reduce landslide risks and support existing early warning systems.

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The Stenungsund Clay Landslide north of Gothenburg: When the main artery between Oslo and continental Europe (E6) was torn apart

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At 1:45 AM on 23 September 2023, alarm reports broadcast that European Route 6 (E6) had disappeared and cars driving over a new scarp in the road and into the dark. When the rescue operation was called off the following morning, it was fortunately concluded that no one was killed or severely injured. Three cars had gone over the edge, a bus and several cars had accidents or had became stranded on broken off segments of the highway. The entire E6 had slid over 50 horizontal meters, a fast-food restaurant was collapsed, a gas station had moved and its buildings deformed, a hardware store was affected, a few other roads were torn apart, a stream rich in fish and other biological values was dammed up, district-heating pipes were broken, and more.

This region in western Sweden is known for instable clays deposited initially in marine water, but following deglaciation were later isostatically uplifted. The terrestrial position of these clays makes them favorable for leaching of salt from the clay, transforming it to 'quick clay'. Additionally, post-glacial transgressions may cause the clay to have more organic rich layers which can contribute to its instability.

In this presentation, geologic setting, stratigraphy, and recent landscape changes of the Stenungsund landslide is discussed. Recent human activity at the site (blasting, fill material, buildings) may have played an important role in the slide event. Some historical and paleo clay landslides from the region are also compared. In order to optimize the prevention of slides in the future we need to increase our knowledge and understanding of how landslide hazards can vary in space and time from a geologic perspective.

Paleo-landslides and paleo-climate: insights from West Greenland

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Landslides are worldwide geohazards that are likely to increase in the future. Landslide occurrences have been prone in nearshore slopes of high latitude areas of Alaska, Canada, Norway, Greenland, Iceland and the Faroe Islands. Alone in Greenland, over 560 landslides have been mapped based on observations from remotely sensed imagery, and geological maps. The nearshore sedimentary record preserves the deposits of historical and paleo-landslides from coastal slopes in the form of mass transport deposits (MTDs). A unique archive of geophysical and geological data was obtained in the nearshore of Karrat Fjord and Vaigat Strait during 2019 and 2021 GEUS expeditions, which aimed to image and sample MTDs related to past occurrences of landslides under the broader Fjeldskreds project. Hence, morpho-structural and seismic-stratigraphic analyses have been performed on >4000 km of high resolution seismic, sub-bottom, and bathymetry data resulting in detailed mapping of the MTDs embedded in the sedimentary records of Karrat Fjord and Vaigat Strait. Besides, ~80 m of sediments recovered in 30 cores have been scanned providing information about the lithology and composition of the uppermost sediments (~6 m), i.e., the last ~10 ka based on sparse ^{14}C dating. Preliminary results of these analyses show spatial and temporal variability in the occurrence of landslides. The distribution and recurrence of MTDs across the stratigraphic succession infers that landslides have occurred in Karrat Fjord and Vaigat Strait in the recent geological past, since at least the last glacial maximum. The estimated sediment volumes of buried paleo-landslides (1-8 km^3) are in an order of magnitude larger than those of historical landslides documented along the slopes (43-50 million m^3). However, further investigation is required to assess the preconditioning factors and triggers of these mega-landslides.

Observations on the recent debris flow in Åre, west-central Sweden

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Recent surficial deposits mapping in west central Sweden conducted by the Geological Survey of Sweden has identified traces of debris flows in the landscape both in the Åre area and the surrounding mountainous region. The assumption is that debris flows have been an efficient geologic agent throughout the time that has passed since deglaciation (e.g., the Holocene).

Debris flows are a mixture of water, sediment, and debris that is mobilized and flows downhill, with considerable damage to infrastructure in their way. The trigger is often high precipitation on susceptible slopes and deposits. Increased precipitation in a changing climate is assumed to, if all other parameters are steady, produce more frequent debris flow events.

Over the last 30 years, the village of Åre has been affected by debris flows at least five times. The mountains in west-central Sweden have been classified as an area of increased risk in a changing climate by the Swedish Civil Contingencies Agency (MSB). The township of Åre has over the years constructed two sediment dams along the most frequently affected stream as well as strengthened the channel walls through the village.

A severe storm, called Hans, affected large parts of Scandinavia during August 2023. The storm delivered large amounts of precipitation across much of Sweden. In Åre, this was particularly true, and after many days of rainy weather a debris flow occurred on the seventh of August.

In the days following the debris flow, the channel of Mörviksån was investigated, and areas with erosion and deposition of sediment were noted. By studying the location where these processes were active as well as aerial photographs to discriminate older scars and detailed elevation models it was possible to reconstruct the debris flow event (Peterson Becher, 2023).

The village of Åre lies on a fan composed of Holocene aged debris flow sediments, which is dissected by Mörsviksån, a stream. Mörviksån drains a 4.5 km^2 catchment, with a relief of around 1000 meters. The catchment's upper parts are primarily above treeline and mainly consist of bedrock and thin or discontinuous layers of till or peat. The lower part of the catchment, however, is covered by thick deposits of silty or clayey till, susceptible to mobilization in a debris flow.

The catchment, with its large upper area, funneled the precipitation into the pre-existing ravines eroded into till. In the upper stretches of the ravines, erosion was common, but as the slope of the channel decreased erosion ceased. Nevertheless, the debris flow had already formed. Two sediment dams exist along the channel of Mörsviksån. The upper dam stopped boulders and tree trunks, but much of the debris flow continued. This led to further erosion and filling of the lower dam with sediment. Once the lower dam was filled, the debris flow diverged into a new channel, which led to subsequent erosion. Although the energy of the debris flow was most likely reduced by the dams, the debris flow continued into the village and clogged a bridge with debris, consequently leading to flooding of the central parts of the village until a new channel formed.

Understanding the geological processes involved, and the precipitation thresholds needed, is crucial to inform us of the susceptibility and risks connected to infrastructure, buildings, and community.

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Evaluating the precision of the Schmidt hammer dating method on large rock slope failures and comparative analysis of failure mechanisms

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With a change of conditions for rock slopes following a changing climate, understanding the past behavior of big rock slope failures is essential to predict potential future events. An understanding of how and when rock slopes failed in the past is therefore of great importance. The most widespread method to date rock slope failure deposits is the cosmogenic nuclide exposure age method. However, this method is both time consuming and expensive. Therefore, alternative methods of dating rock slope failures have been developed. One of these includes the use of a Schmidt hammer to create a local and relative calibration curve based on local reference deposits of a known age. The Schmidt hammer was originally created to test the quality and hardness of concrete. It was discovered that it also had the potential to determine the hardness and thereby the degree of weathering of rocks. To determine the age of rock slope failures the hammer will be used on their deposits. The hardness of the rock will give an indication of how long it has been exposed and by assuming a linear weathering rate, their age can be estimated.

The method contains large uncertainties as there are a lot of factors that may affect rebound value obtained from the hammer. This includes variance in lithology, uneven surfaces, temperature variations etc. The aim of this project is to test the Schmidt hammer dating method with a large amount of data to determine the precision of the method. Some of the tested deposits will be already dated surfaces to see the difference compared to cosmogenic nuclide dating. Further on, the results will be used for a time/frequency analysis supported by a kinematic analysis based on remote sensing data to see if a possible change in post glacial rockslide volumes and timing is accompanied by a change in failure mechanisms. Early results in the study are expected by November 2023 and will be presented.

What is causing the large scale displace-ments along the Siglufjarðarvegur road in the Almenningar area, in central N Iceland?

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Since the Siglufjarðarvegur road, in the Almenningar area in central North Iceland, was constructed in 1968 extensive damages have occurred on and along the road, often causing hazardous conditions. The road crosses three landslides on a 6 km along the coastal area on the eastern side of the Tröllaskagi Peninsula. All of these landslides show clear indications of movement. In 1977 the Icelandic Road and Coastal Administration began to monitor the deformation. In the beginning the measurements were achieved with several years interval, but over the last decades yearly measurements have been performed. In the year 2022, nine GNSS stations were installed along the road and a rain gauge was also installed in the area. This installation gives us for the first time the possibility of 24/7 monitoring on the displacements and a direct connection to weather variations, such as temperature variation and precipitation. The dataset, which spans now over 45 years, gives us a unique opportunity to correlate the displacements to external factors. Written source of deformation in the area dates back to 1916 and since then more than 50 movement events have been registered affecting the road.

Recent studies of the movement of the whole landslides masses, both using “feature tracking” and InSAR shows clearly that the whole landslide areas show signs of movement, but of different rate and the movement occurs on different parts of the landslides masses between years.

Our studies show that the highest movement rate takes place along the frontal parts of the landslide masses and that the movement is strongly related to both weather variations, e.g. precipitation and snowmelt and also to coastal erosion.

Extensive damages occur on this part of Siglufjörður road every year, often causing hazardous condition, which makes the prospect for the road not bright.

Monitoring displacement patterns, acceleration and failure (July 2023) at the unstable rock slope Stampa, Western Norway

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In early July 2023, a rock section named Block4A failed catastrophically from the unstable rock slope Stampa in Western Norway. In this contribution, we present continuous multi-sensor monitoring data since 2019, provide a timeline of the event chain, and share our experiences with early warning and the handling of the situation by responsible authorities.

Block4A was part of a near vertical cliff situated ca. 725-825 m above the European route E16, which runs along Aurlandsfjord. It consisted of a ca. 5,000 m^3 large rock column resting on a highly fractured base, adding to a total volume of up to 50,000 m^3. The Norwegian Water Resources and Energy Directorate (NVE) identified relatively high deformation rates at Block4A during their InSAR monitoring program in the area. From 2019 onwards, we supplemented the existing monitoring system by several different sensors which made Block 4A probably one of the best monitored unstable rock sections in Norway.

Movement at Block4A from 2019 to2022 was characterized by acceleration phases during late springs/early summers and autumns, relatively low and stable displacement rates during summers and very low to zero displacement during winter. This displacement pattern was clearly influenced by meteorological factors. Rising temperatures combined with thawing ice in rock fractures and enhanced water infiltration due to snowmelt in spring/early summer caused acceleration, whereas drainage combined with reduced water infiltration led to slowing down of the movement. Similarly, high-water infiltration by increased precipitation in addition to high ground temperatures in autumn caused acceleration, whereas winter conditions with temperatures below 0°C had a stabilizing effect. In autumn 2022, Block4A accelerated exponentially until cold air temperatures from the beginning of September completely stabilized the system. End of May 2023, Block 4A started moving again, accellerated and reached velocities of up to 0,1 m h^{-1} by June 30th. Between July 1th and July 3rd, Block4A disintegrated and failed in two main stages: (1) After two days of exponentially increasing movement rates and enhanced rockfall activity, ca. 9,000 m^3 detached from the fractured lower base on July 1st. While most of the debris was deposited high up on the slope, one large boulder with a diameter of ca. 10 m travelled all the way down to the fjord, damaging a power line and the road E16. By this time, guards of the Norwegian Public Roads Administration (SVV) followed the situation closely on either side of the affected road section and immediately closed the road. As a consequence, five houses situated at the toe of the slope, though more than 500 m away from the runout zone, were evacuated. (2) On July 3rd, most of the remaining unstable rock volume of ca. 30,000 m^3 including the rest of the base and the rock column of Block4A collapsed. The debris was deposited in the upper part of the slope despite the larger volume and the much larger drop height, compared to stage 1.

The September 16th, 2023 tsunamigenic rock and ice avalanche in Northeast Greenland – preliminary findings

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On September 17th, 2023 GEUS received notice from the police in Greenland that a tsunami had been observed in the national park in Northeast Greenland. A seismic signal was identified indicating a rock avalanche had taken place on the 16th and mapping of tsunami runup in satellite images from after the event traced the source of the tsunami to Dickson Fjord. The Arctic Command of the Danish Military sent a surveillance flight and boat to examine the site and their photos in addition to satellite images allowed us to make a preliminary reconstruction of the event: A mountain peak had collapsed into a narrow gully with a glacier in it. The combined mass of bedrock and glacier ice had continued down the gully into the fjord as a rock and ice avalanche producing the tsunami. The work was undertaken in a large and rapidly assembled international multidisciplinary scientific working group. The event raises many questions about this type of threat to Arctic coastal areas.

Proglacial lake evolution and outburst flood hazard at Fjallsjökull, southeast Iceland

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Arctic regions are warming at more than double the global average rate, causing significant glacier retreat and changing hydrologic patterns. Much of this meltwater is stored in proglacial lakes at outlet glaciers, which can drain in outburst floods if a mass movement event such as a rockfall or landslide enters the lake. Many of these lakes form in overdeepened basins, which can store large volumes of meltwater and contain steep valley walls that may be prone to paraglacial slope failures. Moreover, many lakes are upstream of infrastructure, communities, and tourism sites, resulting in a high potential societal impact in the event of a flood. This process is a well-documented trigger of floods in glacial regions across the world, but it remains understudied in Iceland. However, several large rockfalls have fallen onto Icelandic glaciers in the past decades and may enter lakes in future as ice retreat and lake expansion continue.

We investigate this emerging hazard by mapping proglacial lake evolution and evaluating outburst flood risk in southeast Iceland. This presentation focuses on the proglacial lake at Fjallsjökull, an outlet glacier of the Vatnajökull ice cap, which features many of these risk factors. First, we present results of a multibeam sonar bathymetric survey and report lake volume changes from 1945 to 2021. We then estimate future lake extent and volume based on basin topography and glacier dynamics. Finally, we identify potential source areas of slope failures and postulate scenarios of mass movement-triggered outburst floods in the lake. These results lay the foundation for future work on flood modeling and hazard planning to mitigate impacts on communities, infrastructure, and tourism at Fjallsjökull. This project also serves as an excellent pilot study for this emerging hazard in Iceland and has significant potential for application to proglacial lakes in other Arctic and alpine regions.

Session 5

Urban geology and applied geoscience related to city development

Session Chairs:
Guri Venvik,
Geological Survey of Norway
Fredrik Mossmark,
Geological Survey of Sweden

Integrating geological resources in areal planning: A case study of the Bømoen plus village project

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Fluvial and glaciofluvial deposits are common in Norwegian valleys and hold the country's most important sand and gravel resources. These deposits are relatively large in volume and are often suitable for aggregate excavation and for groundwater extraction. Increased understanding of the spatial distribution of sediments (and bedrock) and groundwater within an area can give a foundation for use of local resources as part of sustainable development. Bømoen Plus Village is a holistic and comprehensive research project focused on the development of a new village, consisting of residential and industrial areas. The aim is to achieve self-sufficiency in energy, water, and aggregates using the local geological resources. The study site, Bømoen (~2 km²) and Bjørkemoen (~1 km²) in Voss, Western Norway, is a glaciofluvial deposit divided by the river Raundalselvi.

A key aspect for the project is resource mapping and development of the area based on geological understanding. The initial phase of the investigation involved a comprehensive study of the area's geology and hydrogeology. This included Quaternary mapping, GPR subsurface profiling (145 profiles using antennas of varying frequencies), and Odex drilling (15 wells with 90mm and 115mm casings, along with information from 37 previously drilled wells in the area). Groundwater wells were installed in all boreholes. Quaternary mapping revealed predominantly glaciofluvial deposits across the area, with fluvial deposits near Raundalselvi. The investigations reveal a high content of boulders in the top layer, deposited during high-energy flows. Some areas displayed horizontal layers typical of layered sand and gravel in a Sandur, while others exhibited more homogeneous sandy sediments. In some areas these were divided by an erosional surface possibly representing river flow paths carving into the Sandur deposits. Odex drilling showed sand and gravel layers down to 25-35m. Fine sand and silt were typically found below the sand and gravel, with till observed above bedrock in some boreholes. Based on the collected data and interpretations, a 3D model was constructed to represent different geological units, assessing their quantities and distribution. These units encompassed till, marine sediments, deltaic foresets, and glacial outwash deposits, aligning with the common stratigraphic sequence found in valley deposits partially submerged below the marine limit.

The availability of sand and gravel plays a pivotal role in sustainable development by facilitating the extraction of significant groundwater volumes. Meanwhile, the dry sand and gravel content of the geological deposit holds immense importance for aggregate materials. The modelled total volume of sand and gravel within the project area is ~55 mill m^3. The average groundwater level is 9,5 m below the terrain, thus leaving 37 mill m^3 dry sand and gravel and 18 mill m^3 saturated sand and gravel resources. The current water abstraction rate for the municipality's reserve water supply in Bømoen stands at 90 l/s, suggesting that the extraction potential for the remainder of Bømoen exceeds this rate due to its larger size and similar geology. Surrounding catchment area connected to Bømoen by valleys and major rivers is more than 500 km², while the average precipitation is ~1330 mm/yr. Groundwater temperature measurements in Bømoen show an average of 6°C, with higher fluctuations observed near the river Raundalselvi. Given water's specific heat capacity of 1,17 kWh/(m^3 °C), a lowering of the water temperature by 4°C through a heat exchanger, coupled with an abstraction rate of 10 l/s per well, yields an effect of 167 kW/well. A seasonally regulated usage of the groundwater through an Aquifer Thermal Energy Storage (ATES) system is planned, possibly coupled with excess heat. Since the hydraulic gradients are high, careful investigations are necessary for optimal localisation of the production and the injection wells.

Bømoen Plus Village will benefit from a coordinated utilization of sand and gravel resources as excellent foundation for buildings, a source for excavated aggregates and as aquifers for extraction of groundwater for drinking water, and for heating and cooling of the buildings.

Conquering the sub-surface: Taking on the Oslo Rift lava pile and infrastructure development

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The Oslo region is the most densely populated area in Norway, with a growing population and a constant need for expansion of infrastructure. Geologically, the Oslo region consists of a basement overlain by folded Cambrian to Silurian sedimentary rocks, unconformably covered by Permian lavas and intrusions, e.g., Larsen et al. (2008). The lava pile is dominated by rhomb-porphyry and subordinate basalt flows; more evolved rocks are preserved in and around caldera structures. The Permian igneous rocks formed in an active rift setting, which also caused extensive faulting and fracturing.

Fault zones and layers which act as aquifers have been the reason for several incidents and has led to delays and cost overruns during infrastructure projects in the Oslo region. Improved understanding of the geology and in particular the relationship between the lava rocks and ground water flow may mitigate some of these issues in future development. In this project we study drill cores, borehole data, and outcrops from three large ongoing infrastructure projects which cut through the lava pile west of Oslo; a railroad tunnel, a water supply tunnel, and a new highway. Parts of the lava rocks in the area have previously been inaccessible for detailed studies, and this is a unique opportunity to describe them and their behaviour. The project combines drone imaging, field mapping and sampling of outcrops with logging of drill cores, wireline log interpretation and fluid flow measurements. Access to the outcrops before potentially problematic sections (such as fractured zones, faults, dykes, and altered tuff layers) are sprayed with concrete is a key feature in this project. In addition to data from the ongoing infrastructure projects, we will also build a database of incidents (e.g. rock falls, issues related to ground water) along existing roads and tunnels, and identify the geologic cause for the incident. An increasing population in the Oslo region leads to a continuous demand for more infrastructure, and more knowledge on how the fracture patterns, dykes and different lava flow units affect rock strength and control ground water flow can help to make future projects less expensive and more sustainable. We find that more collaboration and exchange of data and hands-on experience between industry, infrastructure providers and academia is essential for better decision-making and more sustainable development.

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Mycoremediation of environmental pollutions in urban areas

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For the last 150 years our planet has been dependent on fossil fuels as the primary energy source. This has led to a huge environmental debt for which conventional solutions fall short in addressing. Incineration of oil-based pollutions lead to additional CO_2-emissions to the atmosphere, and land-fills are just a way to postpone the problems to future generations. Hydrocarbon-based pollutants that linger in the environment pose immediate threats to human health and disrupt fragile ecosystems in the long term. Urban areas, in particular, are exposed to these issues and cities and municipalities worldwide are forced to find alternative and sustainable solutions.

Bioremediation is a research area in steady progress (Quintella et al. 2019). Microorganisms are nature's versatile tools, having evolved to thrive in extreme and toxic environments. By harnessing these adaptive skills to enhance bioremediation, microbe efficiency and the remediation processes are optimized and accelerated. Fungi is a group of microorganisms with great remediation potential, in particular hydrocarbon-based pollutions (Gadd, 2010). We develop sustainable mycoremediation systems that utilizes fungi to decompose hydrocarbons, transforming them into non-toxic fungal biomass - a natural and eco-friendly end-product that can be composted and thus recycled back to the natural carbon cycle. The pilot system is also portable, allowing in-situ treatment at polluted sites instead of the traditional approach of transporting the pollutions to the treatment plant. Thus the goal is the reduce CO_2-emissions from both incineration and transportations.

The results from our pilot system at the Ytterby mine at Resarö, Stockholm, show 99.9% degradation of hydrocarbons and a water quality after processing in line with the levels for drinking water. This show the great and untapped potential of mycoremediation and opens up new avenues for use, in particular in urban areas. Both when it comes to old environmental debts in the form of polluted soil and water but also for active industrial production in which hydrocarbon-based substances is involved in the production. Biologically mediated remediation is the way forward to a green and sustainable future for cities and urban areas.

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Geosystem services – what is it and can it be useful for subsurface planning?

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The subsurface is an important constituent of the physical environment. It provides physical space, water, energy, materials, habitats for ecosystems and acts as a repository for cultural heritage and geological history (e.g., van Ree & van Beukering, 2016). As such, the subsurface constitutes a multifunctional natural resource. However, awareness of the multifunctionally of the subsurface is generally low and is not a daily concern for decision-makers (e.g., van der Meulen et al., 2016). This often results in that decisions on access to subsurface resources are instead guided by a 'first come, first served principle', that can jeopardize sustainable development.

Though not fully developed, the concept of geosystem services (GS) has been put forward as a tool to make subsurface resources more visible and acknowledged in decision-making (e.g., van Ree & van Beukering, 2016). Currently there are two prominent definitions: (A) geosystem services are abiotic services that are the direct result of the planet's geodiversity (Fox et al., 2020), independent of the interactions with biotic nature – there is no differentiation between suprasurface and subsurface features, and (B) geosystem services provide benefits specifically resulting from the subsurface (van Ree & van Beukering, 2016). Geosystem services as a concept has the potential to support the systematic inclusion of geosystem services in planning processes and contribute to improved subsurface planning (Lundin Frisk et al., 2022).

Creating thematic maps that show the distribution and potential conflicts of geosystem services can improve the knowledge of planners about the subsurface conditions and resources. Which, in turn, can increase the consideration of these aspects in early planning processes. As part of an ongoing exploratory study, we are developing (1) indicators for mapping of geosystem services in Sweden and (2) subsequent thematic information (e.g., maps) of different geosystem services. The thematic information will be tested in two municipalities with stakeholders (e.g., physical planners) to investigate what type of information is useful in spatial (2D and 3D) planning and in what format it should be presented to ensure that it is easy to read and interpret for stakeholders without prior expertise.

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EuroGeoSurveys' Urban Geology Expert Group brings geo-related knowledge to the decision makers

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The Urban Geology Expert Group (UGEG) is a part of the Geological Surveys of Europe (EGS) and specialises in geological disciplines related to urban challenges. The UGEG undertakes collaborative geoscience projects to inform European Union (EU) policy, as well as provide urban geoscience data, information and expertise to national and local authorities throughout Europe. The UGEG has more than 60 participating members across 26 European countries.

Urban subsurface space provides a valuable resource often forgotten in city planning – out of sight, out of mind. However, if we are to deliver sustainable cities (SDG 11), subsurface use must be planned, integrated, and managed as part of the urban planning process. We present three specific areas where the UGEG is embedding geological information in the urban planning and development life-cycle:

- 3D surface-subsurface digital twins: providing relevant and easily accessible geological data-models to the users at sufficient scale, to support planning, development, for resource extraction and to mitigate geological hazards.
- In the context of the geo-environmental setting, UGEG proposes a catchment-based approach for the urban environment to holistically understand the impacts of geology and climate on the anthropogenic pressure. This includes identifying priorities and nature-based solutions, e.g. to mitigate water related natural hazards including drought, flooding, landslides, sinkholes, saltwater intrusion, sea level rise and storm surges, seismic and volcanic hazards, etc. to underpin urban resilience. Moreover, in order to help city-to-city comparison and best practices exchange, and to cluster cities by a geological point of view, the so called "Urban Geo-climate Footprint" is evaluated for several European cities through a tool developed by the expert group members.
- Interdisciplinary collaboration and communication: The UGEG aims to bridge the knowledge gap between subsurface experts and city practitioners (urban planners, architects, and decision-makers) through the generation of mixed-media communication tools such as videos, webinars and fact sheets.

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Urban Geology - EuroGeoSurveys

Sub-Urban (squarespace.com)

Geological 3D modelling för urban planning in southwest Scania

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The purpose of SGU's 3D models for urban areas is to better provide society with geological data and a better geological understanding for improving the planning of infrastructure projects, especially underground.

Herein, we present a geological 3D model from southwest Scania, comprising an area from Malmö to southern Lund. The visualization and modelling strategy has been adapted to the regional geological conditions and available data. It is based on the collection, digitalization, harmonization and interpretation of external data which, together with SGU's existing data, is integrated into a 3D model. The external data has been collected from Trafikverket, the Citytunnel project, Malmö GeoAtlas (through Tyréns), Statens geotekniska institut (SGI) and VA Syd.

Existing data from SGU includes geological map databases, geological logs (bedrock and soil) from the well archive, airborne TEM measurements and SGU's national soil depth model. Borehole geophysics and seismics have also been an integral part of the bedrock model interpretation.

The 3D model includes both the quaternary soil cover and the bedrock to a depth of approximately –170 m asl. The model is interpolated using 25 interpreted geological cross sections that are based on a conceptual regional geological model of the area and verified based on borehole information 150–100 m from the cross section.

The geological 3D model shows that the soil depth varies from a few meters in central Malmö to up to 100 m in the so called Alnarpsdalen. The soil cover is dominated by tills and clayey tills with interbedded layers of sand and silt. Glaciofluvial deposits are sparse at the ground surface and are often composed of sand. In parts of Malmö, several meters of landfills occur on top of the quarternary soil layers. Allochthonous nappes of Cretaceous limestone within the till occur to the east of Malmö. In Alnarpsdalen, there are thick layers of sand and gravel that constitutes important groundwater reservoirs.

The bedrock in the model area is divided by the Romeleåsen deformation zone. Southwest of the deformation zone, the bedrock is dominated by Palaeocene and Cretaceaous limestones (Copenhagen member, Limhamn member and Kruseberg member) with a few areas of Palaeocene sandstone (Lellinge greensand) in the southwest. Two deformation zones in the Malmö area are associated with a minor uplift. The Copenhagen member is missing in certain areas in Malmö.

Northeast of the Romelåsen deformation zone, the bedrock is more complex with fault related tilted blocks of Cretaceous, Jurassic and Triassic strata. Ordovician and Silurian shales, penetrated by Permian dolerite dykes, dominate in the most northeastern part of the of the model area.

The model and accompanying report will be available via the 3D viewer on the SGU website (apps.sgu.se/sgu3d).

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Session 6
Granite and pegmatite mineral systems: New data – new concepts

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Lithium-caesium-tantalum pegmatites in the Varuträsk area: Source, transport, trap

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The Varuträsk pegmatite is the most extensively studied pegmatite in the Fennoscandian shield (e.g. Quensel 1956) but the broader mineralized system in the Varuträsk area (source-transport-trap) remain unresolved. The Varuträsk pegmatite has been suggested to belong to the c. 1.8 Ga S-type Skellefte granite suite (Kathol & Weihed 2005) but geochronological data (c.f. Romer & Wright 1992, Weihed et al. 2002) indicate a potential need for a more nuanced understanding regarding the direct genetic relationship between the Skellefte-suite and the LCT-pegmatites of the area. As part of the Horizon Europe project Exploration Information System (Grant agreement n°1010557357 – HORIZON-CL4-2021-RESILIENCE-01), we present lithogeochemistry data from various granitoid rock types to explore potential sources of the LCT pegmatites in the region, and we employ structural-lithological mapping and uniaxial compressive strengths (UCS) data of host rocks to probe their transport and controls on entrapment style.

Lithogeochemistry results indicate a continuum between small and elongated bodies of texturally intensely varying pegmatitic-aplitic to equigranular variants of the Skellefte suite and the LCT pegmatites. However, equigranular to porphyritic variants of the Skellefte suite that form plutons and have a higher biotite and lower silica content tend to plot separately on both major- and immobile trace element plots. This indicates that some parts of the Skellefte suite were more fertile than others and possibly derived from slightly different sedimentary protoliths at different stages of the convergent margin evolution, but we stress the need for modern geochronological data to better constrain the granitoids and the pegmatites in time. Nevertheless, a revaluation of the Skellefte suite concept might be necessary to understand the details of the LCT pegmatite mineralized system in this part of the Bothnian Basin.

Mapping data indicate fluid-melt transport mainly occurred along pre-existing structures as veins and dykes of several generations increase in the vicinity of the structures. In general, anatectic veins are folded or boudinaged along the main fabric and these veins are crosscut by undeformed quartz veins at an angle to the fabric, thus indicating early migmatization progressing to hydrothermal processes through lowered P-T conditions with time.

Entrapment styles are always brittle in character and pegmatites are bounded by fracture planes. UCS data on host rocks to pegmatites indicate the competence of host rocks as one key parameter controlling the dip of the pegmatite emplacement. Higher Mpa values favour shallower pegmatite orientations and interestingly, shallow orientations are also restricted to the Varuträsk (and Åkerberg included for comparison) pegmatites that are the most evolved examples in this study. The mechanics of pegmatite emplacement should not be overlooked when mineral system approaches are applied since shallow geometries may allow for more time for vertical pegmatite differentiation and most world class LCT pegmatite deposits show shallow or sub-horizontal dips (Groves et al. 2022).

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Petrography and paragenetic implications for the Järkvissle Li-Sn-Ta pegmatite prospect, Västernorrland, Sweden

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In the Järkvissle area, Västernorrland, north-central Sweden, several mineralized LCT-type (lithium-caesium-tantalum) pegmatites occur within a 4×7 km area (Romer & Smeds 1997). The pegmatites (c. 1.8 Ga) are hosted by Paleoproterozoic (c. 1.9 Ga) siliciclastic metasedimentary and intercalated mafic volcanic rocks. Alongside pegmatites, two granitoid suites occur within the metasedimentary-metavolcanic package: a foliated biotite-muscovite granodiorite – granite, and a foliated and locally pegmatitic garnet-bearing granite. About five km to the E and SE of the deposit, migmatitic metasedimentary rocks and granitoids of migmatitic character (diatexite) occur.

At the Järkvissle prospect, pegmatite dykes are subvertical, subparallel, and mostly N-S-trending. Historical exploration reports and work by Romer & Smeds (1997) describe two types of pegmatites occurring in the area: spodumene-bearing pegmatites (> 4 m in thickness) and barren (spodumene-free) pegmatites (≤ 1 m in thickness). Reported minerals of potential economic interest at Järkvissle include spodumene, petalite, cassiterite, and columbite-group minerals (Tuuri 1985).

Using drill cores from historical exploration drilling, this study provides a detailed petrographical description of the pegmatites and investigates the geochemical features and paragenetic sequence of the ore minerals. The results provide a better understanding of Li-Sn-Ta mineralization at Järkvissle and broader insights for similar Li pegmatite prospects in Fennoscandia and other locations.

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Data driven mineral prospectivity mapping using fuzzy methods for LCT pegmatite systems in Västernorrland, Sweden

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With the increasing need for lithium to fuel the green transition, new approaches to mineral exploration are needed to identify where the unique factors that lead to the formation of lithium-cesium-tantalum (LCT) pegmatites exist. As part of the Exploration Information Systems project (Horizon Europe grant no. 1010557357; eis-he.eu), a tool is being created to give the end user access to an open-source software for mineral prospectivity mapping (MPM). In preparation for the release of this tool, project partner SGU has investigated formational factors that support the occurrence of LCT pegmatites in Västernorrland (VNL), Sweden to create a model to test MPM using fuzzy logic methods in ArcGIS.

LCT pegmatites in VNL have been dated to 1.8 Ga (Romer & Smeds 1997) and are likely related to the occurrence of approximately 1.84-1.85 Ga S-type granites which may have provided a fertile source. The pegmatites occur within the metasedimentary supracrustal sequences, typically within less migmatized meta-greywackes. A spatial relationship between the pegmatites and 1.91-1.88 Ga extrusive meta-mafic rock indicates a potential trap for the flow of the pegmatite forming fluids. The pegmatites typically strike to the NNE and dip steeply.

Three formational datasets were combined to build a prospectivity map for the VNL pegmatites within ArcGIS: source, pathway and deposition. Evidentiary layers for source were proximity to 1.84-1.85 Ga S-type granites, as well as proximity to 1.91-1.88 Ga meta-mafic rock. These factors were sourced from the SGU 1:1000000 bedrock map and SGU aeromagnetic data. Aeromagnetic data aided in identifying non-exposed meta-mafic rock, as well as areas of low magnetic anomaly and high K/U radiometric values, indicating possible granitic bodies at depth. These layers were overlain using a fuzzy AND operator.

Pathway factors used were proximity to deformation zones and contact between 1.84-1.85 Ga granites and the less migmatized meta-greywacke as well as density of these features. These features were then overlayed using fuzzy OR operations. Depositional factors considered were the location of strong Li and K anomalies in till data, well as negative loadings on the 3rd principle component obtained through multivariate analysis which represent strong influence of Li, Be and Zn. These factors were combined using a fuzzy AND operator. The resulting fuzzified data rasters for each formational factor were then overlain using a fuzzy GAMMA operator.

The final results of the prospectivity model show the most prospective regions are strongly controlled by proximity to the less migmatized wacke and the density of contacts between the wacke and granites. One region identified in this model as highly prospective is located to the southwest of Härnösand. This area has no known LCT pegmatites, however sampling of the local bedrock has identified the granites in the area as showing strong fertility indicators for LCT pegmatite formation (Ta+Li+Cs/Ca+Mn). This area showing high prospectivity in the MPM produced from the VNL dataset points to the potential viability of this model for predicting LCT pegmatite occurrences based on the evidentiary model used in this study, and points to Härnösand as an area for potential further exploration. Application of knowledge driven fuzzy weights of evidence methodology (Zhang et al. 2014) may provide further refinement of prospectivity models in VNL.

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Chemical and textural variation of quartz-tourmaline aggregations – Using mineral chemistry to track the magmatic-hydrothermal transition

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The large stability fields and the ubiquity of quartz and tourmaline in S-type granitic systems, make these minerals potential petrological monitors of the magmatic-hydrothermal transition. The contrast in chemical complexity between the two minerals cause them recorders of different parameters. The ability of tourmaline to incorporate a range of major, minor and trace elements will record variations of melt/fluid composition. Contrary, the main trace element composition of quartz is dominated by Al and Ti, which combined with the growth textures can provide information of temperature, pressure and physical state of the crystallizing medium. In this study we have analyzed quartz-tourmaline pairs in order to decipher the magmatic-hydrothermal transition in the Land's End Granite, SW England.

Throughout the Land's End granite, a range of quartz-tourmaline textures and structures can be observed: disseminated in the granite matrix, pegmatitic pockets, quartz-tourmaline aggregations in the form of orbicules, sheets, and larger bodies +/- K-feldspar phenocrysts (massive quartz-tourmaline (-K-feldspar) rocks – MQT/MQTK), veins, and replacement of the granites on a variable scale. The distinct color variation of tourmaline is a first indication of the crystallization mode. Brown-orange tourmaline with major element composition plotting in the middle of the schorl field occur as interstitial matrix mineral in the granites, and cores in quartz-tourmaline sheets. Grains with euhedral terminations growing into miarolitic cavities are typically pale brown/blue oscillatory zoned with composition closer to endmember schorl, and with slightly higher Sr and Sn content compared to granite matrix tourmaline. This type is similar to more erratically zoned pale blue/brown/greenish tourmaline replacing feldspar in the granite. The final main group of tourmaline is typically strongly zoned, from green, colorless and deep blue, associated with veins or extensive replacement of the granite.

Quartz in the different granites and quartz-tourmaline structures has a large range of Ti and Al content. Early-forming quartz in the fine-grained granite has a distinctly higher Al/Ti ratio (~10) compared to phenocrysts and central zones of the matrix quartz of the coarse-grained granite (~5), likely reflecting the more evolved chemical character of the fine-grained granite. Quartz zones coexisting with interstitial tourmaline in the fine-grained granite has 30-60 µg/g Ti, and 300-500 µg/g Al. In a miarolitic cavity formed in a tourmaline-rich part of the fine-grained granite, quartz overgrowing the euhedral brown tourmaline has no apparent cathodoluminescence zoning, and 20-30 µg/g Ti and 500-600 µg/g Al. This zone may be the coexisting quartz generation of the weakly oscillatory tourmaline generation, representing the transitional stage where the crystallization goes form melt dominated to fluid dominated. Overgrowing this zone is a strongly zoned quartz generation with <5 µg/g Ti and 50-150 µg/g Al, likely corresponding to the metasomatic tourmaline generation, representing the hydrothermal quartz-tourmaline crystallization.

Sulphur isotopes and helvine-group minerals of pegmatites in the Larvik Plutonic Complex (LPC), Norway

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The Permo-Carboniferous Larvik Plutonic Complex (LPC) is part of the Permian Oslo Rift in the Southeastern part of Norway. The LPC consist of concentric ring plutons of different ages, commonly referred to as ring sections (RS). Broadly speaking, the age of the complex increases from east (302.0 Ma) to west (287.0 Ma), while the composition changes from quartz-bearing monzonite to felspathoid-bearing to the most evolved nepheline syenites in RS 9 and 10. The complex hosts numerous miaskitic to agpaitic pegmatites which origin and source is still uncertain. Alkaline pegmatites are intraplutonic and an important part of understanding the evolution of the complex as a whole. Sulphur isotope geochemistry can help unlock new aspects of pegmatite formation. Sulphur isotope methods have never been utilized on alkaline pegmatites, despite its mineralogy being suitable for it. Traditionally only sulphides and sulphates have been used for sulphur isotopes, however mineral groups such the helvine-group contains S as one of its main components and potentially enables the use of S-isotope geochemistry. Helvine-group minerals ($Be_3M_4(SiO_4)_3S$), where M = Fe, Mn or Zn, is a relative common mineral in the pegmatites of the LPC, and rarely occurs together with other S-bearing minerals. This is of major importance as being able to utilize a new mineral for S-isotope geochemistry would unluck previously unknown parameters for paragenesis where traditional sulphur minerals are absent. It is worth mentioning that although the helvine-group might be considered uncommon, it is actually occurring in various geological settings and not just alkaline pegmatites. As such this study provides a new set of tools for exploring pegmatites and other rocks.

The sulphides from the central pegmatites of the LPC (292.4 Ma) show primary magmatic source with galenas ranging from -0.65 to -0.23 $\delta^{34}S$ and sphalerites ranging from 0.46 to 1.57 $\delta^{34}S$. Comparatively, the helvines from the central pegmatites has a $\delta^{34}S$ of 0.30 to 0.89, correlating well with the recorded sulphide $\delta^{34}S$ values. Helvine from a pegmatite on the western boarder of the LPC (293.0 Ma) record a $\delta^{34}S$ value of 16.45. Just outside the western boarder of the LPC there are Proterozoic sediments which might have influenced the high $\delta^{34}S$ through crustal contamination. This is not unlike what we generally see from sulphides, indicating that helvine might record external influences on the source, similar to traditional sulphides. The first temperature calculations of the pegmatites of the LPC are given using geothermometry with well-known fractionation coefficients between coexisting sulphides (galena-sphalerite). With the utilization of S-isotope geochemistry on helvine-group minerals, a traditional analytical method can now be applied to completely different minerals from a varied range of parageneses, and thereby open for S-isotope studies in geological settings devoid of sulphides or sulphates.

In situ Rb-Sr geochronology of exotic pegmatite minerals, direct dating of polylithionite-trilithionite, pollucite and rhodizite

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Geochronology of pegmatites have historically been plagued by numerous disadvantages, many of the traditional phases targeted for U-Pb or Pb-Pb (such as zircon or columbite group minerals) are usually unsuitable for geochronology due to the volatile-rich environment found in granitic pegmatites. These phases could have inherited ages, usually exhibit complex zonation, and are as a rule, subject to metamictization which in turn leads to that they are frequently altered with secondary U or Pb minerals. All these factors contribute to difficulties retrieving reliable geochronological information of the pegmatite intrusion.

However the *in situ* Rb-Sr method is a quick, easy, inexpensive and powerful method that can be applied to a large variety of rock-types (Zack & Hogmalm 2016; Hogmalm et al., 2017). This now established approach poses significant advantages over conventional methods, in that inclusions and alterations can be avoided. The high spatial resolution can not only resolve cooling ages, or reheating events but also help us understand recrystallization during deformation. Applied to minerals with a high Rb/Sr ratio such as many pegmatite mineral, there is no need for a coeval Sr-bearing phase (Rösel & Zack 2022). This allows for single spot ages to be calculated, which highlights this method as an attractive tool for pegmatite geochronology.

These new advancements have opened up a whole new range of exotic minerals commonly occuring in evolved grantic pegmatites as a target for in-situ Rb-Sr dating. The Li-bearing micas polylihtionite $K(Li_2Al)(Si_4O_{10})(F,OH)_2$ and trilithionite $K(Li_{1.5}Al_{1.5})(AlSi_3O_{10})(F,OH)_2$ (usually in older litterature denoted as “lepidolite”) are usually indicators for such evolved pegmatites (LCT, lithium-cesium-tantalum) and more fractionated pegmatites can host the uncommon zeolite pollucite $(Cs,Na)_2(Al_2Si_4O_{12}) \cdot 2H_2O$. Premilinary investigations show that these mineral readily incorporate Rb and are almost devoid of intial Sr, making these minerals ideal candidates for this method. This new methodology was applied to pollucite and Li-bearing micas from a vast range of evolved pegmatites from all over the world, ranging in age from Elba (~7 Ma) to Tanco (~2630 Ma). Additionally the rare mineral rhodizte $(K,Cs)Al_4Be_4(B,Be)_{12}O_{28}$ from Ambositra, Madagascar was also analyzed and gave favourable results.

This approach could be a valuable tool in mineral exploration, in particular for the critical elements such as Li, Cs and Ta. Additionally retrieving age information from these minerals advances our understanding of the post-magmatic processes affecting pegmatites.

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Geothermobarometry of the Evje-Iveland granitic pegmatite district, South-Norway

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The NYF-type REE pegmatites of the Evje-Iveland granitic pegmatite field are part of the Setesdalen pegmatite district in the Telemark lithotectonic domain and formed at Ma 900-930. Generally, it is assumed that they were emplaced at 4-5 kbar and 550-600 °C, i.e. at very high pressures compared to most other fertile pegmatite fields. In this study we aim at better constraining P and T based on a combination of fluid inclusion isochores and Ti in quartz geothermometry.

Primary fluid inclusions are common in both the Intermediate Zone (IZ) and the quartz dominated Core Zone (CZ) of the pegmatites. Here, we studied the CZ only, given that it is a well constrained part of the pegmatites enabling easy comparison of different pegmatite localities throughout the district. Thousands of FI data were obtained from 16 localities consistently showing H_2O-CO_2-NaCl fluids. Salinities varies from 6 to 14 wt% NaCl equivalents for most pegmatites and X_{CO2} of 0.030.09. Two localities demonstrated phase separation into CO_2-rich and H_2O rich fluids, respectively.

The newest revision (Osborne et al., 2022) of the TitaniQ geothermometer was used to calculate T's assuming a Ti activity aTiO$_2$ at 1 given the common observation of rutile in the pegmatites. Ti in quartz data are from Larsen et al., (2004). Fluid inclusion isochores were calculated with the computer packages developed by R. Bakker (https://fluids.unileoben.ac.at/Home.html).

Combining isochores and TitaniQ data yielded a cluster of 10 localities forming at 3.8-5.5 kb's essentially confirming earlier P estimates. T's were 400-520 °C i.e. lower than previous estimates. However, this is as expected given that the CZ quartz is expected to solidify later than the IZ and at lower T's. At the two localities showing phase separation of the fluids, we calculated P's at 2.8 and 4.1 kbar, respectively, with the latter overlapping with the TitaniQ/isochore P's.

We also observe a cluster of 3 localities forming at 1.1-1.5 kb, 415-450 °C demonstrating that some pegmatites are much more shallow. Perhaps they are belonging to a younger pegmatite forming event emplaced after a period of uplift of the Telemark domain. This is supported by significantly higher salinities of c. 23 wt% compared to most pegmatites emplaced at higher P's.

Stepwise magmatism and structural reactivation facilitates LCT pegmatite formation: Insights from central Sweden

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Introduction

Two main geological processes are thought to produce volatile-rich melts that crystallize rare element-bearing granitic pegmatites. The classic scenario envisages such melts as late-stage, residual differentiates of crystallizing fertile granites (e.g., London 2016). Alternatively, pegmatitic melts may develop directly during low-degree partial melting of fertile supracrustal ± plutonic rocks, thus bypassing the need for a progenitor granite stage (e.g., Müller et al. 2017). While assessing controls on melt formation at the time of pegmatite emplacement is critical to understanding these mineral systems, constraining tectonothermal factors active during earlier stages in the evolution of host/source rocks may help identify processes that indirectly facilitate pegmatite formation. As part of the EIS project (Horizon Europe grant no. 1010557357; https://eis-he.eu), we present a case study from the Järkvissle LCT pegmatite system in central Sweden to highlight the role stepwise, superimposed magmatism, metamorphism and deformation plays in the formation of LCT pegmatites.

The Järkvissle Li-Sn-Ta pegmatite field, central Sweden

The Paleoproterozoic (c. 2.0 – 1.8 Ga) Bothnian Basin in central Sweden contains several LCT (lithium-caesium-tantalum)-type granitic pegmatite prospects. The best example is the c. 1.8 Ga Järkvissle Li-Sn-Ta prospect which comprises a c. 2 x 7 km field of c. N-S-oriented, subvertical pegmatite dykes intruding a polydeformed package of metasedimentary and intercalated mafic metavolcanic rocks. Important ore minerals at Järkvissle include spodumene, petalite, cassiterite and columbite group minerals, while accessory tourmaline, apatite, beryl and uraninite also occur.

Stepwise tectonothermalism, structural reactivation, and late-stage pegmatite formation

Metasupracrustal rocks and meta-granitoids in the Järkvissle area have been affected by at least two stages of ductile deformation. An early event (D_1) is evidenced by bedding parallel S_{0-1} foliations with variable orientations. A second event (D_2) is characterized by major and parasitic, moderate to tight, c. NNW-aligned F_2 folds, and axial planar cleavages (S_2) that affect S_{0-1} planar fabrics. The eastern limb of a major F_2 fold shows evidence of high-strain, syn-D_2 dextral shearing, and hosts the Järkvissle pegmatite field. Southwest and east of the Li prospect, foliated leucogranites with local migmatitic features (diatexite) represent a phase of high-grade metamorphism - possibly linked to D_2 deformation.

Small volume, weakly deformed to massive pegmatitic granite and pegmatite bodies crosscut metasedimentary rocks and migmatitic leucogranites, and tend to intrude along steep, pre-existing structures. At the Järkvissle prospect, internally massive spodumene-bearing dykes have wavy and sometimes folded forms, and locally deflect $S_{1/2}$ planar fabrics or crosscut tightly folded syn-D_2 quartz-feldspar veins. These observations indicate a late phase of structural reactivation (D_3 at c. 1.8 Ga?) along the earlier formed F_2 fold limb was exploited by evolved melts, leading to syn-tectonic pegmatite emplacement and Li-Sn-Ta mineralization. Thus, stepwise tectonothermal overprinting and late-orogenic structural reactivation are important pre-conditions for LCT pegmatite formation.

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The GREENPEG project toolset to explore for buried pegmatites hosting rare metals and high purity quartz to feed the energy transistion

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GREENPEG, a European innovation project financed by the European HORIZON 2020 programme, has developed an exploration approach for the discovery of buried pegmatite ores in the form of an integrated, multi-method, sustainable and economically viable toolset. The toolset consists of a complementary suite of adjusted conventional and newly invented methodologies and new data processing approaches optimised for the target size, surface environment, depth, geological setting, mineralogy, chemistry and petrophysics of pegmatite ore deposits. Its development is based on a modified genetic model for European pegmatite-type ore deposits by Müller et al. (2022) and a multi-scale (province, district and prospect) and multidisciplinary approach. By improving the targeting of pegmatite deposits, and thus the effectiveness of exploration, the delivered toolset will reduce exploration time and costs, the level of environmental disturbance from the use of relatively invasive techniques, and social impacts such as noise. The toolset developed has been adjusted, optimised and tested for commercialisation under Technical-Readiness-Level-7 conditions in three European demonstration and exploration brown field sites: Wolfsberg in Austria, Leinster in Ireland, and Tysfjord in Norway. The toolset encompass a wide array of technologies, including satellite image processing and both airborne and ground-based geophysics and geochemical approaches and three new instrumental demonstrations to effectively identify buried (up to 100 m depth), small (10,000 - 1,000,000 m^3) and clustered pegmatite ore bodies. The toolset includes three instrumental demonstrations comprising the first European EASA certified helicopter-compatible nose stinger magnetometer which will allow lower altitude airborne surveys down to about 50 m above ground, a drone-borne hyperspectral imagery system and a piezoelectric spectrometer for rapid and efficient detection of buried pegmatites. The toolset comprises as well two freely available databases, a petrophysical database for pegmatite ores and host rocks to adjust parameters of geophysical exploration methods (Haase & Pohl 2022) and a spectral reflectance database of pegmatite minerals and ores for satellite image processing (Cardoso-Fernandes et al. 2022). The toolset will be easily deployable by small and medium sized enterprises and accessible to exploration and mining companies in "strategic knowledge-based consultancy services", offered by GREENPEG partners and as publication during 2024.

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Mineralogical characterization of a Li-phosphate-bearing pegmatite dyke from the Arlanda area, central Sweden

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During an ongoing investigation of potential arsenic-bearing lithologies in the Arlanda area different rocks including granitic pegmatites have been recorded. Granitic pegmatite swarms varying from simple ceramic to highly fractionated and mineralogically complex types occur at the western margin of the Vallentuna granitic massif close to Arlanda airport (Nysten & Jonsson 1998). These dikes belong to the LCT-family of the rare-element class of Cerny (1991). Here a moderately fractionated dyke containing grey microcline, white plagioclase (cleavelandite), muscovite, apatite, beryl, garnet, Mn-(Fe)-Al phosphate, and columbite – tantalite is described.

Geological setting

Thin pegmatite swarms intruding epiclastic Precambrian rocks parallel to their foliation planes occur close to Starrmossen. A local concentration of pale green phosphate pods up to 20 mm in size with a blue alteration rim has been identified using pXRD at Museum of Natural History in Stockholm as triphylite. These pods are set in a matrix of albitic plagioclase, dark grey to black quartz and white muscovite (SWEREF 6612622/665685). No clear zonation has been recorded but bands rich in red garnet are present. Accessory white beryl and dark green to blue apatite also occur. A prominent feature is the presence of light blue vivianite at the triphylite rims. Traces of other phosphates form small euhedral brownish-yellow crystals in vuggy parts of phosphate pods. Columbite *sensu latu* associated with bituminous U-oxides up to a few mm in size is relatively common. Arsenic phases (arsenopyrite/löllingite) occur sporadically in analogous dikes to the south of the pegmatite described above and schorl is a common mineral in many of these rocks.

Mineral chemistry

Manganiferous apatite ($Ca_{4.41}Mn_{0.27}Fe_{0.02}Na_{0.01}P_{2.92}F_{0.99}Cl_{0.01}O_{12}$) has been recorded as well as a hydrated MnAl-phosphate which is sensitive to the electron beam and showing a low total. A several mm large euhedral platy columbite – tantalite overgrowing cleavelanditic albite shows intricate oscillatory rhythmic growth zonation with Mn/(Mn+Fe) = 0.44 and Nb>Ta for both light and dark BSE zones. This pattern is cut by a late interfingering columbite phase with minor Ti and Mn/(Mn+Fe) = 0.29. Small euhedral columbite – tantalite shows Nb-rich cores (ferrocolumbite) and Ta-rich rims (ferrotantalite/ferrotapiolite) suggesting a crystal fractionation trend. The columbites occur both disseminated in the pegmatite matrix as well as inclusions within garnet. A Fe-rich chlorite + quartz form rims on the columbite crystals. Garnet composition varies from core–mantle–rim as Alm 52.2 – 53.7 – 61.4 Sps 47.0 – 45.5 – 37.4 with minor pyrope and grossular components. The increase in almandine towards the rim is probably a metamorphic feature.

Genetical considerations

Fractional crystallization from a fertile granitic source such as the Vallentuna granite (Nysten 2022) is suggested, which would fit into a regional distribution pattern of earlier recorded dikes at Arlanda.

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Magma batch emplacement in the Slaufrudalur pluton, SE Iceland

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Granitic plutons are formed by the successive emplacement and amalgamation of single magma batches (Annen et al., 2015). The emplacement rate, shape and volume of the batches influence the internal architecture of plutons and magma transport in the Earth's crust. Understanding the internal structure of igneous intrusions not only improves our understanding of magma emplacement mechanisms (Mattsson et al., 2020), the emplacement of single magma batches has also fundamental implications for the transport of hydrothermal fluids, elements and heat during and after the lifetime of the larger-scale magmatic system (Bartley et al., 2021). The intrusion of magma batches into plutons has mostly been analyzed by numerical modelling, but must be further constrained by field studies.

We focus on the Slaufrudalur pluton in Southeast Iceland to investigate magma batch emplacement and incremental growth of igneous intrusions. The Slaufrudalur pluton shows a bulk volume of 8-10 km^3 and is the largest exposed granitic intrusion in Iceland (Burchardt *et al*., 2012). The pluton is internally layered and was assembled by cauldron subsidence with magma batches being episodically injected from an underlying reservoir.

We carried out field and GIS mapping, AMS sampling (anisotropy of magnetic susceptibility) and photogrammetry. The pluton as a whole is horizontally layered, except near the margins. The magma batches are distinguishable lithological units that may be quantified in terms of average magnetic fabric with implications for magma flow kinematics. We distinguished eight lithological units from the horizontally layered interior to the non-layered margins. The contact relationships between the units are characterized by magma mingling, mixing and syn-magmatic deformation. Zones of intense mingling between granitic magmas generally occur at the transition from layered interior to non-layered margins. Moreover, we identified hydrothermal alteration and faulting along the wall rock contact and wall-roof transition in the northern part of the study area.

We conclude that: (**1**) the magma batches spread from the margins to the horizontally layered interior of the pluton, (**2**) magma mingling and mixing is more pronounced near the margins, (**3**) roof-wall deformation reflects the interplay between buildup of internal overpressure and magma batch emplacement, and lastly (**4**) wall contacts served as feeders and accommodated vertical pluton growth during cauldron subsidence. The Slaufrudalur pluton offers prime examples of features associated with magma batch emplacement and fluid transport in and around cooling intrusions.

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Geochemical tracers for LCT Li-rich pegmatites: from granite to apatite composition as indicators of Li-mineralization in the Central Iberian Zone

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Introduction

Lithium-enriched aplite-pegmatites are relatively common in the Central Iberian Zone (CIZ) (Spain and Portugal), in a ~75,000 km^2, NNW-SSE striking belt. These aplite-pegmatite bodies are usually dyke-like and appear grouped in pegmatite fields, sometimes spatially zoned around a granite intrusion (Roda-Robles et al. 2018). Their main Li-bearing minerals are spodumene, petalite and *lepidolite*, with minor amblygonite-montebrasite. Field, geochemical, structural and geochronological data indicate that the origin of this Li-mineralization is related to the major Variscan granitic magmatism occurring between 320 and 290Ma. However, not all the Variscan granitic series distinguished in this region are petrogenetically related to the Li-bearing pegmatitic fields. Detailed studies, including bulk-rock chemistry of granitic and pegmatitic rocks as well as major and trace elements analyses of apatite have allowed the determination of the linkage between this Li-mineralization and the different granitic series in the CIZ.

Granitic rocks from the CIZ may be classified into five geochemically distinct series (Roda-Robles et al. 2018): (S1) two-mica highly peraluminous leucogranites; (S2) P-rich highly peraluminous granites; (S3) P-poor moderately peraluminous granites; (S4) moderately to low peraluminous granites; and (I) low peraluminous I-type granites. S1 and S2 have a dominant metasedimentary derivation, whereas the other three granitic series come mainly from metaigneous sources. Chemically, S3, S4 and I series show long, quite continuous trends of decreasing Al_2O_3, Fe_2O_3, CaO, MgO, TiO_2, P_2O_5 and Sr contents as SiO_2 increases. In contrast, S1 and S2 series present shorter compositional trends with higher P_2O_5 and lower CaO concentrations. Contents in the incompatible elements F, Li, Ta, Cs, Rb and Sn are higher in the S1 and S2 than in the other granites, with continuous trends from these granitic series through the simple pegmatites, up to the Li-richest ones. It is remarkable that in the S1 and S2 granitic series there is an inflexion point in the Sr content, with an increase in this element from the most fractionated leucogranitic units up to the Li-rich pegmatites. The observed chemical trends, together with other geological data, clearly suggest that the P ± F-rich, Ca-poor, strongly peraluminous granites of the S1 and S2 suites are most probably the parental granites of the Li-rich pegmatites in the CIZ.

Main chemical variations observed in apatite associated with the different facies of S1 and S2 granites and with the simple, P-rich (intermediate) and Li-rich pegmatites correspond to Mn, Sr, Y and REE. In general, apatite from the Li-rich pegmatites and from the granites related to them are the Mn- and Sr-richest and the Y- and REE-poorest ones (Roda-Robles et al. 2022).

Therefore, the characterization of the chemical signature of the granites combined with the mineral chemistry of apatite may help exploration for Li in the CIZ. Moreover, these geochemical indicators may likely be used in other pegmatitic belts.

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Machine learning-based till geochemical pattern recognition applied to mapping and targeting of potential area for lithium mineralization in Västernorrland region, Sweden

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The increasing demand for lithium driven by the "green transition" is leading to the application of new and innovative exploration methods to numerous mineral systems, including lithium- cesium-tantalum (LCT) pegmatites. Sweden hosts numerous LCT pegmatite mineralisations in the Västernorrland (VNL) region, and as part of the Exploration Information Systems project (Horizon Europe grant no. 1010557357; eis-he.eu), which aims to create an open sourced QGIS toolkit for mineral prospectivity mapping, the Geological Survey of Sweden (SGU) has undertaken preliminary data preparation for MPM using principle component (PC) analysis and k-means clustering to applied to geochemical analysis of till to identify potential prospective areas for further Li exploration.

The Geological Survey of Sweden and Nämnden för Svenska gruvor (NSG) (Lax and Selinus 2005) collected till samples for analysis in the VNL region during the 1980s with a total sample density of around 1 sample per 7km^2 and the samples were analyzed for major and trace elements using ICP-AES and XRF (Al, Ca, Fe, K, Mg, Mn, Ba, Be, Co, Cu, La, Li, Ni, Pb, Sr, Zn (SGU) + Sc, As, V, Y, Ti, P, Na, - Be (NSG)). NSG data were levelled to the SGU data.

Robust PC-analysis and K-means clustering were applied to the till data, both major and trace element data together and trace element data only. PC results from all element data displayed positive scores along PC1 associated with Cu-Co-Mg, and negative PC1 Scores associated with La-Sr-Ca. This result indicated that the first principle component can be used to distinguish till with a mafic component with that of a more felsic origin. The second PC of the all-element analysis provides a further delineation of till samples with mafic, potentially doleritic origin along the negative axis, and more fractionated granites with strong positive PC2 scores associated with Li and Ba.

Examination of the PC scores for only trace elements shows similar discrimination of the mafic and felsic components along the first principle component axis, with similar loading scores to the all-element data. The 3rd principle component shows strong negative scores associated with Be, Li and Zn. The correlation of Be and Li on the negative axis is an indication that negative score can be associated with highly fractionated granites or mineralized LCT pegmatites due to the enrichment in Be in VNL pegmatites. K-means clustering identified six clusters, with the 6th cluster being best associated to potential Li mineralization.

In summary, both PCA and K-means clustering seem likely to be useful in the interpretation and classification of samples into different groups which can be correlated to the existing interpretations of the regional geology and known Li pegmatite mineralization. Outputs of this statistical approach with geological interpretation and knowledge may provide promising information on sites that may represent previously unknown occurrences of mineralization and can therefore be directly used in the selection of possible future additional study. Detailed geological mapping and lithogeochemical study, higher-density sampling and geochemical re-analysis of till samples with modern ICP-MS combined with novel and experimental approaches to indicator element selection may be a way forward in this and other previously glaciated regions with regards to LCT-type granitic pegmatites of this character.

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Discovery of a new rare element pegmatite field in the southern Gothenburg archipelago, western Sweden

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Detailed petrographic and geochemical mapping (using handheld XRF) on Donsö, Styrsö and Vrångö of more than 50 pegmatite bodies revealed the full transition from barren to rare element pegmatites (beryl and chrysoberyl-bearing). Together with LA-ICP-MS trace element analysis, the degree of fractionation can be seen in parameters such as Ba/Rb, Rb/Sr and trace element concentrations of Li, Ta and Cs in muscovites and feldspars, with the larger fractionated pegmatites containing garnet and the most fractionated beryl and chrysoberyl. Of particular significance is the age of the pegmatites of between 1.52 and 1.56 Ga. Such an Gothian age within the Idefjorden terrane distinguishes them from otherwise similar pegmatites from the mainland that are clearly associated with the Sveconorwegian orogeny (for example the well-known 1.03 Ga old berylbearing Högsbo pegmatite is <10 km away from Donsö). The new ages can be linked to the late deformation event that occurred 1.56-1.54 Ga in this part of the Idefjorden terrane. At this time, widespread migmatisation was associated with high grade metamorphism. However, a clear link between migmatisation and pegmatite origin cannot be made, as this time frame overlaps with the last intrusive stage of the Hisingen suite. This study also reveals that the dating technique employed, in-situ Rb-Sr dating of micas, has great potential easily delineating pegmatite provinces, even in areas with polymetamorphism. While biotites give Sveconorwegian ages (938 to 973 Ma; interpreted as thermally activated resetting, with the youngest potentially indicating a cooling age at ca 350^{o}C), muscovites Rb-Sr ages are exclusively Gothian in age, demonstrating that they are not affected by the apparent thermal overprint.

Session 7

Recent advances in understanding iron ores: Iron oxide-apatite (Kiruna-type) and iron oxide-copper-gold deposits (IOCG)

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Structures and textures of liquid immiscibility at Kiirunavaara, Sweden

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The mode of formation of iron oxide-apatite ores is an enigmatic issue that has intrigued the scientific community for more than a century. Theories revolve around two main schools: i) the magmatic, where ore is considered formed from Fe-enriched melts (fluid-rich), or ii) the hydrothermal, where ore is formed directly from hydrothermal, Fe-enriched fluids (e.g., Reich et al. 2022). The present contribution argues for the first school, specifically the case of Fe ore magma origin by separation of an immiscible Fe oxide liquid from a Fe-rich intermediate silicate magma, based on structures and textures observed in Kiirunavaara foot wall (FW) (Fig. 1, and more examples on the poster).

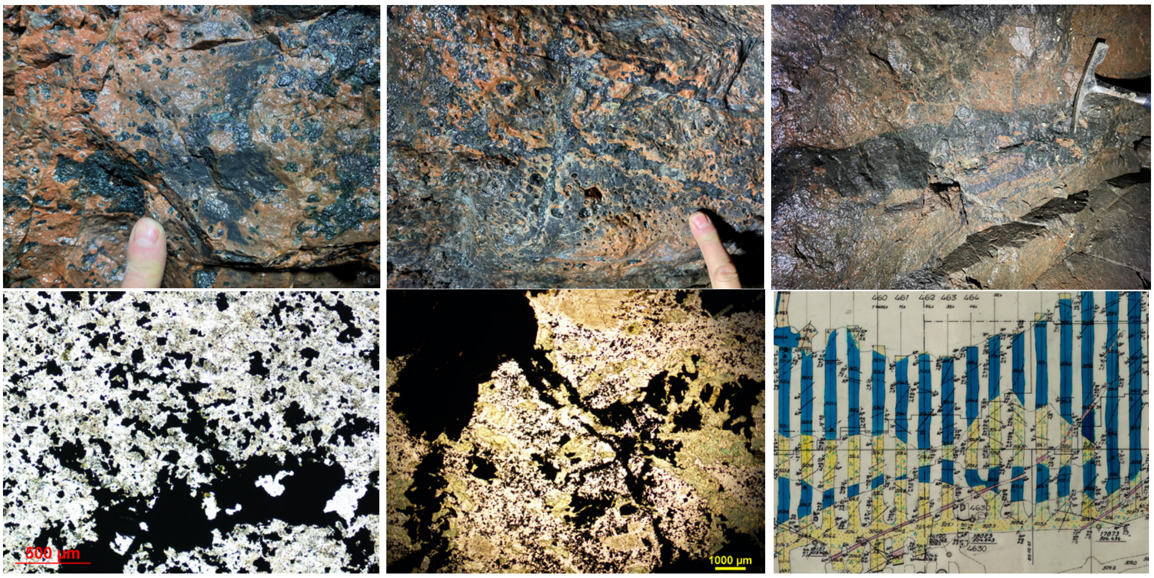

Fig. 1. From Kiirunavaara. A. Fine-grained Fe-rich parts of FW porphyry grade into Fe-oxide-dominated nodules and pods. B. Pods and nodules grade into veins. C. Veins grade into Fe-oxide dykes. D, E. Photomicrographs of textures corresponding to A and B. Drill cores 7024 (D) and 6481 (E). F. Excerpt of underground map from level 503 Y45-47. Abundant Fe oxide nodules and pods (blue markings) are reported in the FW (yellow) near to the ore (blue). A-C from level 275 Y45-46.

Iron-rich intermediate rocks are common in close association with the ore in Kiirunavaara (and other IOA deposits in Norrbotten). In these rocks you observe fine-grained sections 'dusted' with microscopic magnetite, transitioning into rocks where Fe-oxide has concentrated into nodules or larger pods with Fe-depleted surroundings (Fig. 1). The latter can be seen to connect to networks of thin veins that merge into dykes. These features can readily be interpreted as a separation of Fe-oxide- and silicate-rich liquids, where the former has lower viscosity forming flow channels in the latter.

Liquid immiscibility in Fe-rich silicate systems is experimentally confirmed (e.g., Lester et al. 2013) and documented in natural cases, including IOA systems (e.g.,Velasco et al. 2016). One problem correlating experiments with IOA ores is that the Fe-rich liquid obtained in experiments has been too low in Fe and too high in Si. However, recent experiments on volatile-rich systems indicate that nearly pure Fe-P oxide melts can be separated (Lledo et al. 2020). This combined evidence and the structures observed (Fig. 1) strongly suggests that liquid immiscibility is an ore-forming process in Kiirunavaara.

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Dyke porphyries in Kiirunavaara: feeders of the hanging wall volcanism

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Kiirunavaara in northernmost Sweden hosts the largest so far known iron oxide-apatite (IOA) ore body worldwide (>2000 Mt of pre-mining ore). It was also the first IOA deposit subjected to detailed scientific study as to geological relations and origin (Geijer 1910). Here we concentrate on a group of porphyry dykes (DPs) that penetrate the foot wall (FW) and ore before disappearing into the hanging wall (HW) rocks and their role in the geological evolution.

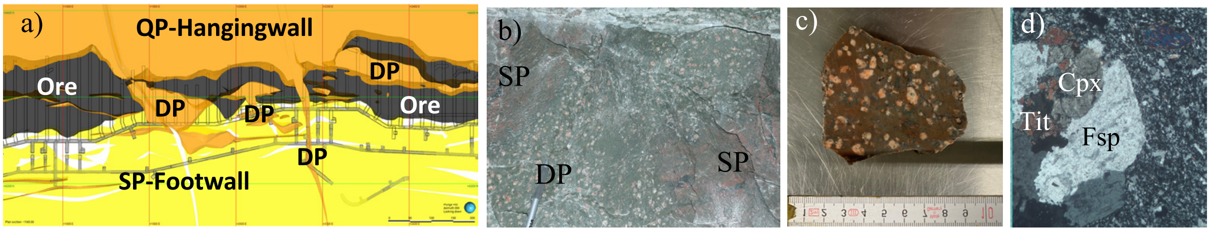

Fig. 1.a. Example DP distribution in FW and ore. b. Greenish DP dyke cutting altered FW porphyry (SP). c. Red-stained DP. d. Photomicrograph of glomerocryst and matrix in DP.

These DPs intrude in an irregular way, winding through, forming dykes of sizes from less than 1 m to >10 m (Fig. 1a,b). The colour varies from dark to green to red (Fig. 1b,c), where the red is due to µm-sized inclusions of Fe^{3+} oxides, while the green is related to abundant groundmass clinopyroxenes (Cpx). Phenocrysts (glomerocrysts) consist of perthitic (antiperthitic) alkali feldspar and minor plagioclase, typically associated with larger grains of Cpx and titanite (Fig. 1d). Texturally, they are inseparable from the volcanic quartz-bearing porphyries of the HW (QP), which they do not intrude.

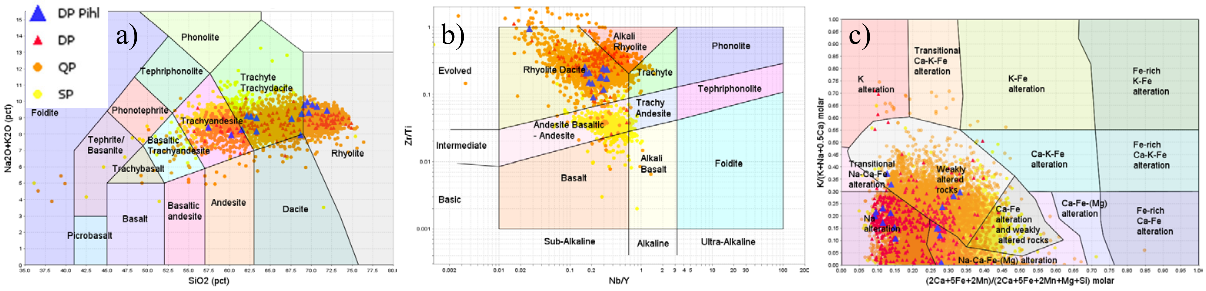

Fig. 2.a. The DPs overlap geochemically completely with the HW (QP) rocks, ranging from intermediate to rhyolitic compositions in major element classifications. b. In contrast, they plot mainly in the rhyolitic field using 'immobile' trace element diagrams. c. Strong sodic metasomatism has affected most rocks in Kiirunavaara, incl. the DPs.

Geochemically, the DPs and the HW rocks are inseparable, while the FW (SP) rocks generally have a different composition (Fig. 2a,b). The primary chemistry of most silicate rocks in Kiirunavaara has been altered by metasomatism, incl. the DPs, leading to dominantly strong enrichment in Na (Fig. 2c). One sample of DP was subjected to LA-ICP-MS U-Pb zircon geochronology. The zircons typically show oscillatory growth zoning, with little indication of older or younger zones. A concordia age of 1880±4 Ma (MSWD=0.79; n=26) was obtained, representing the intrusive age of the DP. This age overlaps, within error, the ages of the ore and its host rocks (Westhues et al. 2016).

In conclusion, the characteristic DPs in Kiirunavaara crosscut the FW and ore and 'merge' with the HW, with which they share textural and geochemical identity, as well as age. Thus, we suggest that the Kiirunavaara DPs represent feeder channels for at least parts of the HW volcanism.

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Mafic underplating as a possible source for iron oxide-apatite deposits in Norrbotten, Sweden

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The Norrbotten region in northern Sweden is one of the most active mining areas in Europe and the hub of Europe's iron production. The northern Norrbotten ore district hosts a rather unique cluster of iron oxide-apatite (IOA) deposits, including the Kiruna and Malmberget iron mines as the most prominent examples. Genetic models for Kiruna-type IOA deposits are controversial and range from a magmatic origin to a purely hydrothermal origin. Martinsson et al. (2016) suggested a combination of both models for Malmberget and Kiruna. IOA mineralization processes are assigned to a phase of back-arc extension at the onset of the Svecokarelian orogeny (ca. 1.88 Ga; e.g. Andersson et al. 2022). Despite the formation processes, a major question remains regarding the source of iron needed for the formation of these large systems. Several potential sources have been suggested, ranging from greenstone rocks to Svecofennian volcanic rocks to mafic intrusions.

A common feature that all IOA deposits in northern Norrbotten share is the existence of ultramafic and coeval felsic intrusions close by. These intrusions are typically magnetite-rich and have a similar age as the related IOA deposits. Drex project has recently acquired dense regional scale (~ 100x100km) magnetotelluric (MT) data array consisting of more than 400 sites around in the area. Data were inverted to obtain a full 3D conductivity model of entire crust. The 3D conductivity model contains extensive enhanced conductivity structure in the upper, middle crust at depth range from about 10 to 30 km. The resolution of the 3D model is sufficient to map pipe-like features that partly reach the surface in the close vicinity of known IOA deposits. Those deep feeders are also mapped in more details with deposit scale MT arrays in Nautanen and Malmberget areas. Enhanced conductivities in the crust can be explained by the presence of sulfides (grain boundary sulfides), iron oxides (magnetite), graphite or iron-rich ultramafic rocks (e.g. Hill 2021). Based on a combination of MT 3D model with field observations and potential fields 3D models we suggest that the crustal conductor under northern Norrbotten represents a large volume of ultramafic rocks emplaced by underplating during the back-arc extension. Tornos et al. (2023) recently showed that assimilation of crustal rocks can promote separation of silicate magma from iron-rich ultramafic melts and is interpreted as the formational process for IOA deposits. The data presented here suggests a comparable model where ultramafic intrusions intrude into the upper crust sourcing from a larger volume of ultramafic rocks caused by mafic underplating. Assimilation of crustal rocks during uprise of these intrusions can subsequently trigger separation and formation of iron rich melts.

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Petrogenesis of Fe-Ti-P-(Zr)-rich rocks and nelsonites in the Raftsund intrusion, Vesterålen-Lofoten AMCG suite, Northern Norway

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The origin of Fe-Ti-P-rich rocks and nelsonites (SiO_2<10 wt%), predominantly found in mafic layered intrusions or anorthosites, has been debated. Fractional crystallization coupled with crystal sorting and/or magma mixing are the most commonly accepted processes suggested for these enigmatic rock types. Another process is silicate-liquid immiscibility. This mechanism has regained attention as a viable process in dry mafic tholeiitic systems. However, little is known about the petrogenesis of Fe-Ti-P-rich rocks found in monzonite and syenite. In this study we present unique occurrences of Fe-Ti-P-(Zr)-rich rocks and nelsonites, associated with the monzonitic to syenitic Raftsund intrusion, Northern Norway, that supports the silicate-liquid immiscibility formation model.

The Raftsund intrusion is a 35 x 70 km large batholith which belongs to the Lofoten-Vesterålen anorthosite-mangerite-charnockite-granite suite and was emplaced around 1800 Ma in migmatitic granulite facies gneisses. Conditions of emplacement, constrained by the QUILF equilibria (Markl et al, 1998), indicate that the suite was emplaced at 4-5 kbar, magmas were hot (800-920 C) and dry (ternary feldspar) at $aSiO_2$=1 and $fO2$=-0.6 FMQ. In this study, we focus on the Fayalite-Augite (Fay-Aug) monzonite which hosts cm-scale vein-like Fe-Ti-P-(Zr)-rich segregations and a 20 x 15 m large nelsonite pod. Fay-Aug monzonite consists of clusters of Fe-rich minerals including fayalite, augite, ilmenite, rare titanomagnetite and allanite, surrounded by a matrix of ternary feldspar. Locally the Fe-rich mineral clusters are strongly enriched in zircon and apatite. Thin rims of plagioclase, enriched in Fe, are present at the contact between the Fe-rich mineral clusters and the ternary feldspar. A previous study showed that silicate-liquid immiscibility is the likely process explaining these features (Coint *et al*., 2020). Segregations of Fe-Ti-P-(Zr)-rich rocks, displaying the same mineralogy as the Fe-rich clusters, occur at the contact with monzonitic enclave in a mingling zone. The composition of ilmenite and titanomagnetite in the segregation and the host Fay-Aug monzonite overlap, suggesting that the segregation of Fe-Ti-P-(Zr)-rich rocks derive from accumulation of Fe-rich melt along rheological boundaries. The origin of the nelsonite pod containing rounded enclaves of monzodiorite, is more intricate as Fe-rich melt produced by silicate-liquid immiscibility usually contains a minimum of 20-30 wt% SiO_2. The nelsonite, hosted by the Fay-Aug monzonite, is composed of titanomagnetite, ilmenite, apatite, mm-large skeletal zircon and sparse altered Fe-rich silicates. Ilmenite and titanomagnetite in the nelsonite are strongly enriched in elements such as Mg, Sc, Zr and Al, compared to the same minerals in the Fay-Aug monzonite and monzodioritic enclaves. Enrichements in elements that should behave both compatibly and incompatibly during fractional crystallization suggest that the nelsonite was also formed by silicate-liquid immiscibility. Fractionation of the Fe-rich melt is required to reach the composition of nelsonite and a Fe-silicate cumulate is expected. Such rocks crop out further north in the Raftsund intrusion.

Silicate-liquid immiscibility is a viable process in evolved dry alkalic ferroan magmas which can lead to local enrichment in accessory minerals such as zircon and apatite. Silicate-liquid immiscibility is also responsible for the formation of nelsonite rocks but requires differentiation of the Fe-rich melt.

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Broadband seismic acquisition and processing of iron-oxide deposits in Blötberget, Sweden

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The transition towards green technologies and decarbonization has rekindled interest in reopening previously economically unviable mines to meet the growing demand for raw materials. This is the case for iron-oxide deposits in the Blötberget mining area of Bergslagen mineral district in central Sweden. The mining activity in Blötberget stopped in 1979 (Nordic Iron Ore, 2011). However, the renewed interest in recent years has led to a series of studies aiming at delineating the geometry and extent of the deposits at depth for optimized mine planning and resource estimations.

The ore in Blötberget primarily comprises high-quality iron-oxides in the form of magnetite and hematite, enriched with apatite. These deposits occur in sheet-like horizons with a moderate eastward dip along an NNE-trending zone (Nordic Iron Ore, 2011). The sheet-like mineralized horizons, ranging from 10-50 meters in thickness, are inclined towards the southwest with a dip of approximately 45° until 500 m depth, beyond which the dip becomes gentler. As of current knowledge, the mineralization is expected to extend down to 1200 m depth, where a cross-cutting reflection disrupts its continuity (Malehmir et al., 2021).

In June 2022, a novel seismic survey was conducted in Blötberget to assess the capability of combining both broadband source and receivers. The data acquisition was conducted above a well-known mineralization horizon. The survey incorporated a combination of collocated MEMs (micro-electromechanical sensors), 3-component geophones, surface and borehole distributed acoustic sensing (DAS), alongside a broadband seismic vibrator (2-200 Hz).

Expanding the bandwidth of recorded data offers several advantages, such as mitigating wavelet side-lobes, reducing sensitivity to scattering and attenuation through lower frequencies, and achieving sharper wavelets through higher frequencies. Broadband data thereby improve resolution and also depth penetration (Ten Kroode et al., 2013).

Leveraging insights from previous seismic studies in Blötberget, the high-fold broadband data facilitates improved imaging of known deposits compared to prior investigations, along with the detection of potential additional resources beneath the mineralization. However, the most significant enhancement lies in the broadband data's capacity to resolve the cross-cutting fault system, delineating the depth extent of the mineralization. This case study underscores the potential of broadband data for achieving high-resolution subsurface imaging in hardrock environments and its role in fostering a more efficient approach to mineral resource assessment in the context of our rapidly evolving era of green technologies and decarbonization.

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Trace element redistribution in magnetite during metamorphic recrystallisation: Evidence from the Malmberget IOA deposit

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The Malmberget Iron Oxide Apatite (IOA) deposit in northernmost Sweden is the second largest underground iron mine in the world. The Gällivare-Malmberget area is characterised by a complex geological history including multiple phases of deformation, metamorphism, and alteration, resulting in a geometrically and lithologically intricate ore deposit (Bauer et al. 2018, Yan et al. 2023). Fe-O isotope signatures in the Malmberget IOA deposit are magmatic to magmatic-hydrothermal. Although, primary ore textures and ore deposition structures have recrystalised at amphibolite facies conditions resulting in medium- to coarse-grained granoblastic polygonal magnetite crystals (Lund 2013, Henriksson et al. 2023).

Aside from Fe and O, magnetite can accommodate a wide range of trace elements into its crystallographic structure (e.g., Dare et al. 2014). However, trace element redistribution in magnetite ore during metamorphism is not well-studied, particularly for IOA deposits. Here we present the results from pilot LA-ICP-MS element maps of a magnetite sample from the Malmberget IOA deposit.

Magnetite trace element maps (for ^{24}Mg, ^{27}Al, ^{29}Si, ^{43}Ca, ^{45}Sc, ^{49}Ti and ^{51}V) were generated by LA-ICP-MS using the Teledyne Photon Machines G2 laser coupled to a Bruker Aurora Elite quadrupole ICP–MS and a HelEx 2-volume sample cell at Lund University. All trace element contents are normalised to ^{57}Fe.

The trace element maps of Mg and Al are characterised by irregular but relatively enriched magnetite cores, depleted magnetite rims, and extremely enriched magnetite-magnetite grain boundaries. Ti also shows elevated content in the irregular core, however no elevated Ti contents can be observed in the magnetite-magnetite grain boundaries. Remarkably, the trace element map of V shows perfectly homogeneous V-contents, regardless of core, rim, or magnetite-magnetite grain boundaries. For the Si, Ca, and Sc trace element maps, no distinct pattern can be observed in the magnetite, instead elevated contents are seemingly randomly distributed across the analysed magnetite crystals.

These observations have implications for the reliability of trace element studies of magnetite when investigating metamorphosed iron deposits, especially when working with in situ methods.

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Formation kinetics of Iron-Oxide-Apatite deposits: Examples from Kiirunavaara and El Laco

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The contentious debate on Iron-Oxide-Apatite (IOA) formation continues to this day (Reich et al. 2022, Tornos et al. 2023). The historically most investigated and debated IOA localities are the Kiirunavaara deposit in northernmost Sweden and the El Laco deposit in northeastern Chile. However, detailed ore deposition characteristics are still not well understood, and characterization of deposition mechanisms are complicated to study due to the isometric crystal symmetry of magnetite. Advanced analytical techniques such as electron back scattered diffraction (EBSD) analysis enables, among other features, the study of crystal orientations and crystal alignments regardless of crystal symmetry and can therefore be applied to understand formation kinetics in IOA deposits. Here, we report the first EBSD analyses on massive magnetite samples from the Kiirunavaara and El Laco IOA deposits.

The applied rationale is based on fluid dynamic experiments of rigid bodies in flows (Zitoun & Sastry, 2004). For magnetite crystals in a flow environment, this suggests that the crystals align one of its crystallographic axes {111} along the principal flow direction. On the contrary, magnetite crystals in a stagnant environment will instead accumulate without any preferred alignment. By evaluating the relative distribution of {001} and {111} we can better understand the different depositional mechanisms and kinetics that form giant Kiruna-type deposits.

EBSD analysis was performed at the Swedish Museum of Natural History using an Oxford Instruments Nordlys detector attached to a FEI Quanta FEG 650 SEM, based on the procedure in Kenny et al. (2020), using magnetite match units from Wechsler et al. (1984). The Oxford Instruments software's Aztec and Channel 5 were used during data collection and post-acquisition processing.

Two clear trends are revealed in the EBSD data from the massive magnetite samples when comparing the relative distribution of {001} and {111}. The magnetite samples from Kiirunavaara show no preferred alignment and suggest a calm crystal settling environment, concordant with crystal settling of magnetite crystals from crystal fractionation or within an immiscible melt (Troll et al. 2019; Zhang et al. 2020). Opposingly, the magnetite samples from El Laco exhibits extreme crystal alignment along {111}, consistent with previous interpretations of massive magnetite lava flows at El Laco.

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The 1.71 Ga iron mineralization event in the southwestern East European Craton, SE Lithuania: what has caused it?

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The Varena Iron Ore deposit (VIOD) in the SW East European Craton, SE Lithuania consists of several ore bodies located within metamorphosed and hydrothermally reworked Paleoproterozoic dolostones. The deposit is covered with 200-500 m thick sediments. Microstructural investigations supplemented with mineral chemistry and geochronological investigations (LA-ICP-MS) were performed to obtain age constraints on the ore-forming event(s) and improve the understanding of the conditions during mineralization process, its extent and distribution.

Peak metamorphic and retrograde hydrothermal reworking were recognised. Skarn assemblages of Mg-olivine, spinel, pyroxene, and calcite were formed during metamorphism at a temperature of 600 - 710^{o} C in the presence of water- dominated fluid. During retrogression, chlorite, serpentine, secondary dolomite and inclusion-rich magnetite (Mag-1) replaced the peak metamorphic assemblages.

Influx of an iron-rich, oxidised and water-rich fluid, occurred during the stage of decreasing pressure, and resulted in dissolution of pre-existing metamorphic magnetite, formation of inclusion-rich magnetite (Mag-1) and precipitation of a new, inclusion-free generation of magnetite (Mag-2). This occurred at a temperature of 300-500^{o} C and lead to intense secondary dolomitization, chloritization and serpentinization. Accessory phases of monazite, baddeleyite and zircon have precipitated from the water-rich fluid together with inclusion-poor magnetite (Mag-2). The approximate U-Pb age of the accessory phases is 1.71 Ga, which can be considered as the age of major iron mineralization.

Origin of the mineralization are key factors for understanding of the extent, distribution and economical value. The 1.71 Ga ore-forming event in SE Lithuania post-dates the 1.75- 1.81 Ga TIB-1 magmatism in Sweden (Salin et al. 2019). Similarly aged metamorphism and deformation at ca. 1.73-1.70 Ga is widespread in the region (Bogdanova.et al. 2001). Iron and apatite ores in neighboring Sweden are mostly of igneous origin and are older, Svecofennian in age, while in Poland they are mostly igneous and Mesoproterozoic in age (1.52-1.50 Ga, Wiszniewska et al. 2002). The VOID mineralization might have been triggered by the 1.67- 1.71 Ga magmas that represent an eastern extension of the TIB-2 magmatism in south-central Sweden.

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Spatial and genetic links between magnetite-(apatite) and IOCG systems

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Magnetite-(apatite) (MtAp) and iron oxide copper gold (IOCG) systems include a complex mélange of ore deposits with diffuse limits and poorly known genetic relationships. At a worldwide scale, MtAp districts are fairly abundant but only locally are spatially related with IOCG mineralization. Conversely, major IOCG districts not always related spatially or temporally with MtAp mineralization. Geology and geochemistry suggest that MtAp rocks are formed by crystallization of ultrabasic iron-rich melts more akin to carbonatites and other silica-depleted alkaline melts, than to silicate-rich magmas (Tornos et al., 2023). The unusual diopside/actinolite and apatite-rich but quartz-depleted composition of these rocks is difficult to explain if they are related to magmatic-hydrothermal systems formed during the crystallization of mafic to felsic water-rich intrusive rocks. More likely, evolved MtAp systems behave as natural analogues of blast furnaces with separation of a deep and dominant layer of massive magnetite capped by a complex assemblage of apatite and Ca-Mg silicates that is chemically and physically similar to that of slag. Fractional crystallization of these late rocks produces a wide variety of coexisting immiscible melts that are not fully understood. Local presence of hematite and abundant anhydrite suggest that these melts were highly oxidized and transported little reduced sulfur. The crystallization of large amounts of magnetite induced water supersaturation of aqueous fluids and the release of vast amounts of aqueous fluids that form large aureoles of alkali-calcic-iron alteration with local replacive magnetite mineralization (≈skarn). In subaerial systems, the formation of the magnetite-slag zonation is inhibited and the violent release of large amounts of aqueous vapor produces large maar-diatreme complexes with crater lakes infilled with breccias. The ultimate origin of these iron-rich melts seems to be related with the contamination of silicate melts by continental to shallow marine sediments, many times evaporite-rich, that underlie most MtAp districts. Melt contamination can be traced through radiogenic and stable isotopes and melt inclusion data. $^{87}Sr/^{86}Sr$ and triple oxygen isotope data (Peters et al. 2021) as well as by the abundance of melt inclusions enriched in different salts, including, carbonates, sulfates and chlorides (Bain et al. 2020). MtAp systems can be the host of, IOCG systems characterized by the hydrothermal precipitation of magnetite and chalcopyrite associated with an actinolite-feldspar hydrothermal alteration. The most likely reason of this association is that magnetite, whatever the origin, is an excellent trap due to its brittle behavior and its capability of buffering both redox and pH at intermediate to low fluid/rock ratios. This is observable in several deposits in northern Sweden where the "IOCG" mineralization postdates and cross cuts earlier MtAp mineralization (e.g. Malmberget, Bauer et al, 2018). However, IOCG-like systems can also form away from ironstones, as veins or stratabound replacements ("periskarn") of permeable volcanoclastic andesite. The ultimate origin of the ore forming aqueous fluids is unknown but could be related with the crystallization of mafic silicate melts or fluids released from an underlying MtAp system.

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Magnetite chemistry and Fe-O isotopes help unravel origin and affinities of the Malmberget iron oxide-apatite deposit, northern Sweden

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European iron ore production is primarily sourced from iron oxide-apatite deposits in the northern Norrbotten ore province in northernmost Sweden. The Malmberget iron oxide-apatite deposit is the largest underground iron ore resource in Europe and is an amphibolite grade analogue of the world-famous Kiirunavaara iron oxide-apatite deposit. The Malmberget rock association is characterised by multiple phases of deformation, metamorphism and alteration that resulted in a genetically ambiguous and geometrically complex deposit. Primary ore textures and emplacement structures of the Malmberget iron oxide-apatite deposit have largely been recrystallised during metamorphic overprint and now comprises dominantly medium- to coarse-grained, granoblastic magnetite. In this contribution, we combine magnetite trace element chemistry and stable Fe-O isotopes to characterise the magnetite of the Fabian-Kapten and ViRi ore bodies and unravel the primary origin of the Malmberget iron oxide-apatite deposit. Trace element and Fe-O isotope data from massive magnetite samples from the Fabian-Kapten and the ViRi ore bodies indicate a high-temperature magmatic to magmatic-hydrothermal origin of the Malmberget iron oxide-apatite ore deposit, regardless of subsequent metamorphic modifications. Magnetite trace element contents and Fe-O isotope equilibrium calculations reveal a temperature discrepancy between the Fabian-Kapten ore body and the ViRi ore body, where the ViRi ore body has a more pronounced magmatic character than the Fabian-Kapten ore body. We explain this difference by the respective ore body's stratigraphic position in the ore-forming, magmatic system.

Geological control on petrophysical properties from the Kiruna mining district

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Easily accessible, near-surface deposit discoveries are declining, and exploration efforts tend to focus more on deeper targets, where geological observations are limited. Subsurface mapping using conventional exploration techniques is not suitable and new approaches are being developed, mainly focusing on geophysical techniques. While geophysical survey results can help to look through the cover and lower the costs for initial targeting, in complex geological settings direct geophysical detection is unlikely. The success of mineral exploration in deeper terrains is limited to our understanding of the three-dimensional architecture of the subsurface, and integrated geological-geophysical investigations tend to achieve more realistic results. Data integration can ensure that geophysical inversions consider realistic geometric relationships and structural variability of lithological units, and their lithological and metasomatic characteristics. Merging geological interpretations with geophysical models requires a good understanding of the physical property distributions and their geological control. Extensive studies in the Kiruna mining district in northern Sweden led to an improved geological understanding of the crustal architecture, which in combination with the good preservation of the Orosirian rocks makes the area a good candidate for integrated modeling. Several iron oxide-apatite (IOA) deposits are situated within the district, including the Kiirunavaara ore that consists of a tabular magnetite-apatite body that stretches 5km in length, 100m in width, and has a moderately steep dip (60°–70°), towards the east (Grip and Frietsch, 1973). Structural studies indicated that E-W-oriented crustal shortening related to basin inversion created a moderate to steep east-dipping stack of supracrustal rocks, with strong strain partitioning between lithological contacts and individual units (Andersson et al., 2021). Hydrothermal alteration has been characterized as epidotization, scapolitization, and albitization within the Kiruna Greenstone unit situated at lower stratigraphic levels (Martinsson, 1997). Higher up in Orosirian volcanic rocks hosting IOA deposits, ore proximal alteration has been described as albitization that transitions into sodic-calcic then sodic-calcic-ferrous style, while towards the top of the stratigraphic pile, the Per Geijer deposits are characterized by potassic style (Martinsson et al., 2016; Andersson et al., 2021; Lupoli et al., 2022).Our study aims to explore the impact of geological processes on the petrophysical properties from 32 outcrop samples. The physical property signatures of density, magnetic susceptibility, and p-wave velocity are investigated in association with lithological variations, alteration, and rock fabric within the Kiruna mining district. Results indicate that density, magnetic susceptibility, and p-wave velocity are influenced by deformation events that alter the rock texture and favor the remobilization of magnetic minerals, while metasomatic processes change the bulk mineralogical composition. These findings provide a framework for the petrophysical footprint of the area and serve as a foundation for future integrated geological-geophysical modeling.

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Character of syngenetic- and hydraulic breccias in the Kiskamavaara IOCG-(Co) deposit, northern Norrbotten, Sweden

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Iron-Oxide-Copper-Gold (IOCG) deposits are important deposits in the energy transition towards a sustainable society because they host a plethora of elements that are used in technological applications that replace fossil-fuel driven systems. However, criteria for the IOCG deposit-type have been vaguely constrained and their formation processes remain enigmatic (Williams et al. 2005, Groves et al. 2010). IOCG's are generally structurally controlled, affected by alkali hydrothermal alteration, brecciated, and host paragenetically early low-Ti Fe-oxides and Fe- and Cu-sulfides. In the classification scheme of Groves et al. (2010) the cobalt hosting, brecciated, shear zone situated and strongly K-feldspar altered, Kiskamavaara IOCG-(Co) deposit belongs to the IOCG sensu stricto group. Kiskamavaara resides in northern Norrbotten, approximately 40 km east of Kiruna in the crustal scale Nautanen deformation zone and local reactivated brittle-ductile faults (Bauer and Andersson. 2021). In this study the Kiskamavaara breccias are analyzed with micro-X-ray fluorescence (XRF), Computerized Tomography (CT) and drill core observations to provide a detailed breccia description of a classic IOCG deposit.

Preliminary results show that the oldest breccias in Kiskamavaara are interlayered syngenetic volcanic and volcano sedimentary breccias that constitute the host rocks for the overprinting mineralization. The volcanic breccia is a monomict, K-feldspar altered, poorly sorted and matrix supported fragmented andesite with flattened, sub-angular clasts. The matrix is fine grained and hosts both disseminated pyrite and early Fe-oxides. Brecciation possibly occurred via autobrecciation of lava flows during deposition. The interlayered volcano sedimentary breccia is polymict, sodic and potassic altered with andesitic, tuffaceous and schistose clasts. Furthermore, the breccia is poorly sorted, matrix supported, vuggy and often sheared. The sub-angular clasts are flattened and indicate short transport. Hydraulic breccias overprint the syngenetic breccias introducing cobaltian pyrite that constitute the infill material together with chalcopyrite and magnetite. The mineralized breccias are typically monomict, strongly K-feldspar and Fe-oxide altered, poorly sorted, matrix supported carrying angular to sub-angular clasts. Chalcopyrite carrying late carbonate veins overprint the hydraulic breccias. In drill core intervals up to 5 m, intense hydrothermal alteration overprints the host rocks and forms a poorly sorted, angular, jigsaw fit breccia with red K-feldspar altered clasts and a matrix consisting of massive magnetite or hematite overprinted by carbonate veining. In these intervals pyrite and chalcopyrite are completely absent. Towards the rim of the deposit, albite replaces K-feldspar in the breccias causing the clasts to appear more whitish-pink than reddish-pink within the pyrite matrix. In the same peripheral area, pyrite-veined biotite-chlorite schists occur. The absence of brecciation and presence of pyrite veining is likely caused by competence differences in the host rocks, but more analyses are needed for conclusive remarks.

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Session 8
Economic geology – metallogeny of the Nordic countries and beyond

Session Chairs:
Nils Jansson,
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Different styles of Na, K and Mg–Fe alteration and REE mobilisation in the Riddarhyttan and Norberg ore districts, Bergslagen, Sweden

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The Riddarhyttan and Norberg districts in the Bergslagen ore province host the most well-known Bastnäs-type Fe-REE deposits, comprising skarn-hosted, magnetite-rich iron oxide deposits associated with localised REE-rich and polymetallic mineralisation (e.g., Cu, Co, Bi, Mo). The prevailing genetic interpretation is that these deposits formed through the replacement of carbonate interlayers by hot Fe-REE-rich magmatic fluids in a syn-volcanic, sub-seafloor setting at around 1.9 Ga. The volcano-sedimentary wall rocks to the deposits underwent variable degrees of syn-volcanic hydrothermal alteration and were subsequently affected by polyphase Svecokarelian metamorphism and deformation. To evaluate the potential for REE mobilisation by the syn-volcanic hydrothermal fluids in the districts, we have compared variably altered felsic metavolcanics and penecontemporaneous metagranites with precursor rocks showing minimal to no alteration. We utilised the lithogeochemical database of the Geological Survey of Sweden, supplemented by newly collected samples.

In the Norberg district, notable Bastnäs-type REE deposits include the Malmkärra, Östanmossa and Johanna mines. The alteration of the metavolcanic rocks varies from pervasive to localised and show K or Mg-Fe signatures. The Mg-Fe alteration is concentrated in the central parts of the district and in proximity to different iron-oxide deposits, likely representing the footwalls to the mineralised skarn horizons. Local zones with Na to Na-Mg alteration are also observed. Around the Malmkärra deposit, Mg-Fe-altered metavolcanic rocks show relative enrichment of Mg and Fe, and depletion of Na, Ca, K, Ba, Sr and LREEs. Similarly, Mg-Fe-altered rocks closer to Norberg show a relative decrease in the LREEs. Conversely, K-altered metavolcanic rocks show no to weak LREE depletion. Metagranites east of the metavolcanic sequence exhibit distinct Na-Mg alteration, characterised by the relative enrichment of Mg and Na, and depletion of Ca, Fe, K, Rb, Ba, Sr and typically the LREEs.

The Bastnäs field, including the Nya and Gamla Bastnäs deposits, is located in the Riddarhyttan district. To the west of the field, likely representing the footwall, the metavolcanic rocks are weakly to moderately Fe-Mg-altered, with relative enrichment of Fe and Mg, and depletion of Na, Ca, Li, Ba, Sr, Pb, Zn, and variable LREE depletion. Proximal to the mineralised skarn horizon(s), the metavolcanic rocks display strong Fe-Mg alteration, with variable REE and polymetallic mineralisation, and show relative addition of Fe, Mg and locally also REE, S, Cu, Mo, Bi, Se and Te, as well as the depletion of Na, K, Li, Rb, Ba and Sr. Local skarn alteration of a marble outside of the main REE-rich mineralised zone shows relative enrichment of Si, Ba, Sr, LREEs, MREEs, Cu, Co, and Mo compared to an unaltered marble. Metavolcanic rocks to the east of the skarn horizon(s) exhibit no to weak K alteration and minimal LREE depletion, and likely corresponds the hanging wall. Further east of the Riddarhyttan district, regional-scale Na, Na-Mg and Mg-Fe alteration of metavolcanic rocks have resulted in variable LREE depletion. In contrast to the Norberg district, Na-Mg altered metagranites typically display low degrees of LREE depletion.

Significant LREE depletion in both districts is related to Mg-Fe-altered metavolcanic rocks, interpreted to be the footwall of the skarn-hosted REE deposits. Variable LREE depletion is also associated with Na-(Mg) alteration of metagranites and metavolcanic rocks. This indicates that syn-volcanic hydrothermal Mg-Fe and Na-(Mg) alteration were able to mobilise the LREEs and supports a genetic relationship between alteration and primary REE mineralisation. However, textural evidence for the remobilisation of REE during metamorphism is present in both districts, and it is difficult to determine how that has affected the chemical composition of the altered rocks. Nonetheless, the extensive zones of hydrothermally altered metavolcanic rocks and penecontemporaneous metagranites found in the districts suggest that the altered rocks could be the primary sources of REE.

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In-situ petrographic description of banded iron formation and skarn-hosted Fe ore on Utö, Bergslagen

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The island of Utö, situated east of Nynäshamn in the Bergslagen Lithotectonic Unit (BLU), has long been studied by geologists for its remarkable representation of Bergslagen's geology (Talbot 2008). It is home for multiple ore types commonly seen in the BLU – Banded Iron Formations (BIF) and skarn-hosted Fe-oxide and base metal sulphide ores (Allen et al. 1996). Utö is the type locality for multiple minerals, including petalite, holmquistite, spodumene and Mn-tantalite, the first three of which are Li-bearing. The Li-minerals were found in Li-pegmatite- and aplite dykes that crosscut the mines, and from petalite, the element lithium was first isolated and discovered by Arfwedson in 1817. Modern studies of the island's ore deposits are lacking and much of the studied material has little textural context as the samples come from mine waste.

We present petrographic descriptions of a series of drill cores sampling the Utö ore bodies from the SGU archive. 60 polished thin sections were prepared from three drill cores, with special focus on borehole U1737 that intersects the BIF. The thin sections were studied using the petrographic and scanning electron microscopes in order to identify mineral assemblages, textural relationships, establish the timing of growth of different minerals and characterize the stratigraphy. Of particular interest is the Li-amphibole holmquistite, that is found in banded Fe-oxides (Fig. 1) and volcanic ash siltstones, similar to that described by Pilava-Podgurski (1955).

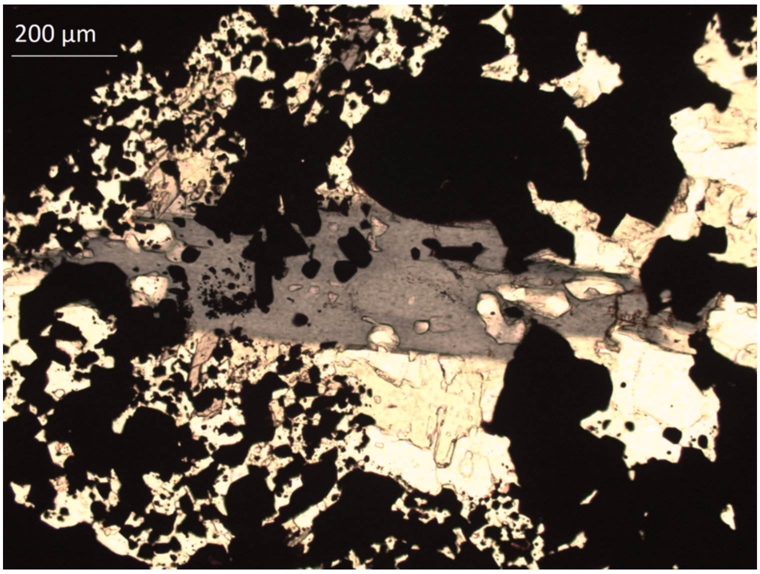

Figure 1. Holmquistite in skarn-altered BIF from drill core U1737.

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New insights on the Agnmyrgruvan Pb-Zn deposit in central Sweden from microscopy, UV-light imaging, and LA-ICP-MS

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Located on the Sollerön island in the Siljan Lake (central Sweden), the carbonate-hosted Pb-Zn (CHPZ) Agnmyrgruvan deposit is believed to be associated with the Siljan meteorite impact at around 377 Ma (Reimold et al. 2005). Along with the nearby Boda CHPZ deposits, the colloform sphalerite of the Agnmyrgruvan deposit was previously studied by Welin (1959), who compared the deposits to the Bleiberg deposit in Austria. Alpine-type CHPZ deposits (including Bleiberg, Mežica, and Raibl) contain colloform sphalerite that has been shown to host high amounts of critical metals, in particular Ge (Melcher et al. 2023; and references therein). With the rising interest in critical metals, the Nordic CHPZ deposits should be revisited to better the understanding of the distribution of these critical metals in sphalerite.

This study combines optical and electron beam microscopy, laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), Raman spectrometry, and ultraviolet (UV) light imaging to constrain formation processes of the Agnmyrgruvan deposit and investigate the distribution of critical metals in the colloform sphalerite. Raman spectrometry was used to investigate the presence of wurtzite, but the results were inconclusive. Individual bands of sphalerite show different luminescence colors under UV-light, such as yellow and orange, but also black (no luminescence). Trace element compositions vary significantly (e.g., Mn, Fe, Cu, Ga, Ge, As, Cd, Tl, and Pb) between the different colored bands of the colloform sphalerite. Sphalerite trace element geothermometry indicates formation temperatures between 130 – 190 °C, which is in accordance with the interpreted temperature by Welin (1959) of <200 °C. Furthermore, the Agnmyrgruvan deposit's unique association with a meteorite impact will contribute to the currently ongoing international work on CHPZ sphalerite trace element geochemistry, where such CHPZ deposits are lacking.

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The role of metamorphism in vanadium enrichment of organic-rich shales

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Shales and mudstones are common sedimentary rocks forming in marine basins throughout Earth's history. Besides being important record holders of Earth's paleoclimate, they are also a target for mineral deposit exploration since they can hold economic resources of critical minerals such as vanadium (V), which is an essential component of redox-flux batteries. Many Paleozoic shales are, however, metamorphosed and deformed. This commonly obscures primary features including V-bearing host phases and the original composition of organic material.

Here we present geochemical and mineralogical data on the Paleozoic Van prospect, Northwest Territories, Canada, to show that V can be released from organic matter during metamorphism and incorporated in clay phases such as illite. The siliceous argillites at the Van Property host up to 0.69% V_2O_5 and are metamorphosed to (sub-)greenschist facies. Its mineralogy is dominated by quartz with minor graphite, illite, muscovite, pyrite, sphalerite, rutile, and carbonates. Microprobe analyses show that two inorganic phases, illite and rutile, host elevated V concentrations. Based on V content, two illite sub-types are identified: (1) low-V illite that has on average 0.8 wt% V_2O_3, and is of illite endmember composition, deformed (e.g., kinked) and occurs close to quartz and carbonaceous matter, and (2) high-V illite that has on average 10.8 wt% V_2O_3, and is of illite/smectite composition, shows no deformation and occurs adjacent to carbonaceous matter. Rutile has up to 4.4 wt% V_2O_3, shows no deformation or alignment parallel to bedding, occurs with sphalerite and pyrite, and adjacent to carbonaceous matter. However, the inorganic V hosts cannot account for the bulk rock V concentration using simple bass balance calculations. The third V-host is here inferred to be carbonaceous matter in which V was incorporated upon sedimentation and early diagenesis due to metalation and formation of geoporphyrins. During metamorphism, maturated carbonaceous matter degraded resulting in the demetallation of V-bearing geoporphyrins and release of vanadyl ion. Some vanadyl ion was incorporated into high-V illite. Vanadium-enriched rutile also formed during metamorphism. This process of V enrichment highlights the role of carbonaceous matter in scavenging V and importance of metamorphism on subsequent V release and its incorporation into inorganic phases. Furthermore, the geochemistry of siliceous, V-rich argillites at the Van Property is compared to other V-enriched shale and mudstone deposits highlighting the diverse composition of host-rocks in shale-hosted V deposits.

Assessing the prospectivity for Fe-Ti-P-(REE) mineralization in the southern part of the Permian Oslo Rift, Norway

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Large volumes of monzonite and syenites including the Larvik Plutonic Complex (LPC), were emplaced between 300 and 278 Ma (Rämö *et al.*, 2023; Pedersen *et al.*, 1995), as part of the Oslo rift. Monzonite from the LPC hosts several occurrences of Fe-Ti-P-(Rare Earth Elements - REE) mineralization (Ihlen et *al.*, 2014), including the Kodal deposit. However, the mineral potential of intrusions further north, which are Si-saturated, have never been studied in detail. We present here the first results of an ongoing multidisciplinary project carried at the geological Survey of Norway. The aim of the project is to assess the mineral potential of the monzonite and syenite for Fe-Ti-P-(REE) mineralization and develop new mineral exploration tools that can be used at regional and local scales.

First, we employed available datasets within a supervised machine learning framework, resulting in a predictive prospectivity map at a regional scale. The predictors include data from airborne magnetic and radiometric surveys, in addition to topographical information. The training dataset consists of whole-rock geochemical analysis categorized based on their P_2O_5 concentration. Samples containing more than 4 wt% P_2O_5 are labeled as mineralized, while those falling below this threshold are classified as barren. Our predictive model suggests that large magnetic anomalies and low potassium on the radiometry, characteristics of mineralization rich in magnetite and poor in alkalis, control the location of the predicted prospective areas. Field work confirmed that one area, basalt of Skien, strongly magnetic and poor in K, gave a false positive. However, when the predicted prospective areas are hosted within monzonite and syenite, Fe-Ti-P-(REE)-rich rocks were found cropping out at the surface. According to the map, the prospective areas not only occur in the LPC but also in intrusions further north, indicating that the potential for Fe-Ti-P-(REE) mineralization is not limited to the LPC.

In addition to the prospectivity map, we acquired new U-Pb geochronology and Hf isotope on zircon indicates that unlike what was previously assumed, the Kodal deposit is not part of the LPC but is younger (282 to 283 +/-2-Ma), has overall lower epsilon Hf (+2.5-+6) than the LPC (299-289 Ma, εHf: +5.5-+8) and belongs to the group of intrusions north of the LPC. These results support that the LPC is not the only mineralized intrusion in the area.

One of the largest prospective areas, located in the Siljan-Hvarnes intrusion, was selected for a drone magnetic survey to better constrain the shape and size of the magnetic anomaly picked up by the regional magnetic survey. A soil survey was carried out in this area, to test if the presence of an Fe-Ti-P-(REE) ore body can be detected using portable XRF and magnetic susceptibility meter. Preliminary results show that soil samples taken over the high magnetic anomaly measured by the drone, registered higher magnetic susceptibility values and higher concentrations of Ca, Fe, P and REE.

This study provides a new set of exploration tools to assess the prospectivity of entire regions for Fe-Ti-P-(REE) mineralization, however a good knowledge of geology is necessary to interpret the results.

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Surface outcrops in the Per Geijer area: macro-scale observations in limited drilling areas

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The continued exploration of the Per Geijer deposit by LKAB in Norrbotten, northern Sweden, has identified new targets in the form of apatite-bearing magnetite, hematite, and mixed ores. Often, drill core data only provides a snapshot of the stratigraphy and can limit the large-scale geological context. For this reason, the historical workings at the Nukutus pit in the Per Geijer area, were mapped and sampled to visualise the various units and textures in three-dimensional- space. Previous geological maps have suggested that the Nukutus pit is the northern–most expression of iron-apatite mineralisation in the area (Martinsson et al., 2013). Our mapping focuses on understanding the relationship between the wall-rock and mineralisation, and the various textures seen within the mineralisation itself.

The macro-scale observations suggest multiple apatite pulses both syn- and post- iron ore formation, which were sampled for microscopy. We identified both banded compositional layers of iron and apatite, and spotty apatite within a groundmass of mixed hematite-magnetite mineralisation, that appear syn-formation with iron. Whereas, iron brecciated by apatite veins, rip-up clasts of iron in an apatite groundmass, and folded veins containing coarse-grained apatite in hematite, suggest various post-iron formation apatite-rich fluids (Miles et al., 2023). The collected samples were confirmed for their composition by a portable handheld XRF. Ongoing microscopic observations will determine textures and mineral relationships at a thin-section scale.

As LKAB continues to explore at Per Geijer, we aim to compare the textures observed here with those found in drill core to understand the lateral continuity of the stratigraphy and provide further insight into the formation of iron-apatite deposits.

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An attempt to quantify element mobility during hydrothermal alteration in Bergslagen with a regional least altered database, Sweden

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The Bergslagen district in central Sweden hosts iron oxide, base metal sulphide deposits as well as less common ore types including Bastnäs-type REE-deposits. Most of the deposits are hosted by a bi-modal (dominantly felsic) volcanic succession and with interbedded limestone units. Many of the deposits are surrounded by strong, regional hydrothermal alteration in the country rock. It is believed that these hydrothermal alteration zones are genetically related to the ores and that they have served as source for metal-rich fluids, leaching certain elements from the country rocks, at least in some of the deposits (De Groot and Baker 1983; Lagerblad and Gorbatschev 1985; Jansson and Liu 2020). Investigations into mass change during hydrothermal alteration commonly use mass balance calculations comparing altered rocks with least altered equivalents to quantify metal depletion during hydrothermal alteration. Critical to this is the identification of least altered samples from the same area and rock-type. However, in many areas where hydrothermal alteration is intense, unaltered, or even "least altered" samples are difficult to find and furthermore, different definitions of least-altered rocks are used in the literature which causes a problem for reproducibility and comparison of the alteration styles in different areas.

This study presents a regional least altered sample database with 134 high quality, low detection limit major and trace element geochemical analyses of metavolcanic and granitic samples which were selected based on a clear set of criteria. The dataset includes samples from western Bergslagen (Hjulsjö area), Utö, the Riddarhyttan area Falun (Kampmann et al., 2017), Garpenberg (Jansson et al., 2013) and Sala (Jansson, 2022). The Hjulsjö area is particularly well suited due to good exposure of relatively low metamorphic grade (greenschist) felsic volcanic rocks, and variable degrees of Na-, K- and Mg-style hydrothermal alteration. It has been the location for a number of previous studies of hydrothermal alteration (i.e., De Groot & Baker 1983; Hallberg, 2003). The area also highlights the relationship between felsic volcanic rocks and co-magmatic granites that can help approximate a least altered felsic volcanic compositions in areas where least altered equivalents of the felsic volcanics are lacking (Hallberg, 2003; Kampmann et al., 2017).

The geochemical compositions of the least altered dataset reveals a consistent magmatic differentiation trend across all studied areas, supporting the notion of a magmatic source of similar composition across the Bergslagen district. A comparison of background metal concentrations in the different regions shows geographical variations. Interestingly western Bergslagen where relatively few and small polymetallic sulphide deposits have been found stands out with particularly low background base metal concentrations. This may suggest that differences in primary fertility of different volcanic centers in Bergslagen presented a first order control on the composition and abundance of ore deposits in the region.

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A lithological context for stratabound REE mineralisation at the birthplace of REE – Bastnäs, Riddarhyttan, Sweden

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The Bastnäs deposit in Bergslagen is the place where Ce, the first rare earth element (REE) was discovered, and it was the world's first hard rock REE mine. Despite its historical importance the processes of ore formation are not understood well. Previous investigations have largely focused on detailed mineralogic and isotopic analysis of old mine samples and tailings, often lacking crucial stratigraphical context. Recent exploration in the Riddarhyttan field by EMX Royalty Corp. has produced new drill cores which were logged and sampled in this study producing thin sections and performing EDS analysis of the minerals.

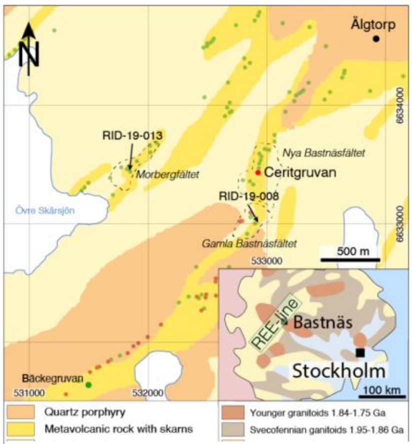

Figure 1 Geological map showing the location of the studied drill cores.

The Bastnäs deposit is one of several REE-enriched magnetite skarn deposits which occur in central Sweden. All of them are hosted in Paleoproterozoic felsic metavolcanic rocks with interbedded marble units. While previous studies mostly focused on the spatially confined but economically interesting cerite mineralization, this study focusses on two drill cores not directly associated with the cerite mineralization. The cores show that REE-enrichment occurs over large areas and throughout the stratigraphy. The first hole was drilled under the old Bastnäs mines ca. 400 m south of Ceritgruvan and the second drill hole is located 1km west (Figure 1) in a place where REE mineralization hasn't been described previously.

Geochemical data collected along the drill core by EMX Royalty Corp. reveal a close association of the REE enrichment with magnetite skarns. Within these magnetite skarns, REE concentrations peak at the contact to the felsic metavolcanic rocks. This suggests preferential flow of the mineralizing fluids along lithological contacts as described by Meinert et al. (1997). The mineralogically is dominated by epidote supergroup minerals (ESM), primarily ferriallanite-(Ce), dollaseite-(Ce) and dissakissite-(Ce). Notably, REE mineralization also occurs along faults, showing a slightly different mineralogy. While the ESM of the magnetite skarn associated mineralization contains inclusions of more REE-rich silicates such as britholite-(Ce) and gadolinite-(Ce), they are absent in the fault-related massive ESM. This is tentatively interpreted as indicating that allanite is a secondary mineral in this system and formed by recrystallisation of primary, more REE-rich silicates and phosphates which are products of earlier intense alteration of the stratigraphic succession. The fact that the mineralization along faults lacks inclusions of primary REE phases suggests that it is a result of late REE remobilization rather than the pathway of the fluids originally causing the REE mineralization.

Work on the characterization of the source of the ore-forming fluids is ongoing, with an emphasis on evaluating the potential contribution of hydrothermal fluids leaching the volcanic host rocks. This aspect is particularly relevant, given that the deposits are situated within metamorphosed, strongly Mg-altered felsic volcanic rocks, and since previous studies (cf. De Groot and Baker, 1983, Dunst et al. *in prep*) have demonstrated that the fluids causing this alteration type can leach REE from country rocks in Bergslagen and form REE-enriched hydrothermal fluids.

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Metallogeny of the Nordics: Fennoscandia and Greenland

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Bedrock of Fennoscandia and Greenland has a well-established mining and mineral exploration history focusing mainly on base and ferrous metals. Today, we see the region with a significant potential of a very large set of metals and minerals. Especially, nearly all included into the to the latest EU set of critical and strategic raw materials (Grohol et al. 2023) could be sourced from Finland, Greenland, Norway and/or Sweden. This is essentially grounded in that: 1) the bedrock is similar to major mineral-rich terrains globally but uniquely for Europe, 2) the Nordic countries comprising a land area comparable in size to the most mineral-rich parts of Canada, USA, Australia, South Africa, or Brazil, 3) there is a continuous presence of modern mining, and 4) locally developed leading-edge mineral exploration, mining, and mineral-processing technology (e.g., Eilu 2012, Boyd et al. 2016, Kolb et al. 2016, Jonsson et al. 2022).

Nordic metallogeny rather directly relates to supercontinent evolution of the region. From early Archaean protocontinent formation, through formation, rifting, and disintegration of Kenorland, Columbia, Rodinia, and Pangaea, to the current continental-margin processes, we see formation of major Au, Cr, Cu, Fe, graphite, Nb, Ni, PGE, phosphate, REE, talc, Ta, Ti, V, and Zn deposits. Mafic-ultramafic magmatic processes have produced Ni-Cu-Co-PGE, PGE-only, Cr, and Ti-V(-P) deposits, submarine hydrothermal systems Cu-Zn-Ag-Au, active margins porphyry Cu-Au and Mo, rifting-related carbonatite and peralkaline magmatism REE-P-Zr-Hf-Nb-Ta-fluorite, somewhat enigmatic processes Kiruna-type Fe±P±REE and IOCG, metamorphic processes Au, graphite, high-purity quartz, and talc-magnesite, passive-margins mineral-sand Ti(-REE-Zr-Hf), and euxinic passive margin settings produced black shale-hosted Ni-Co-Cu-Zn and V-U-Mo deposits.

What is not so well established, or even not much thought about, but where there may well be significant critical metal potential, relate, at least, to 1) large-scale rifting and the recently proven presence of evaporites in the Palaeoproterozoic of the northern Fennoscandia (e.g., sediment-hosted Ni and Au-Co±PGE, and copperbelt-type *sensu lato*), 2) Co, Sc, and V resources in IOCG, and IOA deposits, 3) Be, REE and Li in granitoids (excluding pegmatites), 4) Li in metamorphosed Thacker Pass type deposits, 5) Ga and Sc resources in Ti-V-Fe deposits. Serious work should be aimed on all these. Do we have such deposits, and if yes – where? Also, reasons why there aren't certain globally significant deposit types here (e.g., Carlin gold, evaporite potassium, sediment-hosted Li, red-bed Cu) should be investigated – perhaps the of view non-existence (of economic ores) is not true, after all?

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Structural controls on Ni-Cu-Co mineralisation in the Jotun-Valdres Nappe Complex, south-central Norway

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The Espedalen Nickel-Copper-Cobalt deposits lie within the lower Jotun-Valdres Nappe Complex of the Caledonian Orogeny. Recent studies have focused on the geometrical and geochronological aspects of the regional geology (Corfu & Heim, 2019) or on the processes related to the genesis of the mineral deposits (Mansur et al., 2023). The mineralisation displays typical magmatic textural and compositional features, however, these have been overprinted by deformation. Yet, the extent and origin of the deformation has not been considered in previous studies. We provide new structural and kinematic observations which document the relationship between the sulphide deposits and two separate orogenic episodes and place the mineralisation within a regional tectonic framework.

On a map scale, the distribution and geometry of the deposits shows two main patterns: 1) Minor deposits oriented in NNW-SSE linear patterns. 2) Larger, more massive orthomagmatic sulphide deposits forming mappable bodies in ENE-WSW geometries.

Detailed structural analysis reveals that type 1 geometries occur within steeply-dipping to vertical strike-slip mylonitic shear zones. The shear zones display mutual cross-cutting relationships with the Ni mineralisation: We observe undeformed mineralisation emplaced within ductile dilation zones in the shear zones, and mineralisation that is deformed within the shear zone fabric. These deposits are rather small (i.e. <1-5 meters) and define vertical, segmented geometries. Type 2 geometries are relatively large (i.e. 5-10s meters) flat-lying zones (20-30 degrees) to the NW that hostmassive sulphide bodies. These ubiquitously have tectonised margins with top-to SE kinematics which we interpret as tectonically transported during the Caledonian Orogeny.

Steep strike slip shear zones associated with Type 1 geometries are found as xenoliths within tectonically dissected blocks in the Type 2 massive sulphides geometries. Based on U-Pb zircon dating by Corfu & Heim, (2019) of the host rocks of the mineralisation the age of these steep strike-slip shear zones must be pre-1510Ma, which was interpreted as the crystallization age of the Espedalen Complex.

We present a map-based geometric/structural/metallogenetic model for the formation and segmentation of these deposits on a regional scale.

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The Bergby LCT-type granitic pegmatite field in the Ljusdal lithotectonic unit, central Sweden

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The Bergby LCT-type granitic pegmatite field is located in the Hamrånge area in the southeastern part of the Ljusdal lithotectonic unit. It is the most recently discovered lithium-rich granitic pegmatite field in Sweden. It was identified *in situ* in outcrops and by core drilling in 2016-17, some 10 years after the first find of a spodumene pegmatite boulder in the area, and nearly 200 years after the discovery of the element Li in the new mineral petalite from the island of Utö in the Stockholm archipelago. Since 2021, extensive boulder mapping and drilling by United Lithium, the current license holder, led to the discovery of several additional LCT-pegmatite swarms in the area.

The Bergby LCT-pegmatites are hosted in a metasupracrustal unit comprising mica schists, 1.89 Ga felsic to mafic metavolcanic rocks and quartzites with provenance ages between 2.7 and 1.85 Ga (Bergman et al. 2008). The metasupracrustal rocks were metamorphosed at c. 1.83 Ga in LP amphibolite facies, grading from the stability fields of andalusite in the east, to sillimanite in the west. These rocks have experienced several episodes of ductile deformation including early asymmetric folds and associated thrusts, which are in turn refolded to an easterly plunging synform (the Hamrånge synform) and sheared along wide, c. 1.81 Ga steeply dipping deformation zones (Högdahl et al. 2009), established at the limb of the latter. Granitic pegmatites, including LCT-type ones, within these late-Svecokarelian shear zones were variously affected by this deformation phase, which thus gives a minimum age of their emplacement. Other intrusions in the Hamrånge syncline that post-date peak metamorphism and folding are small granite, quartzmonzodiorite and gabbro intrusions.

Simple and barren granitic pegmatites are common in the western part of the area, whereas the LCT-pegmatites have this far only been identified in the most competent lithologies, represented by the mafic and intermediate metavolcanic rocks and the quartzite in the central part of the synform, overall covering an area of more than 50 km^2. They occur as swarms with individual dykes ranging in width from a few decimeters to more than 10 meters. The Li-ore mineralogy in the different dykes varies; some dykes host both spodumene and petalite, whereas others are seemingly only spodumene-bearing. In some dykes primary petalite is replaced by massive intergrowths of fine-grained spodumene and quartz, so called SQUI. With the present data at hand the LCT-pegmatite field appears to be zoned with dykes rich in petalite and with high Cs-Ta contents in the central part while low Cs-Ta and petalite-poor dykes occur at its margin. In addition to the main ore minerals petalite and spodumene, Li is also hosted by phyllosilicates including cookeite, amblygonite-montebrasite series minerals, tourmalines, and Mn-Fe±Li phosphates. Other minerals characteristic of highly fractionated LCT systems like pollucite and tantalite minerals have also been identified, but the Cs and Ta-Nb contents vary greatly in and between different dykes. Within the framework of the recently started ULiBS project based at Uppsala University, drill cores from Bergby are analysed by the Orexplore GeoCore X10 that conducts simultaneous XCT-XRF scans. Results from a spodumene-bearing pegmatite shows that the measured concentrations of this phase in the core and the calculated Li-contents correlate well (R^2=0.967-0.974) with ore assay data conducted on half-cores.

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SIMS U–Pb constraints on the origin of 1.89 Ga marble- and skarn-hosted Zn-Pb-Ag sulphide deposits, Sala area, Bergslagen, Sweden

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Polymetallic sulphide deposits of Bergslagen in the Fennoscandian shield belong to the globally significant c. 1.9 Ga event of orogenic activity, crustal growth and metallogenesis. Recent secondary ion mass spectrometry (SIMS) U–Pb dating zircon dating by Jansson et al. (2023) indicate that age differences exist between the two principal types of Bergslagen sulphide deposits, namely 1) syngenetic Zn-Pb-Ag and Cu deposits such as Zinkgruvan (formed c. 1.90–1.89 Ga) and 2) carbonate-replacement/skarn-type Zn-Pb-Ag-(Cu-Au) deposits such as Garpenberg (formed somewhat later at c. 1.89 Ga). In this contribution, we present new geochronological data from key igneous units at the Sala Zn-Pb-Ag deposit, one of the most important members of the 2nd type.

Concordant zircon analyses (N=17, in situ secondary ion mass spectrometry, SIMS) from a metavolcanic interbed with relict accretionary lapilli in the marble host to the Sala deposit provided an average $^{207/206}$Pb age of 1889±4 Ma. This age overlaps within error but is slightly younger than a previously reported age of 1894±2 Ma for the same unit (multigrain discordia age, Stephens et al., 2009). The new age is a more accurate age constraint for the deposition of the limestone precursor to the marble host and sets a maximum age of the carbonate-replacement and skarn Zn-Pb-Ag mineralization hosted by it.

The marble host is intruded by subvolcanic feldspar±quartz-porphyritic dacite and granodiorite. A porphyritic granodiorite dyke intrudes and truncates the ore zone and hydrothermally altered carbonate wall rock at the Bronäs Zn-Pb-Ag deposit. Concordant zircon analyses (N=13, SIMS) from the Bronäs granodiorite define an average ^{207}Pb/^{206}Pb age of 1887±6 Ma for igneous crystallization of the dyke. Stephens et al. (2009) calculated a discordia age of 1892+5/-4 Ma for another subvolcanic intrusion north of Sala (Stråbruken porphyry). Mapping by Jansson et al. (2021) shows that it crosscuts both the contact of the alteration envelope in the marble host, and its contact to overlying felsic pyroclastic metavolcanic rocks in the stratigraphic hangingwall. Again, concordant zircon analyses (N=22) from the Stråbruken porphyry define a slightly younger average ^{207}Pb/^{206}Pb age of 1889±3 Ma and provide a minimum age of the hydrothermal Zn-Pb-Ag mineralization in the marble.

The new results are consistent with other geological evidence suggesting an early, pre-D_1 (c. 1.87 Ga) age for sulphide deposits at Sala (Jansson et al. 2021). A transition from volcanism and plutonism combined with intense magmatism, regional extension, and local caldera subsidence at c. 1.89 Ga is inferred as critical for the formation of replacement-style Zn-Pb-Ag-(Cu-Au) deposits, not just at Sala but also at Garpenberg and Falun. In contrast, geochronological constraints for syngenetic Zn-Pb-Ag deposits such as Zinkgruvan indicate that these deposits formed distal to active volcanic centers or during pauses in volcanism during the build-up of the stratigraphic succession.

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Quartz oxygen isotope systematics and the fluid source for Au-Ag-Bi-Te-Se-bearing polymetallic vein deposits in southwestern Sweden

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An over-arching project aim, of which the present study forms a part, is to bridge and expand existing observations and datasets from noble and critical metal-rich polymetallic vein deposits in SW Sweden, using new ore mineralogy and petrography and light stable isotope and fluid inclusion data. Earlier stable isotope studies of the polymetallic Dalsland-Värmland veins in SW Sweden are mainly those of Johansson (1985) and Alm et al. (2003, and references therein). While Johansson´s work was focused on sulphur isotopes, the latter group reported oxygen isotope compositions of vein quartz from the Harnäs and Intakan vein deposits in Värmland. Their quartz $\delta^{18}O$ data from Harnäs exhibited a relatively narrow range, between +10.9 and +12.8 per mil (SMOW), with two analyses yielding slightly lighter compositions, at +7.2 and +9.7 per mil. Notably, the latter two were from a cross-cutting veinlet. The quartz samples from the Intakan vein at +11.5 and +11.6 per mil, basically overlap with the Harnäs data. Our new dataset include $\delta^{18}O_{Qz}$ (all reported as per mil values relative to SMOW) from vein deposits at Knollen (+12.5-12.9), Vassvik (+12.6-12.7), Kilane (+14.5), Nötön (+7.2), Värmlands Nysäter (+7.2-8.5), Vegerbol (+10-11.4), Karlsbol (+11.9) and Glava (+9.9-14.5). Based on the quartz-H_2O fractionation data of Matsuhisa et al. (1979), Alm and co-workers calculated the oxygen isotopic compositions of a fluid in equilibrium with precipitated quartz at an average temperature of 200 °C (from fluid inclusion data) for the early stage of vein formation at Harnäs and Intakan; these fluid composition ($\delta^{18}O$) ranges were -0.7 to +1.2, and -0.1 to 0.0 per mil, respectively, whereas the later vein yielded fluid compositions (based on a temperature of 75 °C) of -14.6 and -17.0 per mil. The calculated fluid $\delta^{18}O$ values for the early vein stage cluster closely around zero per mil, i.e., well correlated with a seawater source. Yet, as argued by Alm et al. (2003), the known geological setting of the vein systems and their host rocks clearly speaks against this interpretation. They further noted that the fluid $\delta^{18}O$ (range) is seemingly too light for a metasedimentary source, while a (primary) magmatic source was deemed unlikely because of the lack of known coeval magmatic activity in the area, and hence assumed that a metamorphic fluid with some input from meteoric water is the most likely interpretation. Utilising additional new fluid inclusion data from various Dalsland-Värmland veins (preliminarily reported by Jonsson & Broman 2020), we find that a significant part of our new $\delta^{18}O_{Qz}$ data fit in a similar fluid model. Combining all analytical data and observations from these vein deposits, including the character and nature of evolution of fluids and mineralisations, their regional extent, the lack of correlation with known penecontemporaneous intrusive rocks in most areas as well as the direct links to active brittle tectonism, suggest a vein formation scenario featuring a singular type of successively cooled, upwards migrating, originally deep metamorphic fluid, that variably mixed with meteoric water in a more shallow crustal setting. The noted metal tenor variability between veins and vein fields is proposed to mainly depend on locally dominant (deep) host lithologies and specific depth of vein formation.

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Critical metals in historical smelter slags from Bergslagen, Sweden: examples from the Riddarhyttan district

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Among the waste products from historical to near-recent mining and processing, pyrometallurgical slag is one of the materials that has largest potential with regards to new production of different metals (e.g., Lottermoser 2011, and references therein). The present work is focused on historical slags produced during the smelting of iron and copper ores from the early 17th to late 19th century in the Riddarhyttan district in the west-central part of the Bergslagen ore province, south central Sweden. A part of the study was performed, together with similar work on Cu slags from the Falun area (Jonsson et al. 2023), within a project on secondary resources in mining-associated waste in Sweden in the form of an assignment to the Geological survey of Sweden (SGU) from the Swedish government (see also Lewerentz et al. 2023).

Different types of slags from the processing of locally mined Cu sulphide and Fe oxide ores were sampled at four different sites in the Riddarhyttan district: Gamla Kopparhyttan, Nya Kopparhyttan, Lienshyttan and Övre Skilå hytta. The samples were subjected to bulk geochemical analysis (by ALS Minerals) and based on the results, a selection was chosen for additional in-depth study, featuring preparation of polished thin sections, polarised light microscopy, powder X-ray diffraction analysis and scanning electron microscopy with back-scattered electron imaging and energy-dispersive chemical analysis. The highlights of the bulk geochemistry results are high to very high contents of the critical metals cobalt (Co) and rare earth elements (REE) in the Cu smelter slags; up to >5500 ppm Co and >23000 ppm total REE+Y, and fairly high to high contents of REE in the Fe smelter slags; up to >4000 ppm total REE+Y. Additionally, the Cu slags – unsurprisingly - have quite significant Cu grades (average at around 2 wt%), and notable contents of Bi, In, W as well as some Au and Ag. The presence of high REE contents in both types of slag was deemed likely as the ores in the district are well known for their locally rich REE mineralisation (including additional metals; cf. Jonsson et al. 2019, and references therein). As to the contents of minerals or, primarily, anthropogenic mineral equivalents and glass and their respective roles as hosts to relevant metals in the slags, more in-depth studies with additional methods are required. For major metals, the applied mineral-chemical methods were functional, but not so for lower or "trace" content metals. The crystalline compounds in the Cu slags are typically dominated by euhedral to subhedral fayalitic olivine-type phases and often dendritic Fe oxides near magnetite-wüstite (characteristically non-stoichiometric), in addition to variable contents of metals and often non-stoichiometric metal sulphides. The latter exhibit textures indicative of rapid cooling as well as unmixing of metal and metal-sulphide melts, including skeletal to dendritic forms and symplectites on diverse scales. Co is indicated to be mainly hosted by the Cu sulphides. The Al-Si-Fe-Ca-K-rich glass component also contains minor Na, S, and indicated Ce (LREE) and Cu. The Fe slags are very glass-rich and also contain calcic silicate mineral equivalents, such as pyroxene and åkermanite-melilite-like phases and their REE may be residing in both glass and silicates.

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FUTURAM – Securing the supply of secondary & critical raw materials in the EU

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Objectives

FUTURAM is a HORIZON EUROPE, Research and Innovation 4-year project which started in June 2022. The project has 29 partners from 11 countries, encompassing geological surveys, universities, NGOs and research institutes as well as industrial partners.

Access to raw materials drives the global economy. It thus determines the competitive position of industry, and our ability to transition toward a decarbonised world in which Critical Raw Materials (CRM) are economically and strategically important for the European economy but have a high-risk associated with their supply. CRM's global primary extraction is limited and monopolised, mainly by China, recycling is not well developed and there are no viable substitutes for these materials with current technologies.

Futuram's objective is to map the supply of CRMs obtained from recycling of six waste streams: batteries, electrical and electronic equipment, vehicles, mining waste, slag and ash, and construction and demolition waste. Much of the data required to understand effective management of raw material supply and demand is available, but scattered amongst a variety of institutions, including government agencies, universities, think tanks, and industry, and need to be harmonised to be fit for use in Secondary Raw Materials (SRM) availability assessment.

FutuRaM aims to build state-of-the-art methodologies and harmonised datasets for mining waste initiated by the ProSUM and ORAMA projects. Furthermore, improvements in reporting practices can be identified and developed specifications to communicate the viability of SRM recovery projects based on the United Nations Framework Classification for Resources (UNFC). FutuRaM has an ambition to integrate SRM and CRM data to model their current stocks and flows, and consider economic, technological, geopolitical, regulatory, social and environmental factors to further develop, demonstrate and align SRM recovery projects.

Case studies in mining waste characterisation

The mining waste case studies of tailings and waste piles have been chosen in Sweden, Finland, Serbia and France. Case studies of mining waste characterization have been designed to provide methodologies for stock and flow assessments, such as exploration techniques, waste characterization, recoverability processes, stakeholder interactions and even policy legislation. Site-specific case studies are also used to test the applicability of the UNFC methodology approach. In Sweden, tailings in Laisvall, Adak and Kristineberg mines were drilled in the autumn 2022. The waste piles in Håkansboda historical cobalt mine were sampled in the spring 2023. The chemical and mineralogical analyses are ongoing and will be followed by beneficiation tests at Geological Survey of Finland.

Preliminary results from tailings indicate that very high primary commodity contents (e.g., Cu, Pb and Zn) in tailings do not guarantee high amounts of associated trace metals identified as CRMs, e.g., In, Ge or Ga. This implies that pre-requisite knowledge about the primary ore characterization (if such exists) may help to target the right waste sites for recovery projects.

Exploring uranium mineral systems: challenges and opportunities

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The objective of exploration, for all natural georesources including uranium, is the discovery of a mineral resource that is a concentration or occurrence of solid material of economic interest in or on the Earth's crust in such form, grade or quality and quantity that there are reasonable prospects for eventual economic extraction. The evaluation of uranium resources is a question that raises regularly according to the expected development of the nuclear energy in the energy mix. Like other commodities considered as critical, uranium is also linked to changes in political situations and possible threads on the supply chain. From a scientific and technical point of view, the knowledge of the uranium mineral system and return of experience from recent discoveries and mining innovation have also major implications on possible assessment of potential resources at the regional scale.

Mineralization processes leading to the formation of economic deposits require the assessment of the main components defining uranium mineral systems (Wyborn et al. 1994). Translating the mineral systems approach into an effective exploration targeting system can be a challenge (McCuaig et al 2010). At the regional and district scale, project generation addresses some critical aspects related to geodynamic setting and major metals enrichment within the different lithological horizons that may correspond to specific structural pathways or chemical fronts. Based on this analysis, a deposit type among the 15 ones defined by the IAEA (2022) can be targeted and used to build up an exploration program including geophysical, geological and geochemical surveys. Presently, Proterozoic unconformity and sandstone deposits are considered as the most promising targets to be explored in terms of tonnage and economy. At the camp scale, proxies and footprints corresponding to each type of deposit, like alteration haloes, syn sedimentary features or redox front, can be identified and used to refine targeting and definition of the drilling program. At the prospect scale, qualification of the metallogenic model and quantification of the mineable resources will be the priority to prepare a scoping study.

Nordic countries have experienced uranium exploration and assessed reasonably assured resources in particular in Finland (Pohjolainen 2015) and Greenland/Denmark (Thrane and Steenfelt 2018) that have recently published an evaluation of the potential for uranium deposits. In Sweden, large resources of uranium are identified as by-products of molybdenum and vanadium hosted in the Lower Paleozoic Alum Shale of Scandinavia.

While uranium exploration and mining are banned since 2018 in Sweden and 2021 in Greenland, strategies to face global warming and greenhouse gas emission may lead to a the launching of a new generation of nuclear plants, implying a new assessment of uranium resources. A parallel can be done with the rare earth supply chain in Europe, transition to CO2 free energy requiring a significant amount of critical metals that implied new exploration projects and new discoveries.

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SGA-sponsored keynote speaker invited for a specific session: Session 8, Economic geology, Metallogeny of the Nordic countries and beyond

Characterization of historical Joma mine tailings using automated mineralogy

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Historical mining activities have left a legacy of sulfidic mine tailings that pose significant environmental and human health challenges due to their elevated sulfide content and the use of inadequate disposal methods in the past. Understanding the chemical and mineralogical composition of these tailings is imperative for evaluating their environmental impact and developing effective remediation strategies, thereby turning what was once considered waste into a resource (Lottermoser, 2010).

This study presents a comprehensive mineralogical characterization of the historical Joma mine tailings using automated mineralogy based on Scanning Electron Microscopy – Energy Dispersive Spectroscopy (SEM-EDS) and Electron Probe Microanalyzer (EPMA). Joma mine tailings originate from flotation of sulfide ore from the Joma VMS deposit – one of the largest base metal mines in Norway. The Joma orebody was mined primarily for copper and zinc during 1972-1998 producing over 11 million tonnes of ore (Eilu, 2012). XRF and ICP-MS analyses show significant concentrations of copper and zinc (0.5 - 1 wt%) along with critical raw materials such as cobalt (300 ppm). Their distribution varies with particle size, with most of the zinc occurring in <38 µm size fraction, while copper is more evenly distributed as a consequence of the employed flotation circuit and the original ore textures. Mineralogy is dominated by pyrite and pyrrhotite, in predominantly unweathered state, indicating that the submerged disposal of tailings preserved sulfides from oxidation. Chalcopyrite and sphalerite are the main ore minerals with a considerable fraction occurring in potentially recoverable liberation state. Electron Microprobe analyses on sulfide phases indicate the distribution of critical metals such as cobalt, silver within pyrite, as well as gold within sphalerite, which has important implications for their reprocessing.

The results of this study show that the historical Joma mine tailings have a substantial potential for environmental impact due to their high content of unweathered sulfides and at the same time contain potentially recoverable amounts of copper, zinc, cobalt and silver. The results can be used to design a more comprehensive sampling campaign of the Joma tailings and evaluate reprocessing strategies.

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The Kodal Fe-Ti-P deposit in the Permo-Carboniferous Larvik Plutonic Complex, Oslo Rift, Norway: using the distribution of trace elements in Fe-oxides and apatite to constrain ore-forming processes

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Iron-Ti oxide and apatite-dominated rocks (i.e., nelsonites) are typically associated with anorthosite–mangerite–charnockite–granite (AMCG) and mafic layered intrusions in magmatic systems (Dymek & Owens 2001; Charlier et al. 2008; Coint et al. 2020; Kieffer et al. 2023). The origin of these non-cotectic rocks in magmatic systems has been widely debated and several petrogenetic models such as liquid-liquid immiscibility, fractional crystallization or mineral accumulation have been proposed, but the subject is still debated (Philpotts 1967; Emslie 1975; Charlier et al. 2011; Namur et al. 2012).

The Kodal deposit, located in the Permian Oslo rift, South Norway, is the largest occurrence of Fe-Ti oxide and apatite mineralization hosted within alkaline monzonitic rock, differing from known magmatic occurrences hosted within AMCG suites and mafic layered intrusions. The orebody consists of an approximately 2 km long, and 100 meters thick, tabular, E-W trending, steeply dipping (70-80 degrees) towards the south. The mineralization is hosted within a medium-grained monzonite and consists of disseminated and massive ore, comprising different proportions of titanomagnetite, ilmenite, apatite and augite and minor amphibole and biotite. Trace element concentrations in titanomagnetite, ilmenite and apatite in the monzonite host rock, disseminated and massive ore were measured to assess which petrogenetic processes contributed to the formation of Fe-Ti oxide and apatite mineralization at Kodal.

Trace element results show that the concentration of compatible elements in titanomagnetite (Cr and Ni), ilmenite (Hf and Zr) and apatite (Sr) is higher in the massive ore relative to the monzonitic host rock. Additionally, field relations and recent zircon U-Pb geochronology from surrounding rocks and mineralization show that the Fe-Ti oxide and apatite mineralization is spatially and temporally associated with syenitic intrusions emplaced within the unsolidified monzonitic host rock of the deposit. The results suggest that the mixing between syenitic and monzonitic intrusions might have triggered liquid-liquid immiscibility, which led to the formation of silicate-rich (Si-rich) and iron-rich (Fe-rich) liquids. Once the liquid-liquid immiscibility onset is attained, elements such as Cr, Ni, Hf, Zr and Sr partition into the Fe-rich liquid relative to the Si-rich liquid (Veksel et al., 2006), explaining their enrichment in titanomagnetite, ilmenite and apatite crystallized from the Fe-rich liquid. Moreover, our results indicate that the most massive (i.e., nelsonite) portions of the deposit result from the fractional crystallization of the immiscible Fe-rich liquid. We present one of the first contributions using trace elements in Fe-oxide and apatite as petrogenetic indicators for the understanding of Fe-Ti oxide and apatite mineralization associated with alkaline systems.

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Mineral exploration in Estonia's crystalline basement: Insights from reinvestigated drill cores in northeastern Estonia

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Although the Fennoscandian shield extends beneath Estonia's Neoproterozoic and Paleozoic sediments, deep ore deposits are not known. Moreover, there is a remarkable archive of crystalline basement drill cores, last systematically studied for mineralization decades ago. The Geological Survey of Estonia has started a project to explore the mineral potential in crystalline basement starting with re-investigation of preserved drill cores employing an automated drill core workstation equipped with VNIR spectrometer, XRF and Magnetic susceptibility sensors to collect geochemical, mineralogical and petrophysical data.

Our primary focus is on the Alutaguse metasedimentary rocks and Jõhvi iron ore occurrence in Northeastern Estonia. These structural zones have previously been correlated with the Svecofennian Bothnian basin (Sundblad et al. 2021) and the Falun subunit in Bergslagen (Sundblad & Kivisilla, 1991), respectively. Preliminary findings from the Jõhvi drill cores showed that in addition to previously documented pyrite, pyrrhotite and chalcopyrite, associations of loellingite and arsenopyrite occur within the magnetite-garnet-pyroxene gneisses. Moreover, fire assay results of mineralized sections showed up to 200 ppb of Au. Further studies with scanning-electron-microscopy (SEM) studies revealed up to 30 µm inclusions of Pb-Bi-Te-Ag and Ag-Au element associations spread in hairline veins in magnetite gneisses. Notably, a similar vein system and mineral association was described in graphite bearing biotite-cordierite gneisses in the Uljaste drill cores, located 45 km west of Jõhvi (Kont, 2022). These findings suggest that such mineralisation occurrences are part of a larger system and connected with a tectonic evolution of the whole Northeastern Estonian part of the Fennoscandian shield.

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In-situ trace element petrogenetic characterisation of Fe-oxide mineralisation in Bergslagen

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The Bergslagen ore field contains over 6000 mineral deposits the majority of which are dominated by Fe-oxide mineralisation of variable styles including banded iron formation (BIF), magnetite-skarn and apatite bearing iron ore. The Fe-oxide deposits are generally considered to have formed from sedimentary processes in the case of the banded iron formations, metamorphosed sedimentary and /or metasomatic processes in the case of the magnetite-skarn deposits and magmatic intrusive processes in the case of the apatite iron ores (Allen et al. 1996).

Trace element contents of Fe oxides have been used to investigate the formation of many types of mineral deposit through for example, determination of the provenance of host rocks, hydrothermal conditions of precipitation and the sources of metals in the minerals (Dupuis & Beaudoin 2011, Dare et al. 2014). In the case of BIF where Fe-oxides precipitate from the water column, their composition has been shown to preserve characteristics of the chemistry of the water body from which they precipitate at the time of their formation. The rare earth element (REE) chemistry of BIF has been used to provide insights into the marine depositional environments (Lawrence et al., 2006). In-situ trace element analyses of magnetite was recently applied to the Stollberg deposit in Bergslagen to show that the magnetite classifies as "skarn" type rather than that from volcanogenic massive sulfide deposits (Frank et al. 2022). The Stollberg study also showed host rock control on the trace element content of magnetite, particularly when the particular BIF layer is sulfide bearing which could be a possible pathfinder for sulfide mineralisation (Frank et al. 2022).

We report the in-situ trace element contents of magnetite and hematite from selected Fe-oxide deposits in Bergslagen with specific focus on the Fe-oxide mineralisation on Utö and in the Riddarhyttan area. The island of Utö in eastern Bergslagen hosts an excellent example of banded magnetite and hematite mineralisation within interbedded limestone and fine-grained felsic volcanogenic sedimentary rock. The study aims to provide insight into the classification and depositional environment of the Fe-oxide mineralisation. We also aim to test the findings reported in Frank et al. (2022) where it was shown that sulfide bearing host rock exerts a specific control on the trace element composition of the magnetite.

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Effect of deformation and metamorphism on metal redistribution at the Sulitjelma volcanogenic massive sulfide deposits

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The Sulitjelma historical mining district in northern Norway shows classic examples of Cu-(Zn) volcanogenic massive sulfide (VMS) deposits, containing more than 20 known ore bodies. The Cu-(Zn) mineralization formed in a marginal back-arc basin setting during Ordovician westward subduction at the Laurentia margin. The basin experienced closure, with ophiolite obduction, as a result of the Scandian phase of the Caledonian Orogeny at 430-420 Ma (Roberts & Sturt 1980). The observed greenschist to amphibolite facies metamorphism is related mostly to Scandian phase deformation and subsequent exhumation.

Deformation and metamorphism can play a significant role in modification of primary deposits and (re)mobilization of metals and elements in sulfide minerals, however the role of crystal plastic deformation in mobilization is not often investigated and therefore poorly understood. Dubosq et al. (2018) showed that several trace elements are introduced or remobilized into deformation-induced substructures within pyrite during deformation. Metamorphic reactions are commonly accompanied by generation of fluids of various compositions which can influence the nature and extent of deformation mechanisms and element remobilization. Our work investigates the interplay between deformation, element remobilization and fluids during greenschist- to amphibolite-facies metamorphism on the VMS deposits at Sulitjelma using both geochemical and microstructural mapping methods to characterize multiphase mobilization of sulfides.

Samples were collected from the Ny-Sulitjelma, Hankabakken, Giken, Jakobsbakken and Sagmo ore deposits and were studied by optical light microscopy, SEM, EBSD, Raman spectroscopy, trace element mapping by LA-ICP-MS, and fluid inclusion microthermometry. We will present preliminary results combining EBSD and trace element data on pyrite grains, showing a complex history of the ores in the area. Numerous fluid inclusion assemblages (FIA) were found with variable compositions (salinity ranging from 0.9±0.3 wt% $NaCl_{equiv}$ to 44.3±1 wt% $NaCl_{equiv}$; presence of different volatiles including CO_2, N_2 and CH_4) and homogenization temperatures (between 138±7°C and 363±5°C) reflecting the evolution of metamorphic fluids that contributed to remobilization of metals during the metamorphic phase of the Sulitjelma deposits.

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Alteration and mass balance calculation at the Rävliden North VMS deposit, Skellefte district, Sweden

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Mass balance calculations of mobile elements in hydrothermally altered zones is a powerful means for understanding alteration processes and vectoring in on mineral deposits (MacLean & Barrett 1993). However, its successful application is subject to uncertainties and several sources of error, such as, 1) sampling errors, 2) analytical errors, 3) choice of least-altered samples, 4) the robustness of the fractionation line, and 5) the certainty in the determination of precursor compositions. This study aims to gauge the effects of these errors on calculated mass changes, using the 1.9 Ga Rävliden North volcanic massive sulphide (VMS) deposit in the Skellefte district, Northern Sweden, as a case study.

The Rävliden North VMS deposit is a recent Zn-Pb-Ag-Cu discovery in the Palaeoproterozoic Skellefte district. A regional lithostratigraphic contact between the metavolcanic Skellefte group (SG) rocks and metasiliciclastic Vargfors group (VG, Allen et al. 1996) rocks is recognised at Rävliden North. Regionally, VMS deposits occur at this contact, hence it is crucial for mineral exploration. However, the contact is complex due to polyphase deformation and recognising lithofacies is difficult due to alteration and amphibolite facies metamorphism.

Stratigraphically, the Rävliden North deposit is located in the lower portion of the Rävliden formation in the top of the SG. The host rocks are Qz-Ser schists and locally graphitic phyllite, where the former has a rhyolitic precursor. Lithogeochemistry suggest that these are calc-alkaline rhyolites with volcanic arc signatures. However, significantly, the footwall and hanging wall rhyolites show differences (Rhy III and Rhy I), and both are different from stratigraphically deeper undifferentiated SG rhyolites (Rhy II). Rhy III has higher Al_2O_3/TiO_2 ratio than Rhy I, and Rhy II has lower Zr/Al_2O_3 and Zr/TiO_2 than both Rhy I and Rhy III. The upper portion of the Rävliden formation comprises a complex volcanosedimentary succession with different facies of metaandesite, metadacite and metarhyolite overlain by breccia-conglomerates with clast populations originating from underlaying lithologies.

The alteration envelope to the deposit is zoned with an inner strong to intense Chl±Tlc alteration and calc-silicate assemblages, and an outer moderate to intense Qz-Ser alteration. To gauge the effects of the aforementioned errors, this study tests different scenarios for parameter 3) and quantifies the confidence of mass balance calculations that is a function of errors 1), 2), 4) and 5).

Selecting least-altered samples is commonly done qualitatively and with arbitrary lithogeochemical criteria, leading to variation in what is considered least-altered. This study defines key alteration minerals (Qz, Ser, Cal, Chl and Tlc) and assesses their abundance on a five-grade scale. For different scenarios, more or less tolerance on this scale can be permitted. As for lithogeochemical criteria, the tolerance for Na depletion and loss on ignition is adjusted.

By testing different scenarios for least-altered sample choice and following error propagation with confidence intervals at each stage in mass balance calculation, the different mass changes in the Rävliden North stratigraphy can be mapped. In doing so, these error sources can be managed to improve ore vectoring.

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Test processing of Seafloor Massive Sulpdie (SMS) ore with VMS ore

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The green shift and the electrification of society have triggered discussions on metal supply adequacy, environmental concerns surrounding land-based mining, and geopolitical implications tied to mineral extraction. Marine minerals, within the Norwegian jurisdiction, offer a potential solution to these challenges. As Norway contemplates opening up its waters for mineral exploration, it must glean insights from prior endeavors, bridge the gap between environmental and geological research, and adopt a holistic approach to the marine minerals' value chain. Green Minerals, in pursuit of a commercially viable venture, has embarked on a comprehensive metallurgical study of SMS samples, demonstrating a commitment to sustainable and efficient marine mineral exploration and production.

In the downstream part of the value chain, mineral processing is a very significant investment and an important factor in the generation of revenues. Mineral processing must therefore be considered at an early stage. In 2022 Green Minerals initiated a metallurgical study of SMS samples from the Mid-Atlantic ridge (TAG area). The samples were provided by the University of Southampton (UoS). The study, performed by the Finnish Geological Survey (GTK), was divided into two phases. The results from the first phase showed that the re-crystallized SMS sample exhibits a simple mineralogy where pyrite, chalcopyrite, and chalcocite are the main minerals representing 99.8 wt% in content.

In the second phase of the study initiated this year, flotation tests of two SMS ores in addition to a VMS ore were performed. The flotation tests were performed by varying the grinding size, pH, and reagent type and dosage.

The following samples were studied for the initial SMS flotation test:

- one low-grade sample that was analysed in the first phase,

- and one high-grade sample additionally provided by the University of Southampton

Further flotation test work was performed to test the combined floatation of the SMS samples with samples of a Volcanogenic Massive Sulphide (VMS) onshore analog ore. The VMS ore used in the test was a low-grade copper-nickel ore from the Kevitsa mine in Finland. These floatation tests at various ratios were performed to understand the possibility of integrating SMS ore in the VMS processing flowsheet. Such a blending strategy may enable the use of existing mineral processing facilities which would significantly decrease the CAPEX of deep-sea mining operations and prove itself as a key enabler for this new industry. As for the onshore activity, blending in high-grade SMS ore into existing conventional, land-based operations with decreasing ore grade, has the potential to significantly extend the life-of-mine for the onshore mine.

Session 9
Geochemical microanalysis - analytical advances and applications

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Differing behaviour of Sr and ^{40}Ar in white mica as a function of deformation and fluid-mediated chemical exchange

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Recent technological advancements now permit *in-situ* Rb/Sr geochronology of mica in addition to the more established ^{40}Ar/^{39}Ar geochronology. Consequently, Rb/Sr and ^{40}Ar/^{39}Ar geochronology can be directly compared in the context of mica grain size, structural positions, and chemistry to elucidate the behaviour of Sr and ^{40}Ar in white mica in response to fluid-interaction and deformation in rocks with different intrinsic properties (i.e., permeability, bulk chemistry). For this purpose, a schist (bulk Sr: 19 µg/g) and a marble (bulk Sr: 518 µg/g) were obtained from the base of an allochthon-bounding shear zone in the northern Scandinavian Caledonides. The shear zone superposed rocks of the Köli Nappe Complex (Upper Allochthon) over continental-ocean transition rocks of the Seve Nappe Complex (Middle Allochthon). The schist and the marble are representative of the Seve Nappe Complex that experienced eclogite-facies metamorphism (2.4-2.6 GPa and 590-660°C) at c. 486-481 Ma. The two rocks were overprinted by high-strain fabrics associated with emplacement of the Köli Nappe Complex, generally occurring in lower amphibolite/greenschist facies conditions at c. 430-420 Ma throughout the Caledonides. In the schist, high-pressure metamorphism is primarily preserved by garnet, high-celadonite white mica (X_{Cel}: 0.22), and apatite. The high-strain overprint and retrogression is reflected by S-C' fabrics, recrystallized plagioclase, low-celadonite white mica (X_{Cel}: 0.09), and chlorite replacement of garnet and crystallization within C' shear planes. Specifically, the low-celadonite mica envelopes the high-celadonite mica within single grains, exhibiting irregular and diffuse boundaries between the two chemical generations. The low celadonite mica are also enriched in V, Sr, Nb, Ba and depleted in Li, Ti, Co, Zn relative to the high-celadonite mica. Single-spot dates from high-celadonite mica, calculated with initial ^{87}Sr/^{86}Sr (0.7281) obtained from apatite, yielded a weighted average of 485 ± 8 Ma (MSWD: 1.3; n: 27). The low-celadonite mica are likely not in chemical equilibrium with apatite and yield a large scatter c. 440 Ma (n: 18). White mica ^{40}Ar/^{39}Ar dates are dispersed from 491 ± 4 Ma to 427 ± 4 Ma (n: 19) with the youngest dates yielded by low celadonite mica. The marble comprises calcite with white mica and minor quartz, plagioclase, titanite, and opaques. High-pressure metamorphism is recorded by high-celadonite white mica (X_{Cel}: 0.28). The high-strain overprint is reflected by the shape preferred orientation of calcite and white mica that defines the foliation, and a grain size distribution of the latter, found as bundles of coarse- to fine-grains and isolated fine-grains within the calcite-dominated matrix. White mica chemistry is homogeneous regardless of grain size and position; a low celadonite generation is not present. Single-spot Rb/Sr dates for all white mica, calculated using initial ^{87}Sr/^{86}Sr (0.7122) obtained from titanite, provide a weighted average of 481 ± 4 Ma (MSWD: 0.8; n: 41). The ^{40}Ar/^{39}Ar dates are dispersed from 486 ± 4 Ma to 428 ± 4 Ma (n: 22) with the youngest dates obtained from the finer grained white mica. Altogether, the schist demonstrates that high-strain deformation and fluid-mediated chemical modification of white mica enabled open-system Sr exchange and ^{40}Ar loss in mica, resetting the high-pressure mica record. The white mica in the marble also exhibits ^{40}Ar loss during deformation, but mica was closed to Sr diffusion. The greater Sr content of the marble and its impermeability relative to the schist likely impeded mica-bulk rock Sr exchange, allowing the high-pressure record of white mica to be preserved. These results demonstrate how bulk rock properties control coupled or decoupled behaviour of Sr and ^{40}Ar in white mica during deformation.

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The origin of pyrite-sphalerite banding in metamorphosed volcanogenic massive sulphide deposits: Using EBSD, EPMA and LA-ICP-MS

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Volcanogenic massive sulphide (VMS) deposits are commonly metamorphosed to greenschist or amphibolite facies conditions after their formation and can exhibit mm to cm thick pyrite-sphalerite banding within the (semi-)massive sulphide lens. The origin of this banding is commonly assumed to be epigenetic, forming as a result of metamorphic remobilization and recrystallization. However, detailed investigations constraining the chemical and physical processes forming this banding have not been investigated yet. Here we present detailed textural (ore microscopy, scanned electron microscopy), microstructural (electron back-scattered diffraction) and compositional (electron microprobe, laser inductively coupled plasma mass spectrometry) results from pyrite-sphalerite bands in massive sulphide lenses from six VMS deposits metamorphosed to greenschist to lower amphibolite facies. The investigated deposits are from oldest to youngest: Kidd Creek, Canada, Flin Flon, Canada, Kristineberg, Sweden, LaRonde-Penna, Canada, Ming, Canada, and Mount Morgan, Australia. All of these deposits are or have been economic relevant producers of Cu, Zn, and/or Au.

Textural observations show that pyrite occurs in two main textures in these massive sulphide lenses including: (1) as disseminated, subhedral, recrystallized grains with concave grain boundaries within massive sphalerite (i.e., caries texture), and (2) as annealed aggregates of several mm to cm thickness forming triple junctions with neighboring pyrite grains. The microstructure of pyrite in these textures was analyzed using electron-back scattered diffraction. Results show that the deformation textures observed in pyrite are both a function of grain size and neighboring phases (i.e., surrounded by sphalerite or pyrite). Abundant intra-grain misorientation angles of $<5^{o}$ show subgrain development between pyrite grains in annealed aggregates (texture 2) in particular with pyrite grains of 35µm size. In pyrite aggregates with >100µm grain size, intra-grain misorientation angles are less abundant indicating that subgrain development and hence dynamic crystallization via dislocation creep is a minor process compared to smaller grains at similar P-T conditions. In contrast, larger pyrite grains in annealed aggregates are recrystallized in the brittle-ductile transition and show both pressure solution and ductile flow deformation.

Chemical remobilization in pyrite-sphalerite bands was tested using both EPMA and LA-ICP-MS analyses. Electron microprobe analyses on pyrite and sphalerite from textures (1) and (2) show a wide range of FeS content in sphalerite (LaRonde and Ming: < 5mol% FeS; Flin Flon and La Ronde: 5.50 – 7.5 mol% FeS; Kid Creek: > 10 mol% FeS) displaying original redox fluid compositions. Rim-core analyses of neighboring pyrite and sphalerite grains in both textures show, however, increasing concentrations of Zn and Fe towards the rim of pyrite and sphalerite, respectively. This cannot be explained by syngenetic dissolution-precipitation since no concentric zoning is observed under SEM. Trace element behavior shows that Co and Ni enriches in low-strain domains within recrystallized pyrite of both textures, whereas low melting chalcophile elements (LCMEs) Bi and Sb and precious element Ag will enrich in cataclastic cracks in pyrite formed under brittle deformation textures. Element behavior in recrystallized sphalerite is more complex.

Microtextural, microstructural and compositional results indicate that pyrite-sphalerite bands formed as result of greenschist to amphibolite facies metamorphism in which pyrite recrystallized and aligned within a preferred direction in anhedral sphalerite. Dynamic recrystallization resulted in subgrain development especially with small grains in annealed pyrite. Chemical remobilization resulted in the enrichment of Fe on pyrite-sphalerite rims and concentration of Co and Ni in low strain domains in recrystallized pyrite. Later brittle deformation formed cataclastic cracks in which LCMEs and Ag enriched.

Precise U-Pb dating of incremental calcite slickenfiber growth by LA-ICP-MS imaging: Evidence for far-field Eocene fold reactivation in Ireland

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LA-ICP-MS mapping produces spatially resolved, quantitative trace element and isotopic analyses in geo-materials at the ppm level across nearly the entire mass range of the periodic table. Dating calcite by the U-Pb method is challenging as it contains very low U and/or high amounts of initial Pb, but opens up many exciting avenues in geochronology, including dating calcite veins in orogens, fossil-free ancient limestones in the geological record and ore-bearing vein systems. A U-Pb image mapping approach (Drost et al. 2018) can circumvent limitations of the U-Pb calcite system, as pixels on a U-Pb age map can be pooled into "analyses" based on elemental or isotopic ratio distributions to produce a spread in $^{238}U/^{204}Pb$ ratio (μ) on concordia. Simultaneous imaging of diagnostic trace elements allows identification and exclusion of zones representing chemically different generations of carbonate or detrital components. Rapid data acquisition is possible using a combination of high-repetition rates (>100Hz) and low-dispersion LA cells.

Our image mapping approach to U-Pb carbonate dating is illustrated with a case study from the Variscan Orogen in Ireland (Monchal et al. 2023). The field locality (Carboniferous North Dublin Basin) exhibits spectacular tight chevron folds and kinematically-linked en-échelon vein sets and bedding-parallel veins with slickenfibers clearly associated with N-S compression (flexural slip). Deformation is conventionally assumed to be Varsican, despite lying c. 150 km north of the Variscan 'front'. LA-ICP-MS U-Pb dating of these calcite vein samples shows relict Variscan U-Pb ages are very poorly preserved. Instead, many calcite veins yield late Eocene ages, including fold-hinge breccias and bedding-parallel slickenfiber veins. U-Pb ages from one bedding-parallel vein indicate protracted (5 myr) late Eocene flexural slip. Detecting several age-homogenous growth domains within this vein was facilitated by integrating spatial U-Pb isotopic information with maps of petrogenetically-diagnostic major and trace elements. The late Eocene folding phase is hitherto undetected on the Irish mainland due to the lack of post-Variscan markers (dykes or Mesozoic-Cenozoic cover sequences), which we link to far-field Pyrenean or Alpine compression (Monchal et al. 2023). Carbonate U-Pb geochronology is often the only feasible approach to detecting compressional reactivation of basement units when younger markers are absent.

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Feature mapping protocol for grain selection in preparation for *in-situ* U-Pb geochronology: Shales and phyllites from the COSC-2 deep borehole

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Dating of minerals such as monazite, zircon, apatite, etc. by microbeam techniques (LA-ICP-MS, SIMS, EPMA), where it is required that the grains remain *in-situ* within their host rock, presents challenges for locating such very small objects and finding a sufficiently large grain population. *In-situ* analysis may be necessary to preserve the textural context of the grains or if the sample is small and/or precious a minimally destructive analytical approach is demanded. Manual searching is laborious, time-consuming and expensive. Fine-grained rocks such as argillaceous sediments or low-grade metapelites are particularly challenging. We were confronted with such issues during dating of monazite in mudrocks and slatey metapelites in core samples from the ICDP project COSC-2 in the Swedish Caledonides (Lorenz et al. 2022), for which we used the electron microprobe chemical U-Th-Pb method. Monazite grains were mostly very small (up to a few microns) and a non-destructive approach was preferred due to the high value and rarity of the samples and the need to preserve textural relationships to depositional, authigenic, metamorphic or vein fabrics. Our method was based on the Oxford Instruments AztecFeature^{TM} software. Polished thin sections were scanned in the Quanta FEG 650 SEM at Heriot-Watt University, Edinburgh using back-scattered electron (BSE) mode generating an array of tiles, which were then stitched to make a high-resolution image of the whole sample area. Sub-areas of the image were inspected under high contrast to identify grains of possible interest for dating (monazite, zircon, apatite, rutile, allanite, titanite) from their EDX spectra. A grey-scale intensity range for each was established for each mineral species, which was used to set threshold values to as a basis for grain classification. This was applied to detect grains of the selected types across the entire image and establish their co-ordinate positions. For each identified grain its size and shape were determined and an EDX spectrum was taken to determine its chemical composition. The workflow is automated but can be interactive, for example, if the system discovers a new grain type it can be added to the search. The output from an automated run can be presented as a spreadsheet that can be sorted and filtered. For the COSC-2 samples we filtered to select grains of suitable size for EMP analysis. Further filtering could, for example, select for composition such as EDX-derived Th or U concentration. After an automated run of 3 days length, a scan of a typical COSC-2 polished section detected 2358 zircons, 3884 monazites, 1475 Ti-oxides, 1048 ilmenites, 2196 apatites and 23 titanites. For monazites 1066 grains had sizes judged to be suitable for EMP analysis (length >10µm). An X-Y graph can be plotted to produce a map with the locations of all these grains. With a little trial and error such maps can be superimposed upon the base image used in the electron probe micro-analyser. Grains can then be located to acquire detailed BSE images and more precise and accurate wavelength dispersive WDX mapping and analysis as a basis for final age data acquisition by EPMA, LA-ICP-MS or SIMS.

While the protocol described here is relatively expensive in terms of SEM machine time, this can be balanced against time saved in locating grains for analysis and the more representative grain populations yielded by the automated, rapid and systematic feature analysis method. Challenges that remain are that some lithologies with abundant non-datable grains exhibiting bright BSE intensity (e.g., pyrite in pelites) yield large numbers of failed grain classifications; also, a more robust and precise method of matching the grain map to base images would be beneficial.

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Micro-scale SIMS and LA-ICP-MS analyses reveal fracture mineral infillings are archives for intermittent paleo fluid-flow and ancient microbial activity

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Fractures and fracture zones are important conduits for advective fluid flow in the crust. Certain processes and environmental conditions, such mixture of fluids of different kinds, redox transitions and microbial activity may invoke supersaturation and hence precipitation of various fracture coating minerals. If this mineral record withstands alteration in the form of dissolution, re-crystallization or diffusion driven modifications, the composition will retain important paleofluid information, essential to understand pieces of low temperature history that are not left in the country rock record. In the last years, significant analytical improvements, particularly in the field of in situ micro-analyses and -mapping facilitate fine-scaled determinations of stable isotopes, trace elements, radioisotopes and preserved organic molecules, enabling detection of past episodes of microbial activity and fluid chemistry fluctuations at an unprecedented level of detail. The toolbox is further expanding in the form of fine-tuned clumped isotope measurements and synchrotron based imaging/in situ analysis. As an example, when applied to single crystals of calcite and pyrite, SIMS ion imaging for $\delta^{34}S$ and transects of spot analyses of $\delta^{13}C$ and $\delta^{34}S$ through crystals with intense growth zonation, from a fracture sampled in an abandoned mine in Sweden, showed bacterial sulfate reduction (BSR)-related fine-scaled isotope variability of almost 130‰ for $\delta^{34}S_{pyrite}$ and an evolution from strongly ^{13}C-enriched calcite reflecting methanogenesis that predate the BSR, to ^{13}C-depleted values reflecting organotrophic BSR (Drake et al., 2021). In situ U-Pb dating using LA-ICP-MS of the same calcite crystals and growth zones targeted using SIMS showed that methanogenesis occurred at 50-30 Ma, whereas BSR occurred at 19-13 Ma when more sulfate rich water infiltrated. This shows that it is possible to distinguish and date shifts in microbial metabolisms and fluid chemistry in a single bedrock fracture. This opens up for widespread exploration of bedrock fractures for discrete periods of fluid flow, and particularly for tiny traces of a significantly understudied “ancient deep biosphere” that may shed light on the evolution of extremophilic microbial life on Earth, such as recent works in Archaean rocks in South Africa (Nisson et al., 2022), as well as serving as important astrobiological analogues (Onstott et al., 2019).

To conclude, key findings so far, with far-reaching interest in the research community include recent discoveries and exploration of: 1. Widespread occurrence of extremely isotopically varied pyrite and calcite ($\delta^{34}S_{pyrite}$ and $\delta^{13}C_{calcite}$), including the largest variability of these widely used isotope proxies yet reported on Earth. 2. Widespread evidence of microbial formation and consumption of the greenhouse gas methane in Precambrian shields. 3. Geochronological constraints of microbial processes at an unprecedented level of detail, that allow delineation of metabolic shifts. 4. Organic molecule- and compound-specific C-isotope evidence of bacterial sulfate reduction from the deep igneous biosphere. 5. Fossilized findings of fungi and proposed syntrophic relationships with prokaryotes. 6. A thermochronological framework for the longevity of deep ancient life in cratons on Earth. 7. A combined approach of studying isotopic inventories of dissolved gases and liquids, with microbial communities as well as biosignatures of fracture coating minerals from isolated borehole sections.

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Multi-dimensional classification and correlation of water and trace element maps in a magmatic clinopyroxene using SpecXY

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Spectroscopic techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Raman or hyperspectral imaging are important in modern geoscience. In recent years there has been a shift away from using exclusively single-spot analysis towards 2-dimensional maps. Maps help to reveal patterns in a sample that would not be revealed by single point measurements. Filtering and extracting signal information from multiple combined pixels can help improve the signal-to-noise ratio and therefore the accuracy of the data. However, the amount of data and information in the dataset increases significantly when maps are used instead of single spot analysis. Combining multi-layered numerical datasets - bringing together different types of information (e.g., obtained using different instruments or measurement settings) - expands the ability to explore and investigate individual datasets in much greater detail.

To explore these large datasets, we have developed SpecXY, a user-friendly software solution for preparing, manipulating, exploring, extracting, and comparing spatially resolved spectral datasets. SpecXY can be used to visualise and classify spectra, perform peak deconvolution, and correlate spectral data with chemical data (e.g., from EMPA, LA-ICP-MS) or other numerical data of the same area.

In this contribution, an application example is used to demonstrate the workflow implemented in SpecXY. Spatially resolved data sets are used to investigate the magmatic history of a single augite crystal. By combining spatially referenced FTIR imaging of clinopyroxene water content with spatially resolved quantitative chemical data (EPMA), it is possible to investigate the correlation between the components of these independent datasets, which can be used as a proxy to monitor the effects of fluid in magmatic processes. In the studied augite from Aetna, Italy, oscillatory zoning, and sector zoning in major and trace elements and preserved zoning in water content can be observed. A dominant correlation of water content with Al is present, supporting the role of Al as a key element facilitating the incorporation of H^+ cations. A secondary correlation of the water signal with other elements (e.g., Ti, Fe and Cr) can be observed.

Isotopic evidence of microbial colonisation of the Lappajärvi impact structure, Finland

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Deeply fractured rocks within meteorite impact structures have been proposed as suitable locations for deep microbial colonisation of Earth's crust (e.g. Osinski et al. 2020), but studies of reporting biosignatures proving such colonisation are still scarce. Modelling shows that habitable conditions for microbial communities in a ~4-km impact structure, can be established tens to a few hundreds of years after the impact in most parts of the crater (Versh et al. 2006). For larger impact structures, the time before habitable conditions is achieved is obviously longer. According to Schmeider & Jourdan (2013), the cooling between roughly 370 and 250 °C of the ~23-km, ~78 Ma Lappajärvi impact structure, took place between ~600 ka and ~1.6 Ma after the impact event. This well-preserved impact structure is a good target for exploration of ancient biosignatures of microbial colonisation. Yet, no proof of microbial colonisation of the Lappajärvi impact crater has been reported.

Here we use secondary-ion mass spectrometry (SIMS) micro-analysis ($\delta^{13}C$ and $\delta^{34}S$, see e.g. Drake et al. 2015a, 2015b) of pyrite and calcite, precipitated in rock fractures and cavities, to detect microbial processes in the crater structure. Recently, SIMS analysis ($\delta^{34}S_{pyrite}$ and $\delta^{13}C_{calcite}$) of deep fractures from Siljan (Drake et al. 2019, 2021) and Lockne (Tillberg et al. 2019) impact structures in Sweden, proved microbial sulfate reduction (MSR), methanogenesis and anaerobic oxidation of methane (AOM). However, U–Pb dating for fracture-hosted calcite at Siljan (Drake et al. 2019) and Rb/Sr for adularia-calcite at Lockne (Tillberg et al. 2019) showed that the microbial activity was > 100 Myr younger than the impact events. This attests to the high level of evidence needed to put forward claims of impact-related colonisation, but also to the potential of using a coupled biosignature-geochronology approach to track colonisation events of meteorite impact structures.

In the present study we present isotopic evidence for microbial colonisation of the Lappajärvi impact structure, in particular $\delta^{13}C_{calcite}$ values diagnostic for methanogenesis and AOM. Radiometric dating of the calcite crystals is in preparation to test the hypothesis of impact-related colonisation. The confirmation of meteorite impact structures as favourable environments for deep biosphere communities substantially enhances our present understanding of the records of colonisation and evolution of microbial life in the deep biosphere. It also enhances our present understanding on deep energy cycling (e.g. gas cycling) of these systems and involve considerable astrobiological implications. Our results show that the Lappajärvi impact will add important input to this discussion.

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Looking into a microscale with high resolution (spatial, volume and mass) using LG-SIMS: multifaceted applications at NordSIMS

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Secondary Ion Mass Spectrometry (SIMS) stands as an essential in-situ analysis tool for precise determination of isotopic and trace elemental compositions, being renowned for its outstanding sensitivity and spatial-volume-mass resolution capacities, as well as its capability to measure both positive and negative ions. In addition to microprobe (spot) analysis, ion imaging analyses are revolutionising our understanding of geological/ biogeochemical processes.

The NordSIMS laboratory is equipped with a CAMECA ims1280 large-geometry SIMS (LG-SIMS) instrument. Installed in 1995 and regularly upgraded to remain state-of-the-art, the laboratory has undertaken numerous projects across a broad range of fields including geochronology, cosmochemistry, geobiology, ecology and nuclear safeguards, often pioneering new applications. This presentation provides an overview of SIMS capability and highlights several unique applications conducted at NordSIMS, which remains dedicated to pushing the boundaries of micro-analysis.

Using micro-XRF for characterization of geochemical environments in annually laminated lake sediments from Central Finland

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Annually laminated (varved) lake sediments with their high-resolution proxy records and robust age control form an important archive for paleoclimate reconstructions (e.g. Brauer et al. 2009, Ojala et al. 2012). The winter and summer climatic signals in varved lake sediments may be extracted through a careful investigation of the clastic and biogenic components of each annual layer (e.g. Brauer et al. 2009, Zolitschka et al. 2015, Saarni et al. 2015, 2016a, 2016b). A prerequisite for paleoclimate reconstructions from the physical and chemical proxies in lake sediments is a thorough understanding of site-specific deposition mechanisms and environmental conditions both in the lake basin and its catchment, and their response to climate forcing (e.g. Saarni et al. 2015, 2016a, 2016b). As a first step towards a 2000-year climate reconstruction from six varved lakes in Central Finland, we have used ultra-high resolution micro-XRF measurements (Bruker M4 Tornado: 20 µm spot size, 20–50 µm steps, 15–60 ms counting time) from epoxy-impregnated sediment blocks for producing elemental maps that illustrate major element distribution in the varve structures. Between-site comparisons of the elemental maps from our research lakes demonstrate a wide variability of geochemical environments in the sediments, even within a fairly small geographical region. These high-resolution maps together with thin sections from the same epoxy-impregnated sediment samples will provide an opportunity for a deeper understanding of how elemental distributions vary between seasons in varved sections representing different climatic periods of the past 2000 years, such as the Little Ice Age (LIA) (e.g. Briffa 2000, Bradley et al. 2016) and Medieval Climate Anomaly (MCA) (e.g. Matthews & Briffa 2005). In addition to providing geochemical data, the elemental maps will be used for measuring physical parameters of the varves, such as thickness of the clastic and biogenic lamina and grain size variation in the spring flood layers. The geochemical and physical proxies obtained this way, will be compared with contemporary weather observation data and reconstructed climate data for establishing connections between chemical and physical varve composition and environmental/climatic forcing. The large and detailed multi-lake dataset allows investigation of proxy sensitivity within varying time scales and between different locations, and will eventually be used in reconstructing paleoclimate.

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NordSIMS-Vegacenter: analytical advances and novel methods

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The NordSIMS-Vegacenter national research infrastructure is a resource for (micro)analysis and microimaging research in the earth, environment and planetary sciences. The center is equipped with SIMS, TIMS, MC-ICPMS, and HR-ICPMS instruments, two laser ablation systems, SEMs, and other supporting facilities. The principle scientific goal is to advance our knowledge of the field via groundbreaking geochemical and isotopic investigations of the widest possible range of samples. As a research infrastructure, all scientists are welcome to apply for analytical time at our facilities. In this contribution, we present an overview of the wide range of analytical capabilities and novel methods that NordSIMS-Vegacenter has to offer.

Automated mineralogy of complex carbonatite-hosted rare earth element (REE) minerals

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Carbonatite-hosted REE-minerals represent a challenge for microanalytical tools, such as automated mineralogy (AM). The most common REE-minerals at the Fen carbonatite complex, Norway, are parisite, bastnäsite, and monazite, which often show complex intergrowth and associations, commonly at micrometer-scale. A better understanding of these complex mineralogical textures is also necessary to comprehend the changes in flotation properties of the various concentrates and by-products during mineral processing beneficiation studies. We therefore acquired automated mineralogical data of feed material, of the initial and main REE-concentrates, as well as from the by-product at the Norwegian Laboratory for Minerals and Materials Characterisation (MiMaC), Department of Geoscience and Petroleum (IGP), NTNU. Flotation products were collected at the IGP-NTNU Mineral Processing Laboratory. Additionally, drillcore pieces were scanned using micro-computed tomography (μCT) at the NTNU CT scan facilities of the Center of Excellence PoreLab to locate minerals with higher densities (i.e., REE-minerals, thorite). This allows to produce thin-sections (long- and cross-sections) including the high-density target minerals. These thin-sections containing the target minerals were subsequently scanned using automated mineralogy to correlate the high-density minerals in 3D (μCT) and 2D (AM). The MiMaC Laboratory hosts a ZEISS Sigma 300VP field emission SEM and ZEISS Mineralogic software for automated mineralogical analysis. In SEM-based automated mineralogy using Mineralogic, EDS spectra are collected systematically covering a high-resolution grid in the analyzed sample, whereby each individual EDS spectrum identifies a mineral based on the contained element wt% (e.g., Graham 2015). For this study, a step size of 2 μm was used with an acceleration voltage of 20kV. The mineral list for the phase classification is generated prior to the automated run and optimized after the run, allowing to add missing mineral phases. An element wt%-based mineral classification, as used with Mineralogic, enables the distinction of the complex REE-minerals parisite, bastnäsite, and monazite, including the subvarieties that contain varying amounts of Ce, La, Nd, and Y (Silva et al., 2023). The results of this study show that bastnäsite and parisite are the main REE+Y-minerals and commonly are associated and intergrown with carbonates, but also quartz and other mineral phases. Monazite is locally replacing bastnäsite and parisite. Furthermore, using Mineralogic allows to locate elemental Th and U and visualize that elemental Th is mainly present in the Th-mineral thorite, and U in uraninite and coffinite (Lode et al., 2022; Magnushommen, 2022). A correlation of micro-analytical workflows, such as 3D μCT and 2D automated mineralogy when combined with mineral processing beneficiation studies provides an excellent opportunity to optimize sampling/sample preparation and processes that are necessary for an efficient extraction of rare earth elements.

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Application of geochemical micro-analytical methods in tracing Nickel through the battery value chain: a case study from Finland

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Nickel (Ni) is an essential raw material widely used in the cathodes of rechargeable batteries. As the electric vehicles market grows fast, the global demand for Ni in lithium-ion batteries production is also rapidly increasing. The global Ni value chains are complex due to the unevenly distributed primary mining sources, multiple refining processes and their manufacturing demand. The ability to identify the Ni sources and fingerprint Ni along its value chain is critical yet challenging. Magmatic sulfide deposits are one of the important sources for Ni, are abundantly distributed in Finland. Finland also offers a complete value chain from mining and refining to the recycling of batteries. In this study, we collected the ore deposits samples from Kevitsa Mine in the north Finland, which is regarded as one of the largest Ni reserves in Finland. Mineral concentrate and processed samples with a large variety of properties along the multi-stages of battery value chain with known source of Kevitsa are also obtained. We first used a µ-XRF for quick elemental mapping and sulfide mineral identification for the core and mineral concentrate samples. Then it is followed by using a scanning electron microscope (SEM) to acquire high-resolution mineral feature analysis and mineral composition quantification. Sulfur bearing mineral grains, e.g., chalcopyrite, pyrite, pyrrhotite, pentlandite and cobaltite were imaged and positioned by SEM for further trace element and sulfur isotope in-situ analysis with LA-ICP-MS. For processed samples along the value chain, such as residue and solution after leaching, iron removal samples and the $NiSO_4$ powder, they were prepared as pressed pellets and their bulk trace elements and sulfur isotope compositions were obtained by in-situ LA-ICP-MS. Finally, the trace element compositions and sulfur isotope ratio of these samples are compared by multivariate data analysis to extract the robust fingerprint that possibly remained along the value chain. The effect of extractive and refining metallurgy in altering geochemical signature of the original ore deposits would also be evaluated. The above laboratory analyses are all implemented at the Espoo Research Laboratory of Geological Survey of Finland. By a combined application of the multi micro-geochemical analytical techniques, we aim to develop a geochemical fingerprinting tool to trace Ni from the original mining ores to the end products. The outcome of this research would help to reinforce the transparency, reliability and sustainability of the raw materials supply along the complex battery value chain.

New insights into the origin and fate of REE zoning in garnet from in-situ trace-element mapping

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Garnet is without a doubt the most useful and versatile mineral in the study of lithosphere dynamics, as it provides a direct record of pressure, temperature, time, deformation, and fluid flow in metamorphosed rocks. The concentration and zoning of rare earth elements (REE) in garnet are central to extracting such information; REE in garnet enable garnet chronology (Sm-Nd, Lu-Hf), and impart a "garnet-stable" signature on cogenetic phases, which allows petrochronology and general petrogenetic tracing of garnet stability in minerals and melts. There is nevertheless significant uncertainty in the actual meaning of REE compositions and zoning in terms of the mechanisms by which garnet grows and incorporates REE, and the possible role of REE diffusive re-equilibration.

To provide new insight into the REE systematics of garnet, we applied quantitative trace-element mapping of garnet grains from metamorphic rocks that record peak temperatures above 750°C and cooling rates as low as 1.5 °C Myr^{-1}. The mapping was done using an ArF excimer laser ablation (LA) system equipped with a fast-evacuation ablation cell coupled to a high-resolution double-focussing single-collector inductively coupled plasma mass spectrometry (ICPMS) instrument at the Vegacenter, Swedish Museum of Natural History. The results were compared with numerical simulations of REE diffusion in garnet using experimental diffusivity constraints.

Garnet in all samples preserves Rayleigh-type or oscillatory growth zoning with sharply defined interfacial angles that match the garnet habit. Oscillatory zoning, in particular its uniform restriction to peripheral parts of metamorphic garnet, can be explained through the kinetics of garnet nucleation and growth and thus neither require nor indicate external forcing, such as tectonic processes or alternating between open- and closed-system behaviour. Re-equilibration of REE compositions appears restricted to domains with nebulous and patchy zoning, which likely form by interface-coupled dissolution and re-precipitation reactions mediated by fluids or melts. In all cases, the observed growth zoning is inconsistent with the fast diffusivity predicted by experiments. These observations demonstrate the reliability of REE signatures in magmatic tracing and petrochronology, and establish Lu-Hf chronology as an accurate and precise means of dating garnet.

Quantifying crystallographical orientations of planar deformation features in olivine using combined optical and WBSD data

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Planar deformation features are a common feature in shock-deformed olivine, both experimentally in conditions corresponding to crustal shear zones (Druivenak et al., 2011) and impact structures e.g., (Stöffler et al., 1991) and in deep crustal shear zones (Ryan et al, 2022). Hence, the identification of different planes associated with the shock deformation is essential to access the stress levels during deformation, important feature during studies of earthquake deformation. This study utilises a combination of optical and EBSD data combined to infer which of the possible crystallographic planes that are represented by the planar deformation features in olivine, observed in samples from the Reinfjord ultramafic complex, associated with lower crustal earthquakes (Sørensen et al., 2019, Ryan et al, 2022). First, calculated plane traces are compared with the observed plane traces in the free open source Matlab ® toolbox MTEX for analyzing and modelling crystallographic textures by means of EBSD or pole figure data (Bachmann et al., 2010), then the dip and dip direction of the observations of planes in the optical microscope. Our results demonstrate: 1) That several planes are active during high stress deformation of lower crustal olivine rich rocks; 2) Some planes develop recrystallization features, whereas others , whereas others develop later and do not develop recrystallization features.

By looking at several grains, we found that the developed fractures highly depend on the orientation of the host grain with respect to the external stress field. Using the demonstrated methodology, it should be possible to map out the relative abundance of planar deformation features along different crystallographic planes in high stress deformed olivine and other transparent silicates. The method can be refined by calculation of the exact thickness of the sample using interference colors calculated using the code published by Sørensen (2013) now available in MTEX. This will enable the calculation of exact plane inclinations extracted from multifocal optical images that can be compared with crystallographic planes calculated in MTEX from the EBSD data.

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In-situ Lu-Hf garnet geochronology by LA-ICP-MS/MS

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Lu–Hf geochronology is a powerful tool to date a variety of geological processes, by targeting high-Lu low-Hf minerals such as apatite, xenotime, lawsonite and garnet, therefore useful for dating a wide variety of lithologies and geological processes. Traditional application of this dating method requires chemical separation of the isobaric parent (^{176}Lu) and daughter (^{176}Hf) isotopes prior to high-precision analysis. Often, this results in a loss of textural context of the analysed minerals. The recent development of in-situ (laser-ablation based) Lu–Hf geochronology by LA–ICP–MS/MS and NH3 reaction gas allows the resolution of ^{176}Lu, ^{176}Hf and ^{176}Yb interferences, as Hf reacts with the NH3 to form high-order reaction products which can be measured independently of Lu and Yb (Simpson et al., 2021). This method offers a number of advantages including rapid analysis with high spatial resolution, as well as targeted control on textural relationships of the analysed mineral, the simultaneous collection of trace and major element data, and the ability to include or exclude mineral inclusions from data signals. For garnet, in-situ Lu–Hf geochronology is an important tool to directly date metamorphism and couple the timing of garnet growth with P–T conditions, distinguish polymetamorphism in single grains or samples, and to undertake rapid campaign-style geochronology across large metamorphic terranes. Some first applications of these types of strategies will be presented, including data from a variety of lithologies and metamorphic facies, with a focus on strengths and limitations of the method.

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Taking the pulse on garnet through high-precision Lu-Hf domain chronology

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Garnet Lu-Hf chronology is among the most reliable methods to precisely date high-pressure and -temperature metamorphism. This technique is conventionally done on bulk grains or grain populations, providing grain-averaged ages that may not inform on individual pulses of garnet growth. Domain dating —dating of single growth zones— allows such pulses to be dated but is challenging for "common-sized" grains due to sample size requirements and sample loss using conventional micro-mill sampling. To overcome these limitations, we developed a new method that combines low-loss micro-sampling by laser cutting with a refined Lu-Hf routine.

We applied this method to date multiple growth zones in a single 1.3 cm-sized garnet grain from a mica schist from the Schneeberg Complex, Austria. The garnet grain was chemically characterized by major- and trace-element mapping (EPMA, LA-ICPMS) and five compositionally distinct micro-domains were extracted using a laser mill. Each single zone was divided into multiple garnet aliquots to enable multi-point isochrons. The four inner zones, corresponding to ~ 85% of the total garnet volume, yielded identical ages with a weighted mean of 98.4 ± 0.1 Ma (2σ). The outermost zone shows a strong chemical contrast with the rest of the grain, yielding a resolvably younger age of 97.8 ± 0.3 Ma. The timing of distinct garnet-growth episodes, together with the variations in trace-element chemistry, were evaluated in terms of mineral reactions.

Our new protocol for Lu-Hf domain geochronology of "common-sized" garnet allows distinct pulses and pauses of garnet growth to be resolved within less than 1 Ma. The data show that garnet growth in metapelites may take less than 1 Myr and, within that short time, likely progresses in several pulses. Our results demonstrate that garnet growth may occur much faster than changes in P–T conditions caused by tectonic processes. This growth style constitutes a rare opportunity to investigate reaction overstepping and the rapid pushes of the system to attain equilibrium during periods of efficient matrix element transport. High-precision domain dating opens new possibilities not only for precisely determining the pace of tectonic processes but also for bringing unique insights into the causes and rates of garnet growth in metamorphic rocks.

What do in-situ Rb-Sr mica ages tell us? Lessons learned from the Greater Gothenburg area

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In the last decade, LA-ICP-MS/MS has enabled the collection of a world-wide data set of Rb/Sr ages of micas that arguably is already larger than all published Rb/Sr ages collected the previous 70 years. While this new technique has already been successfully applied to a wide field of research (from paleoclimate to outer space), one of the most fundamental questions in geochronology is not satisfactorily answered: are we recording cooling ages or formation ages? Almost canonical values for closure temperatures for the Rb-Sr system are widely used in the literature for biotite (ca 350ºC) and for muscovite (ca 500ºC). However, it needs to be stressed that neither experimental calibrations nor field data is very robust, and none of this data is using the high spatial resolution now available by LA-ICP-MS/MS. Instead of invoking thermally activated diffusion as the major mechanism (thermochronology), age systematics can often be equally well explained by mineral recrystallization due to metamorphic reactions and/or fluid infiltration (petrochronology).

The area around Gothenburg is ideally suited to study the behavior of muscovite and biotite in this regard. Being situated in the middle of the Idefjorden terrane, it has been subjected to two high grade metamorphic events, the Gothian and the Sveconorwegian orogenies at ca 1.5 Ga and 1.0 Ga, respectively. In several published and ongoing studies, it can be shown that in-situ Rb-Sr ages of muscovite trustfully record formation ages derived from systems thought to be insensitive to consecutive events (e.g., U-Pb ages from zircon and columbite). For example, Rb-Sr muscovite ages for the Högsbo pegmatite are 1.03 Ga in age (Rösel & Zack 2022) and the pegmatites from the Southern Gothenburg Archipelago are 1.52-1.54 Ga in age (Zorc & Zack, this meeting). The latter example is of relevance, as it demonstrates for the first time that muscovite can survive thermal overprint of up to 650ºC, if thermal conditions along the Göta Alv shear zone are representative (clearly Sveconorwegian migmatites are widespread here, less than 15 km away).

In contrast, Rb-Sr biotite ages are invariably younger compared to concomitant Rb-Sr muscovite ages. Biotites occur in clearly Gothian, Sveconorwegian or in Kungsbacka intrusives (ca 1.3 Ga), yet they all record ages of between 0.90 and 0.93 Ga. The easiest explanation would be that biotite has a lower closure temperature than muscovite. However, there is currently no further evidence that would support this notion. If the Rb-Sr system in biotite would close around 350ºC, clearly resolvable age zonations should be observable within single grains, which is not the case. Furthermore, the analytically significant age range of 5% is not a function of chemical variability which should influence Sr diffusion (Mg# in various biotite range from 5 to 40 but are not correlated with age). Finally, a 1 km continuously cored bore hole (GE-1; see Sjöqvist et al., this meeting) does not reveal a variation in Rb-Sr biotite ages, although a markable decrease in age should be observable. While no comprehensive explanation is currently available, the possibility remains that biotite is more reactive to infiltrating hydrothermal fluids in comparison to adjacent muscovite.

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Session 10
Geochemistry: Open session

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Principle component analysis applied to till samples and its use in prospectivity mapping of the REE Line, Bergslagen, Sweden

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The National Till Geochemical Mapping Program at SGU has been ongoing since 1995 (Lax & Silenus 2005) with a goal of providing a uniform geochemical survey of till from Sweden. This is an unbiased dataset of nearly 60 elements that can be used as a proxy for interpreting sediment covered bedrock the regional geochemistry within exploration, and in particular mineral prospectivity mapping (MPM). Within the Bergslagen mining district of Sweden lies the “REE line”; a series of Fe-Cu-REE mineralisations of the Bastnäs type occurring over an approximately 100km stretch (Holtstam & Andersson 2007). This area is a target for further exploration of REE prospects, as well as an ideal test bed for MPM methods using machine learning (ML) to in aid identifying further potential REE mineralisations within this district. Preparation of SGU till data for analysis included removing data with high analytical uncertainty (As) and replacing values below detection limit (DL) with ½ DL. The data set was then opened via centered log ratio (clr-) transformation and principle component analysis (PCA) was applied to the opened data.

Results

The first 3 principle components (PC) explain 67% of variance within the samples. PC1 shows the strongest loadings with an eigenvalue of 17. PC1 demonstrates a clear trend where REE, U, Th and Zr are associated with strong positive loadings. Strong negative PC1 loadings are associated with Ni, Cr, Co as well as base metals (Zn, Cu) and Fe, K and Mg. Negative scores on PC2 are associated with heavy mineral elements Sn, W, Nb. Strong positive scores from PC3 are associated with Ca, Sr, and Na.

Discussion

PC1 demonstrates a clear division between till with mafic and felsic origin. Negative scores on PC1 indicate a mafic control, however the base metals, and alteration factors are also represented. Positive loadings on PC1 appear to reflect fractionation that occurs within felsic magmas enriching in incompatible elements. Negative loadings on PC2 are associated with heavy mineral fractions within the till and may indicate till underwent a degree of reworking post-deposition. Positive loadings on PC3 are correlated with high levels of Ca, Sr, and Na, and align with areas of mapped carbonate when applied to the bedrock map.

PCA was able to take the nearly 60 elements and reduce them to a smaller number of variables. Within MPM aided by ML, the PCs of till data can be used to identify regions of potential mineralisation. In the case of the REE line, negative loadings on PC1 indicating mafic source rock for till and appear to indicate areas with higher levels of K and Mg alteration. Bastnäs type REE deposits form within skarn altered (Mg±K, Na) carbonate bodies, which act as a trap for the metal bearing fluids (Holtstam and Andersson 2007), and potential areas with high trap potential are represented by PC3. These two PCs encompass important formation processes of the Bastnäs type mineralisation model and demonstrate how incorporation of dimensionally reduced till geochemical data into machine learning and AI enhanced mineral prospectivity models in the future may aid in narrowing down prospective regions into more targeted exploration areas.

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Hydrochemistry and spatial variation of Arsenic, Boron and other trace elements in water bodies, Sud Lipez of the Bolivian Altiplano

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The Sud Lipez is located southwestern part of the department of Potosí. Several sub-basins such as the Laguna Colorada, Pastos Grandes, Capina and Chalviri are located within the Altiplano Puna Volcanic Complex (APVC), between 4200 and 4500 m a.s.l (Rocha et al., 2021). Geologically, the rocks are predominantly dacitic to rhyolitic with a silicic composition (Murray et al., 2023). According to the available dates, the oldest volcanic centers are the Capina caldera 8.3 Ma, therefore Pastos Grandes came into activity for the second time 2.9 Ma ago and the La Laguna Colorada is an ignimbritic shield is the youngest 2.2 Ma (Ort et al., 2013). The region is characterized by its aridity, where precipitation is less than 150 mm/year, high evapotranspiration and occupied by salt flats and shallow saline lakes with accumulation of salts such as borax. The objective was to understand the processes and mechanisms that govern the hydrochemistry and spatial variation of arsenic, boron and other trace elements, as well as the influences exerted by different water bodies in this volcanic area. Thirty-seven water samples were taken from various sources; including springs, hot springs, streams, river, lake and groundwater. Field measurements include determinations of temperature (T), pH, Ox-Red potential (ORP), electrical conductivity (EC) and total dissolved solids (TDS). Water samples were collected for analysis of anions, cations, and trace elements.

The bodies of water that contribute to the Laguna Colorada, Pastos Garndes, Capina and Chalviri show variable temperatures (3.3 - 32.4°C) with a slightly alkaline pH (6.4 - 8.5). The salinity varies from 146 to 123600 uS/cm, with oxidizing conditions. The predominant water type in the Laguna Colorada is Na-HCO_3-Cl, Capina is Na-Ca-HCO_3, Pastos Grandes and Chalviri is Na-Cl. The concentrations of As exceed maximum permissible limits in Laguna Colorada (4 – 66730 µg/L) and (B) (0.05 – 522 mg/L). Pastos Grandes (5 – 2210 µg/L) and (B) (0.44 – 1.4 mg/L). Capina (9 – 51 µg/L) and (B) (0.05 – 0.3 mg/L). Chalviri (77 – 767 µg/L) and (B) (1 – 5 mg/L). The predominance of the type of water is associated with the dissolution of Na- and Ca-silicate minerals, as well as the dissolution of dolomite, calcite and the presence of ulexite. However, the significant variation observed in the hydrochemical characteristics of the four sub-basins is mainly due to the alteration of the volcanic rocks from decitic to rhyolitic and igmibritic composition due to the interaction with water, which dissolves these minerals, generating As-containing solutes and elevated B concentrations are due to accumulation in saline lakes. The bodies of water that contribute to the Capina Lagoon seem to be the most suitable for irrigation and animal consumption, since it has more favorable properties in terms of water quality.

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Analytical tools and techniques for assessing uranium sources and mobility along a mine value chain: A case study of an iron ore mine in northern Sweden

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Elevated concentrations of uranium (U) can be of environmental concern due to U's nephrotoxic and carcinogenic properties. U can be released into the environment through various anthropogenic activities including the nuclear fuel cycle starting from U mining and milling to the disposal of spent nuclear waste, as well as military operations, phosphate fertilizer application, and coal combustion. While environmental studies related to U have primarily focused on U ore mining and milling operations, U can also be found in trace quantities above typical crustal abundance levels within other ore types, such as iron ores. When U-bearing minerals within these ores are exposed through mining and milling, they become susceptible to weathering and oxidation, potentially mobilizing U into groundwater and surface water.

This study emphasizes the different tools and methodologies that can be used for the identification of trace element contaminant sources and the assessment of trace element mobility along a mine value chain, with a focus on U, using an iron ore mine site in Northern Sweden as a case study. Solid (rock, tailings, and ore) and water (groundwater, process water from the processing plant, and surface water) samples were collected at different points along the mine value chain. Total element concentrations were determined through Inductively Coupled Plasma – Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma – Atomic Emission Spectrometry (ICP-AES) to identify U sources. Additionally, geochemical modeling using PHREEQC was performed to calculate U speciation within the water samples. After determining the U speciation, conditions that could potentially influence the release of U into the water at different points along the mine value chain were identified.

In the solid sample analysis, sequential extraction tests were conducted to distinguish mobile U present in highly soluble minerals that could potentially leach and release U into the water at various points along the mine value chain, from stable U residing in insoluble minerals which require prolonged contact time and mild to acidic pH conditions for U release. Furthermore, hydroseparation tests were carried out on solid samples to concentrate U-bearing minerals in heavy mineral concentrates. The heavy mineral concentrates were subsequently mineralogically characterized using a Zeiss Sigma 300 VP Scanning Electron Microscope with Energy Dispersive Spectroscopy (SEM-EDS) to identify the U-bearing minerals.

The preliminary findings of this study revealed the significance of mine water pumped from an open pit at the mine site as a crucial U source. Subsequent investigations into potential U sources in the open pit were carried out. The minewall technique (Mend, 1995) was employed to assess U leaching rates, measured in $\mu g/cm^2$/week from various rock types within the open pit. The different U minerals leached from these rock types were concentrated through hydroseparation, followed by mineral characterization using the SEM.

This study highlights a diverse set of tools and techniques available for identifying trace element contaminant sources and understanding their behavior in mining value chains. Early recognition of potential contamination sources along the mine value chain is essential for the implementation of targeted management and mitigation measures, thereby reducing contamination mobility and the risk of downstream environmental pollution.

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Leaching dynamics of Pb, Zn, and F: Short-term leaching of waste rock from the Ivittuut mine site, South Greenland

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The mining site of Ivittuut was actively exploited for more than 130 years in the interest of cryolite, Na_3AlF_6, (Johansen *et al.*, 1995, 2010). The Ivigtût intrusion belongs to the Gardar Province and is located by the Arsuk Fjord in South Greenland (Karup-Møller and Pauly, 1979). Between 1854 and 1987, the cryolite was blasted, crushed, sorted on site before being shipped to Denmark for further processing (Johansen *et al.*, 2010; Søndergaard and Mosbech, 2022). The high-grade ore (i.e., purest cryolite) was prioritized and sold, while the low-grade ore consisting of cryolite, quartz, siderite, galena, sphalerite and chalcopyrite, together with the host-rock material were classified as waste rock (WR). This material was used to build the roads, the quay and barrier between the fjord and the open pit at the mine site (Johansen *et al.*, 1995, 2010). After the mine closed in 1987, little to no remediation was done at the mine site and the waste rock, including sulphides, is exposed to weathering processes. These processes leach heavy metals from the waste rock and release them into the environment as measured in a monitoring project of the fjord, where elevated Zn and Pb concentrations are observed (Johansen *et al.*, 1995). The monitoring project over the past 30-40 years has estimated the release of dissolved Pb into the fjord to range between 133-333 kg (Johansen *et al.*, 2010; Bach *et al.*, 2014). The release of Pb has showed a decreasing trend over this monitoring period, with up to 3 times decrease observed since 1982. In contrast, the release of Zn has shown little to no significant change (Johansen *et al.*, 2010; Bach *et al.*, 2014). This study aims to investigate the influence of temperature and type of leachant on weathering of the WR by applying short-term leaching experiments simulating mineral weathering and dissolution reactions. The shake flask tests were designed to estimate the amount of Pb, Zn and F leaching from a synthetic sample resembling the WR at the Ivittuut mine site. To mimic the sub-arctic conditions at Ivittuut tests were carried out both in a 2-degree cooling room and at room temperature. The two temperatures enable a direct comparison of the leaching process in sub-arctic conditions to waste rock leaching in warmer climate. The waste rock at Ivittuut is located onshore, but also at places partly to fully submerged in the seawater. Therefore, both seawater and rainwater were used as leachants. The experiments involved subjecting the WR to a continuous 24-hour period of shaking, followed by the extraction of leachate and filtration. In addition to testing the WR, control experiments were conducted for both seawater and rainwater to establish the baseline levels of Pb, Zn, and F present in the leachants before any additional factors were introduced. The produced leachants were analysed for changes in physio-chemical parameters and chemical composition, which of results are still awaited.

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Lake record of black carbon from southern Sweden reveals increased flux in the early 18th century

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Black carbon (BC) is produced by the incomplete combustion of organic matter and fossil fuels. The BC particles consist of highly condensed and aromatic carbon compounds with high resistance to degradation and are thus important for long-term carbon storage in soils and sediments. BC particles are also part of the particulate pollution with severe health consequences.

Here we present BC concentrations and accumulation rates derived from sediments of a small lake (Odensjön) in southern Sweden. The lake is situated at 60 m a.s.l. on a bedrock ridge, has a diameter of app. 150 m and a maximum water depth of 20 m. The lake is the southernmost site in Sweden with varved sediments. We have retrieved an 89 cm long freeze core and established a chronology based on ^{210}Pb, ^{14}C and varve counting. BC was quantified using the thermal chemical oxidation method (CTO375), and the proportion of BC derived from fossil fuels and biomass was assessed using radiocarbon measurements on the BC fraction.

Our BC record has relatively high maximum concentrations (>0.92%) and shows an early increase in concentration and accumulation rate starting around CE1700. This early rise in BC accumulation rate took place around 150 years before the main phase of industrialisation in Sweden and was likely an effect of increasing population and small-scale industrialisation in the region. The BC accumulation rate continued to increase steadily until an accelerated rise in the mid-20th century that has remained high until the present. The ^{14}C measurements of the BC fraction show that biomass was the main source of BC (72-91%) throughout the studied period. The maximum deposition of BC derived from fossil fuels was found in the 1970-1990. The BC deposition has remained high since 1990 with an increasing proportion derived from biomass burning and is probably linked to the increased use of biomass for energy production in Scandinavia.

Black carbon cycling and accumulation after a mega-fire in a boreal forest in Sweden

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Black carbon (BC) is produced by the incomplete combustion of biomass and fossil fuels and has large effects on the carbon cycle, the climate system and human health. Wildfires are a major BC source, but BC production, degradation, and storage in lakes and soils in boreal forests are poorly understood. The lack of understanding of the processes controlling BC cycling from wildfires limits future predictions of the effects on BC production and interaction with the carbon cycle and climate system in a warmer world.

In this project, we address the lack of knowledge about BC cycling in boreal forests by using the large 2014 Västmanland fire as a model system to study the storage of BC from wildfires in soils and lake sediments. Here we present our initial results of BC quantification in lakes inside the burnt area. Our preliminary results show that the post-fire lake storage of BC was determined to a large extent by local lake settings with larger lakes receiving higher BC loads and that local fire conditions also probably influenced the deposition of BC. Further analyses will include studies of the effect of fire on erosion rates, charcoal deposition, and BC storage in catchment soils.

Inferred Hadean crustal composition and evolution through coupled ^{146,147}Sm-^{142,143}Nd systematics in Paleoarchean Acasta Gneisses

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Reconstructing the composition and evolution of the Hadean crust is hampered by the limited availability and preservation of rocks older than 3.8 Ga. A range of analytical techniques, including whole-rock ^{146,147}Sm-^{142,143}Nd (TIMS), major and trace element compositions (XRF and quadrupole ICP-MS), and U-Pb zircon dating (LA-MC-ICP-MS) were employed to investigate the petrogenesis of Paleoarchean layered gneisses from the Acasta Gneiss Complex (AGC) in the Northwest Territories, Canada, and to identify their corresponding sources.

Rock samples were cut into slabs on the basis of their compositional layering to create diverse whole rock samples for analysis. These samples exhibit varying differentiation patterns. The two most mafic samples follow a tholeiitic AFM trend and have μ^{142}Nd close to zero, whereas five intermediate- to felsic samples track a calc-alkaline trend and have negative μ^{142}Nd values from −4 to −8.5 ppm. Zircon U-Pb data from the calc-alkaline samples form bands along concordia, indicating ancient lead loss, but with major clustering around 3.55 Ga.

In contrast to previous results from the AGC, the samples reveal a strong correlation between μ^{142}Nd and $\varepsilon^{143}Nd_{3.55Ga}$ (R^2=0.9), implying preservation of their initial ^{142,143}Nd compositions. This observed correlation results from mixing, suggesting interaction between an ancient crust and melts derived from a source with significantly more radiogenic Nd isotope composition. One possible end-member of this relationship is represented by three felsic samples having an average μ^{142}Nd value of approximately −8.1 ppm and a corresponding $\varepsilon^{143}Nd_{3.55Ga}$ of −5. Using this information, a two-stage ^{142,143}Nd model age of 4.22±0.01 Ga and a $^{147}Sm/^{144}Nd_{source}$ value of approximately 0.14 for the Acasta precursor crust are estimated. Considering the correlation between Lu/Hf and Sm/Nd observed in global crustal rocks, a corresponding $^{176}Lu/^{177}Hf_{source}$ value of 0.016 is inferred, indicating that the AGC protocrust likely had an intermediate composition. When combined with an extraction age of 4.22 Ga, the modeled evolution of this protocrust aligns with the $\varepsilon^{176}Hf_i$ zircon record until 3.6 Ga.

The Acasta Gneiss Complex thus preserves a lengthy geological history starting with the formation of a basaltic-to-andesitic protocrust during the late Hadean. This crust persisted for a minimum of 600 million years, during which it underwent intermittent re-melting and differentiation into felsic continental crust.

Geochemistry of neurodegenerative diseases

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Medical geology is a growing field in which elemental distribution from natural and anthropogenic sources are studied, and uptake by humans through exposure pathways such as ingestion, inhalation, and dermal contact are linked to diseases (Selinus et al. 2010). This project aims to increase the knowledge of how we are affected by our environment and focuses on neurodegenerative diseases, e.g., Multiple sclerosis and Parkinson's disease (MS and PD), and potential links to elemental distribution in bedrock, soil, sediment, and groundwater. Neurodegenerative diseases have been shown to be linked to an excess of heavy metals, including Fe, Cd, Mn, and Cu, as well as to a deficiency of elements, e.g., Zn (Branca et al., 2018, Mezzaroba et al., 2019). Recently, acid sulfate soils were shown to overlap with MS prevalence in Finland (Åström & Roos, 2022). Therefore, soil and groundwater geochemical data from the last 35 years (SGU) will be used in collaboration with regional data on the number of patient cases with neurodegenerative diseases (SNR) to determine possible relationships (Fig.1a). Spatial and population weighting will be carried out using the geographical information software QGIS (Fig.1b). Statistical methods including the mean absolute deviation and the upper whisker of a Tukey box plot will be used to determine threshold values for selected elements and linear regression to determine any statistically significant correlations between elemental concentrations and disease occurrence (Rothwell & Cooke, 2015). These data will then be analyzed to locate areas for further environmental sampling. For example, acid sulfate soils under agricultural land constitute a metal source directly linked to food production and drinking water resources. An environmental forensic approach using a multi-element and multi-isotope approach to pinpoint sources, transport pathways and different ways of exposure to target elements will move medical geology forward (Fig.1c). The compiled data will then be presented as a risk assessment mapping tool, to ensure that the choice of residence will not jeopardise personal health and open the potential for increased monitoring of residents of potentially endangered areas.

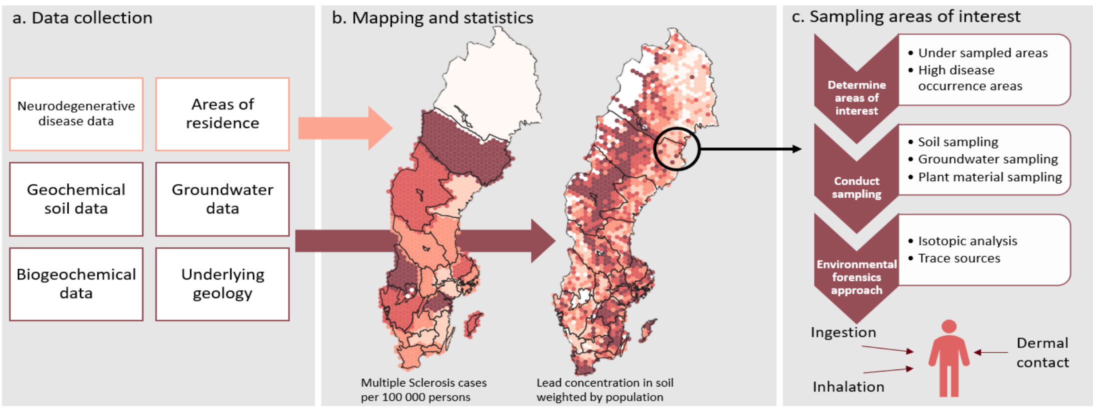

Figure 1(a-c). Project flow for determination of links between elements and neurodegenerative disease in Sweden

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Polymetallic-phosphate-TOC associations in Swedish alum shales

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Scandiavian alum shale and other black shale formations of different age can act as important source of metals or host of economically important mineral deposits. Knowledge on the depositional and diagenetic environment of black shales and their associated trace metals (TM's) is of significant importance for prospecting, mining and extracting critical metals from shales as well their impact on the surficial environment such as soil and groundwater. Modern studies and mapping of black shales are needed in Sweden, as a response to the Governments Official Investigations (SOU 2020:71). We have analyzed the composition of alum shales in southern Sweden to investigate the coupling between TM´s and phosphates/TOC and sulphates. Our preliminary results show that there is a strong positive correlation between phosphorous and REE´s and a strong negative correlation between TOC and REE´s (from Sm to Lu), indicating that REE´s are mainly accumulated in phosphates within the shales (Fig.1). Stable nickel isotope analyses have additionally shown that the heaviest signatures are coupled with the shales with the lowest concentration of silicates whereas the lightest values are associated with the highest concentration of silicates. The negative correlation between REEs and TOC may be related to redox conditions in the sedimentary environment. Organic-rich layers often develop under reducing conditions where organic matter accumulates and persists. REEs, on the other hand, are more mobile in oxidizing conditions, and their concentrations can be diluted when transported or leached from the sediments. Hence, areas with high TOC (indicating reducing conditions) may show lower REE concentrations due to leaching or dilution. The correlation between P and REEs have been shown before but the accumulation process has been heavily debated (Elderfield and Pagett, 1986, Wright et al., 1987, Piper et al., 1988, Picard et al., 2002, Martin and Scher, 2004, McArthur and Walsh, 1984, Ilyin, 1998). It has been shown in previous studies that older phosphorites have significantly lower REE contents than younger phosphorites, indicating a sensitivity towards maturation and/or diagenesis. However, other studies have shown the opposite, with a high REE concentration in phosphates in metamorphosed shale deposits (Engström, 2019). Our future studies will focus on comparing REEs in phosphate rich shales of different ages and also identify the major minerals phase for the accumulation.

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
P	0,72	0,72	0,75	0,77	0,82	0,91	0,85	0,85	0,87	0,82	0,78	0,71	0,67	0,62
Fe	-0,36	-0,35	-0,32	-0,32	-0,30	-0,02	-0,25	-0,13	0,02	0,10	0,24	0,39	0,45	0,54
S	**-0,52**	**-0,54**	**-0,52**	**-0,53**	**-0,50**	-0,23	-0,46	-0,36	-0,23	-0,17	-0,04	0,10	0,17	0,24
TOC	-0,32	-0,37	-0,43	-0,45	**-0,51**	**-0,66**	**-0,57**	**-0,66**	**-0,77**	**-0,79**	**-0,86**	**-0,88**	**-0,89**	**-0,87**

Fig.1. Correlation between REEs and P, Fe, S or TOC, showing the strong positive correlation between P and REEs and the negative correlation between TOC and REEs.

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Effects of gypsum treatment on sulfate and nutrient mobility in farmlands of SW-Finland

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In SW and S Finland, postglacial farmlands near the Baltic Sea are susceptible to erosion and nutrient leaching, especially when soil structure is poor. Treating these fields with gypsum can reduce erosion due to clay colloid flocculation and enhanced soil structure/water infiltration. Large-scale gypsum applications in recent years have significantly reduced nutrient and suspended matter runoff into recipient waters. However, concerns have arisen about potential issues such as nutrient (Mg and K) replacement through cation exchange due to the excessive Ca addition and sulfate flushing that could potentially result in permanent layers of sulfate rich water at the sea/lake bottom, causing an environment low in oxygen and associated release of iron-bound phosphorous.

Previous studies in the area have been limited to the upper 60 cm of the soil. However, the flow path of discharge water from the soil reaches depths well below 100 cm. In this study, we sampled two-meter-deep soil profiles from farmlands, collecting samples with 10 cm and 20 cm increments from the topsoil and subsoil, respectively. To account for different hydrological conditions, we collected one soil profile from the center of each farmland and another profile from the slope, which is typical for the area and close to the recipient stream. In total, we collected 24 profiles, which included three different subareas with distinct treatment histories and their corresponding untreated (reference) fields. In the field, we evaluated the topsoil structure and measured the pH for the entire profile. Soil type was determined by assessing organic matter content through loss on ignition and by analyzing grain size using a sedigraph. Additionally, we measured electrical conductivity, which indicates the presence of total dissolved ions, including those from dissolved gypsum, from a 1:10 soil water extract. We conducted analyses of easily soluble, cation exchangeable, and near-total element concentrations, including elements such as Ca, S, Mg, and P, from extracts obtained using water, ammonium acetate, and aqua regia, respectively.

The primary objective of this study is to assess how gypsum treatment influences the transport and mobility of sulfur and nutrients, from the topsoil to the subsoil, and ultimately to the recipient stream over time.

Isotope geochemical characterization of deep subsurface microbial methanogenesis at the Siljan impact structure, Sweden

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Deep fracture networks in crystalline bedrock can be important habitats for microorganisms that can influence geochemical cycles. Accumulations of methane have been found in the Siljan impact crater, a meteorite impact structure of Devonian age and the largest impact crater in Europe, located in Sweden (Drake et al., 2019). Previous investigations showed that ancient microbial methanogenesis occurred in the fractures of the impact structure (Drake et al., 2021). In this study, modern methanogenesis was investigated using gas, water, and microbial analyses on samples taken from 400 m depth at the ring-shaped depression of the impact crater, below the contact between downfaulted sedimentary rocks and the crystalline basement. Isotopic compositions, such as strong ^{13}C-depletion of the methane in free gas confirmed a dominantly microbial origin, and presence of C_2 to C_5 hydrocarbons indicated a minor thermogenic methane mixing fraction. Multiply substituted isotopologues of methane ($\Delta^{13}CH_3D$) for both the free gas and the incubation head space indicated disequilibrium fractionation due to kinetic isotope effects caused by microbial methanogenesis. Groundwater incubations supplemented with indigenous oil from Siljan boreholes successfully produced methane. Gas analysis showed a positive isotopic relationship between $\delta^{13}C$ values of methane and the CO_2 in the headspace, indicative of carbon fixation pathway, which was also indicated by positive $\delta^{13}C_{\text{-CO2}}$ values of the free gas. Substrate experiments showed fastest production of methane with methanol as the electron donor. Metagenomic data from groundwater samples and transcriptomic data from incubations further elucidated which metabolic pathway the methanogens were utilizing and their possible syntrophic relationships. These results showed that methanogens were actively producing methane in the Siljan impact structure fracture network and gave insights into microbial methanogenesis in the deep biosphere in general, and in highly fractured and porous rocks of meteorite impact craters in particular.

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New zircon U-Pb-Hf isotope constraints on the crustal growth and crustal recycling in the southern Nagssugtoqidian Orogen of West Greenland

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The Nagssugtoqidian Orogen is found both on the west and eastern part of Greenland separated by the Inland Ice and is viewed as a ca. 250 km wide, south- to southeastward trending belt that preserves varied Archean and Paleoproterozoic rocks affected by polyphase deformation and high-grade metamorphism (Kolb, 2014). The Nagssugtoqidian Orogen in West Greenland mainly occurred between 1.92 and 1.75 Ga due to the convergence and collision of the North Atlantic Craton and a poorly defined craton to the north (Garde & Hollis, 2010). The southern Nagssugtoqidian Orogen (SNO) comprises mainly Archean orthogneisses (dated to 2.87-2.81 Ga) metamorphosed at amphibolite facies conditions between 2.81 and 2.72 Ga, directly after emplacement. The SNO is defined as a separate area from the central- and northern parts of the orogeny by the Ikertôq thrust zone and extends south to the southern Nagssugtoqidian front (SNF). The metamorphic grade increases to granulite facies conditions towards the west and to the north near the margin to the CNO, where gneisses are interleaved with supracrustal material (Engström & Klint, 2014). The Paleoproterozoic reworking and/or recycling during the orogeny extends from Kangerlussuaq to southern Disko Bugt (Marker et al., 1995). The SNO largely remains unexplored particularly in the proximity of Kangerlussuaq. In this study, we present new zircon U-Pb geochronology and Hf isotope constraints on a suite of rocks collected around Kangerlussuaq, Umiiviit, Point 660, and including also one sample from the Aasivik Terrane from within the southern Nagssugtoqidian foreland. This data aids the interpretation of potential Archean protolith crust being reworked, constrains later Archean (≥2.7 Ga) crustal growth, and shows the extent of subsequent crustal growth and reworking/recycling during the Paleoproterozoic (1.92-1.75 Ga) Nagssugtoqidian Orogeny itself.

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Geochemical conditions during the deposition of Tremadocian alum shale in the Baltic paleobasin of northern Estonia

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Alum Shale represents a widely recognised mudstone formation rich in organic content, spanning several hundred square kilometres across Scandinavia and the Baltic region (Nielsen & Schovsbo, 2011). This formation encapsulates over 20 million years of geological history, spanning the transition from the Cambrian to Ordovician periods, characterised by significant biotic events (Bian et al., 2023). In the eastern Baltic region, particularly within Estonian territory, the Alum Shale (locally referred to as graptolite argillite) is found as a younger and thinner succession. This 7-meter-thick sequence dates back to the Tremadocian age (Early Ordovician), with the earliest black shale interlayers originating from the Cambrian period (Stage 10). This study presents the analysis of samples from eight different drill cores, including their trace element compositions, and isotopic δ^{98}Mo and δ^{238}U data.

The trace element and isotope data have facilitated a better understanding of certain geochemical and basinal conditions during the deposition of Tremadocian Alum Shale in the eastern Baltic. Trace element proxies, focusing on uranium, molybdenum, vanadium, aluminium, and total organic carbon contents, suggest relatively open marine conditions. The pronounced enrichment of trace elements (Mo > 200 mg/kg, U > 100 mg/kg, and V > 1000 mg/kg) likely occurred within a perennial oxygen minimum zone on the shelf area rather than in a silled euxinic basin. Furthermore, Cd/Mo and Co×Mn cross-plots suggest the presence of upwelling in this geological system.

The determination of the combined δ^{98}Mo and δ^{238}U isotope system has provided insights into palaeoredox conditions. The δ^{238}U ratios exhibit a similar range of variability throughout the sections (-0.74 to -0.21‰, with an average of -0.44±0.14‰). In contrast, the δ^{98}Mo ratios categorise the samples into two distinct populations: a notably lighter δ^{98}Mo (−0.31 ± 0.14‰) at the Cambrian-Ordovician boundary and a heavier one (0.66 ± 0.21‰) in the Ordovician samples. In comparison to the older Miaolingian-Furongian Alum Shale (with δ^{98}Mo ~1.0‰ and δ^{238}U ~0.0‰; Zhao et al, 2023), both isotopes display lighter values in the currently examined sections. The coupled δ^{98}Mo and δ^{238}U system enables the modelling of the ranges of global coeval seawater composition (Lu et al, 2020). The possible δ^{238}U coeval seawater ratios during the Tremadocian period range from -0.89 to -0.34‰ (compared to modern seawater at -0.39‰). For δ^{98}Mo, the range extends from 0.7 to 1.67‰ (in contrast to modern seawater at 2.34‰). The lighter isotopic composition, compared to modern seawater and Miaolingian-Furongian Alum Shale, indicates the presence of relatively larger proportions of oxygen-deficient seafloor areas. Moreover, the combined geological record, spanning from the older Miaolingian-Furongian to the presently assessed Lower Ordovician Alum Shale, underscores notably dynamic and heterogeneous redox conditions during the deposition of Alum Shale in the Cambrian and Ordovician periods.

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Session 11
Subaerial and subaqueous mafic magmatism in the Nordic Region

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The explosive volcanism of the Oslo Rift – insights from the ignimbrites of the Drammen Caldera

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The 15 calderas in the Permian Oslo Rift are key to understanding some of the Early Permian explosive volcanism in Northern Europe. Many of these calderas have 100's to >1000m of preserved ignimbrite stratigraphy, yet although these deposits have been recognised for decades, they have rarely been studied with modern petrographic and geochemical methods. In this study, we focus on the silicic ignimbrites of the Drammen Caldera, a 7x7 km caldera located in the Lier Valley about 40 km south of Oslo. Here, we present field observations, textural and petrographic results, and geochemical analyses.

The central portion of the caldera has been heavily eroded by glaciers and is now covered by Quaternary deposits. Caldera-margin outcrops and ignimbrites are identified along the valley sides. The caldera is largely bordered by the Drammen biotite-granite, with a porphyritic version of the Drammen granite, including late-stage molybdenum mineralisation, located at the eastern boundary. Generally, the caldera margin is characterised by ring faults, dykes, and brecciated granite.

Two main ignimbrite sequences are preserved in the caldera: 1) A eutaxitic crystal-poor, lithic-rich ignimbrite in the east (Sørumlia ignimbrite) and 2) a heavily welded crystal-rich ignimbrite in the west (Lian ignimbrite). The ignimbrites are massive and have few depositional structures in the exposed sections. In the Sørumlia ignimbrite, the clast lithologies vary through the stratigraphy, where clasts include coarse/fine-grained granite, fine-grained mafic rocks, rhomb porphyry and aphanitic rocks. The Lian ignimbrite has a less varied clast population dominated by fine-grained mafic rocks. Additionally, both the Lian and Sørumlia ignimbrites have fragments of a purplish grey porphyry with pink alkali feldspar phenocrysts. Clasts of this porphyry have a greater degree of roundness than the other lithic clasts, indicating that the porphyry was partially molten when entrained in the ignimbrite.

Fiamme content in the Sørumlia ignimbrite is variable, comprising up to ~20% of the volume and ranging in size from <5mm to 30mm. The Lian ignimbrite does not contain fiamme, but the purplish grey porphyry shows a moderate flattening. In contrast, such a flattening of the porphyry fragments is not observed in the Sørumlia ignimbrite. The flattened porphyry in the Lian ignimbrite has a preferred orientation dipping towards the northeast, whereas the Sørumlia ignimbrite's fiamme shows a much larger variation in the orientation.

Petrographically, the ignimbrites are considerably altered with pervasive albitisation. Quartz is, however, a common primary igneous mineral. The quartz grains show a large variation in appearance and size, with both euhedral crystals and fragments. Evidence for crystal fragmentation is found using SEM cathodoluminescence, with quartz cementation healing the fractures. Moreover, the cathodoluminescence studies have shown complex zonation in the quartz crystals, with textures indicating multiple stages of growth and dissolution.

We conclude that the two major ignimbrites of the Drammen caldera contain information about the complex magma chamber dynamics leading up to explosive eruptions. Crystal fragmentation likely took place during magma chamber decompression and eruption. Ongoing work, including zircon U-Pb dating, will shed more light on the details of the caldera evolution.

Geochemistry of sills from the early stage of the Oslo Rift

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The Oslo Rift is a mildly alkaline, highly magmatic rift formed in the latest Carboniferous to Permian times, as a branch of the Skagerrak Centered Large Igneous Province (Kirstein et al. 2006, Torsvik et al. 2008). Sill intrusions radiometrically dated with large uncertainty to 305–300 Ma (whole rock Rb-Sr) are considered the first magmas emplaced during the prolonged rift activity (up to 50 Myr; Sundvoll & Larsen 1994). Their relation with the first effusive basaltic phase and a line of gabbroic plugs is still unresolved. The sills have been investigated from the 19th century, but they are still poorly studied with modern techniques. We aim at characterizing the sills geochemically, and document their interaction with the host rocks. Due to recent infrastructure developments, spectacular new sections and boreholes have become available. We sampled sills emplaced in Cambrian and Ordovician black shales from new road sections (Jevnaker, Kistefoss), one borehole core (Brevik; Schovsbo et al. 2018), and classic localities (Gran, Slemmestad, downtown Oslo; Scott & Middleton, 1983) covering a 150 km long transect along the Oslo Rift. The sills vary in thickness from decimeters to tens of meters, and in some sections they cumulatively make up over 90% of the stratigraphic thickness. In one quarry section in proximity of a gabbroic plug (Buhammeren), the subvolcanic bodies cross the stratigraphy and form a variety of dykes. The sills range in composition all across the TAS diagram, between lamprophyric (camptonite) and rhyolitic end members. The majority of the sills are alkaline, but the Slemmestad section is entirely tholeiitic. We observe strong local chemical variability in relatively immobile elements such as Ti or REE in the investigated rocks, both within the same locality and among different sampling sites. Tightly defined major and trace element correlations reflect a strong role of fractional crystallization coupled with some crustal assimilation. For example, sills from outcrops sampled downtown Oslo show exclusively evolved compositions, along with evidence of strong crustal assimilation. Local tapping of specific mantle sources is needed to explain some of the observed variation. Future work will focus on clarifying the relationship with the basalt phase through geochemistry and geochronology, and the interaction of the sills with the organic- and sulfide-rich host shales through isotope geochemistry (e.g. $^{187}Os/^{188}Os$), disclosing mechanisms of organic matter maturation and potential hydrocarbon generation. Clarifying the origin and timing of emplacement of these sills will help understanding the magmatic evolution of the Oslo Rift.

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Oxygen isotope composition of basalts from the 2021 Fagradalsfjall eruption, Iceland

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The basalts of the 2021 Fagradalsfjall eruption were the first erupted on the Reykjanes Peninsula in 781 years and offer a unique opportunity to determine the composition of the mantle underlying Iceland, in particular its oxygen isotope composition ($\delta^{18}O$ values). The Fagradalsfjall basalts show compositional variations in Zr/Y, Nb/Zr and Nb/Y values that span roughly half of the previously described range for Icelandic basaltic magmas and signal involvement of Icelandic plume (OIB) and Enriched Mid-Ocean Ridge Basalt (EMORB) in magma genesis. We show that Fagradalsfjall $\delta^{18}O$ values are invariable (mean $\delta^{18}O = 5.4 \pm 0.3‰$ 2 SD, $N = 47$) and indistinguishable from "normal" upper mantle, in contrast to significantly lower $\delta^{18}O$ values reported for erupted materials elsewhere in Iceland (e.g., the 2014–2015 eruption at Holuhraun, Central Iceland). Thus, despite differing trace element characteristics, the melts that supplied the Fagradalsfjall eruption show no evidence for ^{18}O-depleted mantle or interaction with low-$\delta^{18}O$ crust and may therefore represent a useful mantle reference value in this part of the Icelandic plume system (see Bindeman et al. 2022).

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Heavy rare earth elements and the origin of primitive volcanic rocks

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Why?

Heavy rare earth elements (HREEs), especially lanthanides from Sm to Lu, are widely used to constrain the origin of basaltic and more primitive volcanic rocks. The reasoning for this lies in the strong compatibility of HREEs in garnet, which increases from Sm to Lu. Partial melts from sources with residual garnet thus acquire high ratios of less compatible HREEs to more compatible HREEs (e.g., high Sm/Lu or Dy/Yb).

Evidence of residual garnet in the HREE composition of volcanic rocks is often thought to reflect melting at pressures above the spinel-garnet transition in the mantle. But what is the influence of mantle temperature and mantle rock type (i.e., peridotite vs. pyroxenite) on melt HREE composition, since they both dictate not only the pressure but also the degree of meting and the amount of garnet in the source? This is what we wanted to find out.

How?

We utilized REEBOX PRO (Brown et al. 2016), a simulator of adiabatic decompression melting of the mantle, to study the behavior of HREEs (namely Dy and Yb) in partial melts of the mantle. We simulated partial melting of depleted peridotite, pyrolitic peridotite, pyroxenite, and peridotite-pyroxenite mixtures at mantle potential temperatures of 1350–1650°C and lithospheric thicknesses of 50–150 km. These parameters are fitting for continental environments (e.g., continental flood basalts), but may be relevant for oceanic island environments as well.

What?

Our results show that low Dy/Yb ratios (i.e., flat REE pattern typical of mid-ocean ridge basalts) do not necessarily indicate shallow melting within the spinel stability field. Such REE patterns can also be generated beneath thick lithosphere (~100 km), given that mantle potential temperatures are high (>1500 °C) and garnet is completely consumed from a peridotitic source by melting. On the other hand, high Dy/Yb ratios typical of oceanic island basalts can be generated beneath thinner lithosphere (~50 km), if the source is pyroxenitic and thus rich in garnet.

Based on our findings, the pressure of melting cannot be judged based on HREE without taking account of the thermal regime and mantle source composition. For further information and application to continental flood basalts of the Karoo large igneous province, see Heinonen et al. (2022).

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Off rift volcanism at the Bight rift segment, north Atlantic

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Volcanism on the Bight Rift segment

From Iceland to the Bight Transform Fault (BTF), rifting in the north Atlantic is characterized by the Reykjanes Ridge. Southward continuation of the rift from BTF is characterized by an orthogonal rift segment named the Bight rift (BRS). The rifting of BRS is divided into 4 overlapping rift zones, named B1 a and b, B2 and B3. Characterized by shallow rift valleys, attaining a depth of some 300 m in respect to the surrounding borders. The volcanism within the active rift zones is represented by elongated pillow ridges and occasional seamounts.

Off rift volcanism on the Bight Rift segment

Detailed analysis of an area of 142x109 km reveals several seamounts dotting the entire segment. We analyzed some 800 seamounts, shape, and location within the segment. This analysis does not show any correlation to the magnetic information of the segment. However, density distribution of the seamounts do show correlation to the gravity anomaly of the segment, suggesting a correlation to active mantle upwelling under neath the segment and supporting the fact that a numerous off rift eruptions have taken place on the BRS.

The 2022 Meradalir eruption of the 2021–23 Fagradalsfjall Fires, Reykjanes Peninsula, and associated phenomena

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The Meradalir eruption began on 3 August 2022 and lasted until 21 August 2022. It was the second of a series of three eruptions to date, bracketed by the 2021 Geldingadalir and 2023 Litli Hrútur eruptions. Together these eruptions make up the Fagradalsfjall Fires.

The eruption was monitored through a combination of time-lapse photography, UAS-borne lidar surveys, and physical sampling. The UAS consisted of a DJI Matrice 300 RTK quadcopter carrying a DJI L1 lidar paired with a DJI D-RTK2 GNSS base-station. Using an electrical generator allowed for recharging of batteries in the field and near-unlimited surveillance of the activity.

The Meradalir eruption started with >8 discrete vents on a single ~250 m-long fissure segment which, over the first days focused onto a single vent which persisted until the end of the eruption. It was a dominantly effusive eruption, covering an area of 1 km^2 with $5.7\times10^6 \pm 7.6\times10^5$ m^3 (dense rock equivalent, 30% porosity) of lava. The primary volcanic structures of the eruption were the main spatter cone vent, a perched lava pond, four rubbly pāhoehoe lobes, and a significant ropey and slabby pāhoehoe squeeze-out. The final outer dimensions of the vent were 89 m by 105 m and 18 m high with slopes of 25° to 30°. The final internal structure of the vent consisted of two circular pits with diameters of 20 and 27 m. Material forming the vent edifice is primarily dense spatter bombs with lesser quantities of lapilli. The vesicularity of the lapilli covers a wide range from dense, almost vesicle-free, to golden pumice (>95% vesicularity).

The perched lava pond formed within hours of the eruption beginning in response to the vents having opened in a bowl-like depression adjacent to the 2021 Meradalir lava field. The pond formed west of the erupting vents and covered an area of 0.040 km^2 and was 12 m high by the end of the first day. The second day saw a minor decrease in area (0.036 km^2), but the surface of the pond rose by 9 m. On the third day the pond grew to 0.042 km^2 and a height of 25 m. The pond area barely changed over the following week whilst the height continued to increase up to a maximum of 35 m on day 9. After this the pond drained, reducing in area and height.

The lava field produced by this eruption consisted of four rubbly pāhoehoe lobes. The first lobe reached a length of approximately 1.3 km measuring from the edge of the proximal lava apron and a width of around 250 m. This lobe grew to its maximum length in just two days. Inclement weather prevented on-site observations for the next five days, by which time two additional lobes had been emplaced either side of the first with lengths of approximately 1.4 and 1.3 km and widths of between 200 and 250 m. The similarity of these three lengths suggests that 1.4 km was the critical length of lavas emplaced in this scenario. A relatively minor lobe filled the northern part of Meradalir and began to overflow the third lobe, but the eruption ceased before this lobe could reach its critical length.

The most peculiar product of this eruption was not actually a product of this eruption but rather a result of it. Sometime between day 3 and day 7 of the eruption (the days with stormy weather), ropey and slabby pāhoehoe flows were emplaced along the southern and south-eastern margins of the Meradalir lava field. These flows filled the low between the 2021 lava field and the valley sides, partially covering the former. Upon examination of the surface textures, it became apparent that this new lava had been squeezed out of tumuli cracks within the 2021 lava surface and flooded along the edges of the lava field. Lidar surveys revealed that the surface of the 2021 lava had bulged by 3 m in the south and 3.6 m in the north. The interpretation is that the weight of the 2022 lava had compressed the 2021 lava field enough to squeeze out still-molten 2021 lava which had resided in the Meradalir lava field for the preceding months.

Evolution of the eruptive plume through image and tephra analysis and physical plume modelling, study of the Eyjafjallajökull 2010 eruption

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On April 17th and 18th, 2010, the Eyjafjöll volcano (Iceland) erupted $27x10^6 m^3$ of tephra during an initial phreatomagmatic phase. Most of the emitted tephra was carried out to sea due to strong northerly wind dispersing ash towards Europe. On April 17th, the eruptive activity was characterized by a pulsating behaviour and the formation of a bent-over plume featuring collapse-like features. We document the behaviour of the plume formed on April 17. Videos from a camera pointing at the summit of the volcano were analysed to reconstruct the plume's rise velocities and travel trajectories, and to record the evolution of the eruptive activity. Tephra density measurements and reconstruction of total grain-size distribution were undertaken to complete the eruption source parameter requirements and atmospheric parameters were obtained from observations recored by Iceland Meterological Office. These were used as input parameters for a one-dimension physical model (PPM; Michaud-Dubuy et al., 2018) of explosive volcanic plume to simulate the time evolution of the explosive activity and the eruption plume behaviour in a stratified atmosphere under windy and still conditions. The model output is a buyoant plume heavily effected by the strong wind that prevailed during this stage of the eruption, yet did not produce a full or partial collapse of the plume. This outcome agrees well with observations. The explosive activity produced tephra that is a mixture of dense juvenile lithics and highly vesicular pumices in roughly equal proportions. We interpret this to imply that a sluggish plug was formed repeatedly, due to degassing and cooling, in the top section of the volcanic conduit. It periodically paused the explosive activity, which resumed when the accumulated pressure placed on the plug by the rising magma overcame its tensile strength. Cyclic repeat of this process resulted in the pulsating explosive activty that typified the eruption. Formation of accretionary lapilli in the early phreatomagmatic phase induced premature sedimentation of the ash grade component in the plume and thus increased its buoyancy. The simulated average altitude of the plume (e.g. 6627 m.a.s.l.) indicates a discharge of 5.10^5 kg.s^{-1} , which compares to the lower end of the estimated average discharge proposed by Gudmundson et al., (2012), i.e. 5 to 10.10^5 kg.s^{-1}. This type of plume studies have important implications for assessing potential volcanic hazard in Iceland, because it can be used to investigate if and how changes in eruptive behavior of explosive eruptions may affect the potential hazards. We have extended this type of plume study to one of the largest basaltic explosive eruption in Iceland, the Veiðivötn 1477 CE event (V1477). It erupted from an ~65 km long discontinuous volcanic fissure and produced ≥10 km^3 of freshly fallen tephra that covered an area of ~53,000 km^2 (about half of Iceland). The goal is to retrieve key eruption source parameters via field observations and use them to numerically model the V1477 plumes to obtain better insight onto the eruption behaviour of this spectacular basaltic phreatoplinian event.

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Water in clinopyroxene from the 2021 Geldingadalir eruption of the Fagradalsfjall Fires, SW-Iceland – a mineralogical perspective

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The magmatic water content is an important factor controlling the activity within a volcanic system, as key physical properties are significantly influenced by the presence of water (e.g., density, viscosity, melting temperature). The pre-eruptive magmatic water content can be recalculated by using phenocrystals of nominally anhydrous minerals, which can incorporate water in the form of hydroxyl (OH), associated to structural defects. By performing H_2-treatments of individual, crystallographically oriented clinopyroxene crystals, the water lost during magmatic processes can be reconstructed and quantified by infrared spectroscopy. By applying this method to clinopyroxene phenocrystals from lava samples collected in April 2021 from the Geldingadalir eruption, SW-Iceland, we obtained pre-eruptive water contents of 0.69 ± 0.07 to 0.86 ± 0.09 wt. % H_2O. These values are higher than those expected for the source of mid-ocean ridge basalts (MORB: 0.3 – 0.5 wt. % on average) and reveal a significant plume (OIB) contribution. Another consequential implication of such water concentrations is that the ascending magmas attained water saturation only at very shallow levels within the plumbing system. This can account for the episodic, shallow, vapor exsolution causing the observed pulsing behavior of the lava pond and within the upper conduits.

The making of monogenetic lava shields: a case study of the mid-Holocene Trölladyngja eruption, Iceland

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Monogenetic lava shields—gently sloping, conical lava mounds that erupted from a central vent—are some of the grandest expressions of basaltic magmatism in Iceland's volcanic rift zones, with volumes of single eruptions exceeding 10 km^3. Shield eruptions differ in several significant ways from the more frequent, and more extensively studied fissure eruptions. Lava shields are thought to form by lower intensity, but longer duration effusive eruptions than fissure eruptions, and tend to be compositionally more primitive (higher MgO) and variable (Sinton et al. 2005). Moreover, many of Iceland's lava shields formed in the early Holocene, suggesting a causal link to deglaciation and associated increase in magma production rates. These differences appear to require fundamentally different geodynamic conditions and magmatic supply chains governing lava shields and fissure eruptions (Eason & Sinton 2009). However, the details of how and why lava shield eruptions occur remain poorly understood due to the scarcity of geochemically well-characterized eruptions.

In this ongoing work, we investigate the formation of monogenetic lava shields by carrying out a detailed geochemical case study of the mid-Holocene ~15 km^3 Trölladyngja lava shield in the Northern Rift Zone of Iceland and its nearest neighbouring fissure eruption Fjallsendahraun (~1362 CE). We present a dataset comprising whole-rock major, trace element and Pb isotope data from 44 samples as which cover much of the spatial extent of Trölladyngja, as well as whole-rock and glass major and trace element data from tephras (n = 10) from the Fjallsendahraun craters. Compared to Fjallsendahraun and other Icelandic fissure eruptions, the Trölladyngja lavas show greater variability in terms of both crystal content (from aphyric to plagioclase-olivine-phyric) and major element compositions (from primitive to moderately evolved basalts; MgO ≈ 7–12 wt.%). Similarly, the observed range in trace element (e.g., La/Sm, Nb/Zr) and Pb isotope ratios—that preserve signatures of mantle source, melting degree and magma mixing—suggest variable contributions from geochemically enriched and depleted mantle sources. Together, these observations indicate that the Trölladyngja eruption was not fed from a single well-homogenized magma reservoir—a conventional model for fissure eruptions—but rather, appears to involve variably evolved melts from a dynamic plumbing system that experiences recharge of mantle-derived primitive melts during the course of the eruption.

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The 3 ka Búrfellshraun lava flow field, Northeastern Iceland: lava dynamics and surface morphology

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The Búrfellshraun eruption, which predates the well-known H3 eruption being approximately 3000 years old, is part of Iceland's North Volcanic Zone and has gained attention due to its platy-ridged surface morphology and as a terrestrial analogue to Martian flood lavas (Keszthelyi et al. 2004, 2006). Through comprehensive satellite mapping, geochemical analysis and studying syn-emplacement processes and surface features, this study provides insights into its eruptive history, lava dynamics and the formation of its platy-ridged surface morphology. Our results challenge the previously interpretations put forth by Haack et al. (2006) that the platy-ridged surface morphology in Búrfellshraun is a result of a major breakout event. The preservation of pahoehoe at the leading flow front and along the margins of the Búrfellshraun lava flow field contradicts the inference of a turbulent drainage from the core of the flow field: rather these evidence are suggestive of slower, more nuanced formation process typical for pahoehoe. We propose that the formation of this surface morphology shares similarities with the processes that shape sea ice, and that this process is more widespread than previously recognized. In sea ice formation plates and pancakes, resembling a honeycomb or a polygonal pattern, emerge due to the interplay of temperature gradients and a wavy-motion behavior. Similarly, we suggest that it may be a result of interplay between lava temperature differentials and cooling mechanisms, as well as due to a wavy-motion behavior of the liquid lava, probably generated by a pulsating activity of the vent. The ponding of lava within the graben where the Búrfellshraun eruptive fissure is situated played a role in setting up the right condition for the wavy-motion behaviour. Furthermore, field mapping along with image analyses of aerial photographs has revealed a striking absence of clear borders within the platy-ridged surface morphology. Notably, two distinct lava channels originating from different eruptive fissures are observed, yet no contact is observed in between these channels. This strongly suggests that the Búrfellshraun eruption was not a singular event, but rather a series of eruptions interspersed with brief cessation periods. This phenomenon is reminiscent of other Icelandic volcanic eruptions, such as the 1975-1984 Krafla Fires and the recent 2021, 2022 and 2023 Fagradalsfjall eruptions, where successive eruptions overlapped and obliterated contact between different lava flows. Furthermore, our findings revise the established extent of the Búrfellshraun flow field. Our geochemical data indicate that certain vents, previously mapped as part of Búrfellshraun flow field, do not belong to it and thus represent a significantly older event. Furthermore, our results raise the need for reevaluation of the volcanic activity in this area. Also, a new information about the eruptive history of the Búrfellshraun eruption and its volcanic landscape, and new insights into its flow dynamics and processes responsible to form the platy-ridged surface morphology may have implications for our understanding of the emplacement histories of Martian flood lavas.

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Dyke complexes of the Scandinavian Caledonides

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Dyke complexes (c. 615 – 560 Ma) exposed in the Scandinavian Caledonides are part of the Central Iapetus Magmatic Province, a large igneous province related to the opening of the Iapetus Ocean and an earlier phase of the North Atlantic Wilson Cycle. These include a >1000 km long dyke complex preserved in the Särv, Seve and Corrovarre nappes (Andréasson et al., 1998; Hollocher et al., 2007; Tegner et al., 2019) and dykes of the Seiland Igneous Province preserved in the Kalak nappe (Robins and Takla, 1979; Reginiussen et al., 1995). The compositions of the >1000 km long dyke complex is mainly tholeiitic and displays lateral geochemical zonation from enriched to depleted basaltic compositions from south to north. In addition, the central part of this dyke complex (in Trøndelag, Norway and Jämtland, Sweden) displays alkali basalt compositions. In contrast, the dykes of the Seiland Igneous Province are entirely composed of alkali basalts including ankaramite, picrite and lamprophyres. In this talk we will review the geochemical details of the basaltic magmas in the Scandinavian dyke complexes and discuss their origin from heterogenous and most likely multiple mantle plumes, and from enriched subcontinental lithospheric mantle.

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Holocene volcanic and magmatic activity at the Reykjanes Volcanic Belt Iceland

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The Reykjanes Volcanic Belt (RVB), SW-Iceland, is a trans-tensional plate boundary on the Reykjanes Peninsula (RP), the most populated region of Iceland, with 2/3 of the country's population. It displays a left-lateral shear plate motion of 17-19 mm/yr striking 70-80°E that includes an extensional component of 7-9 mm/yr (e.g., Árnadóttir et al., 2008; Clifton and Kattenhorn 2006). The RVB features six distinct N25-50°E volcano-tectonic lineaments, expressed as hyaloclastite ridges and subaerial linear vent systems, distributed onto a 6-14 km-wide WSW-ENE trending belt along the crest of the RP. Holocene volcanic vent systems are absent south and north of this belt.

RVB post-glacial lavas span a compositional range of picrite to quartz-normative tholeiite and define a trend implying common origin. The picrites (MgO = 13±4.25 wt%) are present as 10 pahoehoe lava shields and are RVBs' oldest post-glacial formations. Each shield covers <10 km^2 with volumes of 0.001-0.4 km^3 (collective volume = 0.7 km^3). About 14 olivine tholeiite lava shields (MgO = 8.5±0.6 wt%) are present in the RVB and range in age from 2.5 to 14.1 ka. Collectively, the shields cover ~700 km^2. The total volume is 32 km^3, or ~ 75% of the of total post-glacial magma volume (= 43 km^3) erupted in the RVB. Individual shields range from 1-167 km^2 and 0.01-9.8 km^3. The lava shield volumes do not exhibit systematic temporal distribution and the ages of the larger volume shields range from 5.2 to 14.6 ka. RVB has also produced about 100 post-glacial fissure eruptions, which collectively cover ~600 km2 with a total volume of ~9.8 km^3. Coverage by individual lava flow fields ranges from 0.001 to 60 km^2 and the volume from 0.001-0.7 km^3. The maximum length of these fissure-fed lavas is ~17 km (e.g., Jónsson 1978; Gee et al., 1998; Peate et al 2009).

The RVB eruption record over the last 4 ka indicates a periodic pattern for volcanic activity, where 300-400 year-long eruption periods are separated by 6-1000 year-long periods of volcanic quiescence Sæmundsson et al 2020). Also, in each eruption period, the whole of the RP appears to be activated. The last eruption period culminated in 1240 CE and the ongoing eruption at Fagradalsfjall Fires may signal the onset of a new eruption period on the RVB (e.g., Bindeman et al 2022). If so, (1) 2021-2023 has already provided a great insight into the volcanic activity during previous eruption periods and (2) the social implications of this new eruption period have the potential to be enormous, simply because today the Reykjanes Penisula is the most populated region in Iceland and features number of infrastructures vital for its communities and Iceland as whole.

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The 2021, 2022 and 2023 eruptions of Fagradalsfjall Fires, Reykjanes Peninsula Iceland

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On March 19, 2021, eruptive activity resumed on the Reykjanes Peninsula (RP) after 871 years of quiescence with an eruption within the Geldingadalir within valley. A year later this event was followed by the 3-18 August 2022 Meradalir eruption and now the third event has begun on 10 July 2023 Litli-Hrútur eruption, and ongoing at the time of writing. Past activity on the RP, has occurred as a series of centuries-long Eruption Periods, known as 'fires'. We suggest this recent activity within the Fagradalsfjall volcanic system (FVS) demarcates the onset of a new Eruption Period on the RP, we term the Fagradalsfjall Fires. The 19 March to 18 September 2021 Geldingadalir eruption, was preceded by 3 weeks of seismic unrest in the Fagradalsfjall region, initially associated with movements on the RP plate boundary and then emplacement of a 9 km-long regional dyke between Fagradalsfjall and Keilir. The eruption featured up to 12 small vents on 10s- of-meters-long NNE-trending en-echelon fractures. It produced minor cone-forming tephra and pahoehoe to 'a'a lavas. By end of September 2021, the eruption had built a cone more than 100 m above the pre-eruption surface. The initial time-averaged eruption rate was 3.7± 2.1 m^3/s and at day 39 it rose to ~8.2 ± 3.9 m^3/s and stayed at that level for the remainder (from day 183) of the eruption. The 2021 lava field covers ~5 km2 and its DRE rock volume is ~0.1 km^3. The 2022 Meradalir eruption started with continuous 5-20 m-high curtain of fires along a 300 m-long fissure and a discharge of 25 m^3/s, dropping to 15 m^3/s within 2 days. By the end of the eruption its lava had covered 1.3 km^2 and had a volume of ~0.01 km^3. The 2023 event started on 10 July 2023 at 16:40 on a 200 m-long en echelon fissure system, which quickly developed a set of erupting fissures forming a 1 km-long vent system, discharging lava at a rate of 40 m^3/s for the first 5 hours. By the end of day 1 the activity was confined to a 100 m-long fissure segment and the magma discharge had dropped to 16 m3/s, by day 3 it had dropped further or to 9-10 m^3/s and by day 15 it was at 5-6 m^3/s. At the time of writing the lava flow field covered ~1.3 km^2 and had a volume of 0.012 km^3.

Phase equilibria and pre-eruptive conditions for basaltic magmas at Öræfajökull volcano via the peripheral promontory Ingólfshöfði, Iceland

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Öræfajökull is an ice-covered, intraplate central volcano in southeast Iceland (64.00°N, 16.65°W) of a transitional alkalic composition. Öræfajökull has had two historical eruptions: (i) a silicic Plinian eruption (~72 SiO_2 wt%) in 1362 CE of VEI (Volcanic Explosivity Index) 6 and produced in the range of 3-6 km^3 DRE (Dense Rock Equivalent) of tephra, and (ii) a hybrid icelandite flank eruption in 1727 CE (~58 SiO_2 wt%) producing tephra and lava of unknown volume. Both eruptions had a significant impact on the local population via tephra fall and jökulhlaups (i.e., lahars), including PDCs (pyroclastic density currents) in the 1362 event, which is also the largest explosive eruption in Europe since Mt. Vesuvius in 79 CE. After 289 years of dormancy, Öræfajökull showed signs of unrest in 2016-2018, resulting from magma injection into the volcano's plumbing system, which may indicate that the volcano is preparing for an eruption. Little is known about how Öræfajökull volcano prepares for an eruption or the nature of its plumbing system, which is essential knowledge for interpreting pre-eruption unrest signals. In this study, we are examining the plumbing system that fed peripheral basalt eruptions around the Öræfajökull volcano and, here, exemplified by the basaltic promontory Ingólfshöfði ~20 km south of Öræfajökull volcano. The magma that produced Ingólfshöfði rose directly through the crust and thus bypassed the complex plumbing of the main volcanic edifice. We are, therefore, starting by constructing Öræfajökuls plumbing system in its simplest form before undertaking the more complex plumbing system closest to the volcano. Ingólfshöfði is a plagioclase-olivine-pyroxene phyric alkali basalt (SiO_2 ~48-50 wt%) that was constructed by a shallow submarine eruption featuring both phreatomagmatic (i.e., Surtseyan) explosive phases and subaerial effusive (lava producing) phases. The former constructed the basal tuffaceous lapilli-tuff-dominated basal sequence, and the latter the capping lava flow field. Information on the manner of magma ascent was achieved by comprehensive analysis of the magma and mineral compositions. The observed chemical compositions and textures of phenocrysts, glomerocryst populations and melt inclusions reveal two distinct generations of plagioclase, clinopyroxene and olivine that indicate at least two mush-like magma storage levels were present below Ingólfshöfði at the time of its formation. Pressure and temperature calculations using clinopyroxene compositions indicate that the lower storage zone is located at ~7.5-11 km depth (i.e., in the range of ~3-4 kbars), and the upper storage zone is located at ~1-3 km depth (i.e., ~0.5-1.5 kbars). Crystallization experiments were performed in internally heated pressure vessels (IHPV), using glass from Ingólfshöfði with different H_2O/CO_2 ratios at P between 0.5-4 kbars and T of 850-1150°C in order to establish the phase relationships and to determine both, the pre-eruptive and potential magma evolution condition of this magma. Liquidus conditions were achieved at 1 and 2 kbar at 1150°C, but not performed at other P conditions. At 1100°C, Cr-spinel is the first phase crystallizing under H_2O-rich conditions, followed by plagioclase as H_2O decreases in the melt. As temperature decreases, clinopyroxene and olivine cocrystallize along with previous phases at 2 kbars, whereas at 4 kbars, clinopyroxene crystallizes first, with respect to olivine, which comprises the dominant mineral assemblage at 1075°C at dryer part of the phase diagram. The onset of ilmenite and magnetite crystallization occurs on the cooler (1050-1075°C) and dryer part of the phase diagram without Cr-spinel present. At the driest conditions, solidus is reached below 1000-1050°C for all pressure conditions. The residual glass has basaltic affinities in the range 1050-1150°C, however as crystallization evolves, the glass reaches intermediate (~53-57 SiO_2 wt%) and rhyolite compositions (~70 SiO_2 wt%) at 850-1000°C respectively with phases of plagioclase, clinopyroxene and magnetite. The results highlight that fractional crystallization can produce such evolved magmatic compositions spanning the liquid line of descent for Öræfajökull magmas.

The Central Series of the Rum Igneous Complex, NW Scotland: the rises and falls of magma in a large mafic-ultramafic volcano of the early NAIP

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The Central Series of the Paleocene mafic to ultramafic Rum complex is the youngest of the three main cumulate series that make up the layered igneous complex of this famed Scottish island (Emeleus & Troll 2008). The Central Series lies along the Long Loch Fault and provides insights into the feeder system to the Rum intrusion at an erosion level of about two kilometres below the former land surface. Much of the Central Series consists of a mélange of steep sided bodies of magmatic breccias that stretch along the Long Loch Fault (LLF) in a relatively narrow zone and is composed of blocks and clasts of all sizes derived largely from break-up of the former conduit walls (Troll et al., 2020; Emeleus & Troll 2008). Repeated movements of the LLF are thought to have been responsible for opening and closing of the magma conduit, resulting in repeated replenishment events, each of which gave rise to new cumulate formation within the Central Series and the bordering Eastern and Western Layered Series, which crystallized under relatively tranquil conditions. The Central Series probably acted as the feeder zone supplying the neighbouring layered series. The more complete of these is the Eastern Layered Series in which 16 conformable units can be distinguished. Others are presumed either to lie unseen at depth or to have been stripped by erosion. The Central Series, although often neglected because of its relative inaccessibility and complexity, formed from successive magma replenishments alternating with large-volume side-wall collapses of previously deposited cumulate material (Upton et al., 2023). It could thus be thought of as representing the 'pulsing heart' to the Rum volcano and deserves to be regarded as a site of major volcanological and petrological importance.

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The complex formation of glaciovolcanic ridges

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Tindars and tuyas have often been said to be formed by monogenetic subglacial eruptions and their ideal structure is generally described in four stages. Stage I is the melting of the overlying glacier and formation of pillows by an effusive eruption. Stage II is the production of pillow breccia and hyaloclastite by the process of phreatomagmatic fragmentation due to decrease in pressure. During stage III, the edifice has breached the surface of the englacial lake and lava starts flowing laterally, forming a delta of pillow lavas and hyaloclastite once it reaches the shoreline, and subaerial lava when the edifice has grown tall enough. Here, the fourth and last stage generally describes the melting of the surrounding glacier which reveals a flat-topped volcano with almost vertical walls (Edwards et al., 2015). However, before the volcano is revealed, it is most likely covered again by the glacier as is evident by glacial deposits on the sides and top of these types of formations (Bennett et al., 2009). This would then become stage IV and the reveal of the formation would be stage V. These formations, however, are not always this simple. Their internal structure often indicates that they were formed in more than one eruptive event (e.g., Pollock et al., 2023). For instance, boreholes in the hyaloclastite ridge (tindar) Lambafell in the SW of Iceland, reveals a subaerial lava at around 50 m depth which is overlain by hyaloclastite and pillow breccia. This same lava is also present in the face of one of three mines in the mountain. This evidently means that the ridge formed in a more complex manner than the four-stage monogenetic formula suggests. To further support the additional stage in the tindar and tuya formation, the whole of Lambafell is covered by reworked primitive material which is glacially deposited. Additionally, various methods are and have been used to investigate the formation of Lambafell further. Those are Ground Penetrating Radar (GPR), geochemistry and componentry of borehole samples, along with field observations and lidar droning. These methods work well in giving a comprehensive understanding of how such formations come to be.

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Mafic volcaniclastic deposits in the Oslo Rift

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The basaltic volcanism in flood volcanic provinces and rift settings is generally considered to be typified by extensive lava flows. However, it is becoming apparent that mafic volcaniclastic deposits are often present, although these deposits remain a comparatively understudied component of volcanism in most settings. In the case of the Oslo Rift, substantial work over the last ca. 100 years defined the mappable extents of rift related deposits and established a broad stratigraphic and temporal framework, and examined the petrological and geochemical aspects of deposits. That notwithstanding, detailed textural and stratigraphic examination of most rift related deposits is absent. Broadly, the basaltic activity in the Oslo Rift is grouped in three phases: extensive fissure-fed flows in the initial rift phase (B1); sporadic thin compound flows intercalated within the rhomb-porphyry lavas in the main rifting phase (B2); and small volume flows in the late-stage central-volcano phase (B3). Examples of the late-stage basaltic deposits are found at the base of a volcano-sedimentary succession north of Oslo city in an area around Grefsenkollen. Previous workers mapped and briefly described these basaltic deposits as a single basalt flows with localised areas of agglomerate. Detailed mapping and stratigraphic analysis has identified the presence of several basaltic units, including distinct mafic volcaniclastic units. We present preliminary findings from detailed outcrop and thin-section observations of one of these mafic volcaniclastic deposits. Characteristic features are typically dense (non- to incipiently-vesicular) clasts, large clast size distribution (fine lapilli to blocks/bombs), ash and crystal rich groundmass, and sparse spatter clasts. Features such as cuspate margins, glassy quench rinds, fragmental groundmass, and spatter clasts are all evidence for the explosive volcanic origin of this unit, but we find no evidence to support phreatomagmatic origins as is often found for mafic volcaniclastic deposits in other regions. An eruptive mechanism involving explosive ejection from moderate to large scoria cones with ash jetting, flank collapse, and minor fire fountaining is proposed. Substantial further work and characterisation of basaltic rift deposits, especially those associated with the late-stage rift is required to understand the extent and prevalence of this activity across the Oslo Rift.

The Biggest "Buttes" of Scania?

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Volcanogenic outcrops are common in central Scania, southern Sweden, numbering over a hundred (Wikman & Sivhed 1993). The area has recently been referred to as the most "volcano-dense" region worldwide by some (Jaretag 2019), and the eruptions have been linked to Jurassic and Cretaceous magmatism in the Northern Sea (Bergelin et al. 2011). The restricted occurrence of these outcrops has been attributed to the intersection of the Sorgenfrei-Tornqvist zone (NW-SE) and the Protogine deformation zone (NE-SW) (Wikman & Sivhed 1993), the former of which has produced numerous diabase dikes of Permian ages across Scania. The outcrops generally come in two varieties: columnar basanite and tuff layers of which the former predominates in surface exposures. The columnar basanites have been described as volcanic "pipes", plugs, or necks (e.g., Bölau 1965), implying that these intrusions have considerable vertical extent and represent some type of "pipe-shaped" or "cone-shaped" structures (cf. kimberlite), representing the upper plumbing system of volcanoes. Assuming the columnar basanites are indeed "pipe-" or "cone-shaped", columnar jointing should develop horizontally, and possibly radiating. "Cone-shaped" structures, like plugs may have vertical jointing in their upper parts, but this would require the formation of calderas, which is unlikely for magmas of low viscosity. However, if the outcrops are remnants of eroded basanite flows, columnar jointing should be vertical or sub-vertical, similar to colonnades and entablatures (Long & Wood 1986).

In the summer of 2021, we undertook a field campaign to measure the orientations of columnar outcrops—using a handheld GPS unit to record coordinates, and a geological compass to measure dip directions and plunge of columns. We visited over 50 locations of interest and were able to measure a total of 216 orientations at 37 of these. 68% of measurements have steep plunges of over 45° and 37% have plunges exceeding 70°. Only one basanite outcrop indicates a possible radial configuration of columns. Many outcrops seem to represent the cores of drumlins and are often exposed at the stoss side of these, and several of these have spectacular colonnades and entablatures, as would be expected from lava/magma cooled against horizontal surfaces.

Based on the predominating sub-vertical- to vertical direction of columnar jointing we argue that the predominating occurrences of basalt in central Scania represent erosional remnants of relatively thick lava flows. We propose a simple scenario where Jurassic and Cretaceous magmas of low viscosity erupted from fissures along older Permian structures. In some places these magmas could have interacted with groundwater, resulting in phreatomagmatic events, producing tuff and ash layers. Our interpretation is that columnar outcrops dominated by sub-vertical to vertical represent the remnants of eroded lava flows, resulting in over a hundred buttes, later shaped into drumlins by glaciers. Many of these buttes are small, but spectacular, illustrating that it's not the size that matters, but rather how they are presented.

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Session 13

Archaean through Mesoproterozoic geodynamic evolution of the Fennoscandian Shield

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Formation of the granite-migmatite belt i S Finland by transtensional tectonics

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The term Late Svecofennian granite-migmatite zone (LGMZ) of southern Finland was coined by Ehlers et al. (1993) who defined it as a 500 km long and 100 km wide belt transecting the southern Svecofennides from WSW to ENE. The zone comprises rocks of varying origin subjected to high temperature and low pressure (HTLP) metamorphosis forming various types of migmatites. These migmatites were intruded by so called late-orogenic granites at 1.85 – 1.82 Ga.

Based on structural field evidences and analogue modelling, Cagnard et al. (2006) suggest that the LGMZ formed as a consequence of lateral flow during compression of hot and weak lithospheres. A situation in favour of HTLP metamorphism, migmatization and granite formation.

Given the variability of potential source rocks (e.g. metavolcanites, various types of metasediments and granitoids), the geochemistry of the late orogenic granites is diverse and attempts to classify the late orogenic granites geochemically is challenging.   ious types of metasediments and granitoids.

L et al. (1998) presented a geochemical method to distinguish granitoids formed by melting of a hot and weak lithosphere and granitoids formed in more cratonic environments. The rocks formed from a hot weak lithosphere are High-K- Calk-alkaline (HKCA) rocks typically occuring in post-collisional setting during large relative movements of terranes along major shear zones.

We treated a geochemical data set with about 150 so called late orogenic granites (1.85 – 1.82 Ga) with the method presented by Liegeois (1998) and found out that these rocks plotted in the field of HKCA and Shoshonites. According to Liegeois (1998) these type of rocks series were generated by melting a K-rich andesitic lower crust or from a subduction enriched phlogopite K-richterite bearing lithospheric mantle.

To produce HKCA magmas, a hot and weak lithosphere is required in combination with displacement of terranes along deep shear zones, that also allowed magma bodies to rise.

It seems that there is no need to look at the late-orogenic event as a period of crustal thickening, but as a long-lived lateral flow during the post-collisional period.

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The origin of the Archaean Lake Inari TTG-amphibolite complex of the Lapland–Kola Province, northern Finland

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Earth's early basaltic crust has transformed into a thick TTG (tonalite-trondhjemite-granodiorite) crust during the Archaean Eon (4.0–2.5 Ga). The formation of TTGs as the result of melting of hydrated mafic rocks is well established by geochemical modeling and experimental methods, but field studies are rare. Our study investigates the migmatite structures, geochemistry, and geochronology of the 2.9–2.6 Ga Lake Inari TTG-amphibolite complex in the Lapland-Kola Province (Lahtinen & Huhma 2019), northern Finland. The complex shows various migmatite structures such as metatexites, metatexite-diatexite transitions and massive diatexites. The amphibolites are basalts in the TAS classification and have flat or slightly LREE-enriched REE patterns. The TTGs have two geochemically different end members; one showing lower and the other higher HREE, Mg, Sc, Y, Co, and Zn signature. The difference is likely due to the presence or absence of garnet in the source. Fluid-fluxed melting of basalts probably formed the Lake Inari Complex. Buoyant diatexite melts migrated upward and disaggregated amphibolites but were ultimately trapped in the deep crust.

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Isotopic evidence from crustal growth during the Svecofennian orogeny – a study from the Central Finland Granitoid Complex

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The Paleoproterozoic Svecofennian Province is a part of the Fennoscandian Shield extending from Central Finland and Sweden southeast to Estonia and Russia in the southeast along the southern boundary of the Archean Karelia Province. The Central Finland Granitoid Complex (CFGC) is the core of the Svecofennian Province composed mainly of plutonic rocks varying compositionally from diorites to granodiorites and granites. At outcrops mixing and mingling textures, synplutonic dykes, and mafic magmatic enclaves highlight the simultaneous nature of mafic, mantle derived magmatism and more evolved felsic magmatism in the CFGC (Mikkola et al. 2018).

The mainly calc-alkaline CFGC plutonic rocks have been emplaced between 1.90 and 1.87 Ga, based on U-Pb geochronological data indicating relatively fast crustal growth. Both whole-rock Sm-Nd (ε_{Nd} -1.7–+2.5) and Lu-Hf (ε_{Hf} -8–+9) from zircons point towards relatively juvenile sources for the plutonic rocks without involvement of Archean crustal component (Heilimo et al. 2023). As a whole, isotopic evidence and geochemical characteristics (Heilimo et al. 2018) collectively points to crustal growth with maturing arc characteristics at 1.90–1.87 Ga. A possible scenario would be amalgamation of island arcs during the Svecofennian orogeny. The maturing arc characteristics fits in a larger scale to the proposed Great Proterozoic Accretionary Orogen (e.g. Condie 2013) resulting in formation of the supercontinent Nuna (Columbia). We propose that 1.9 Ga ago the CFGC was part of the active margin of the Great Proterozoic Accretionary Orogen.

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Geochronological data from newly discovered or rediscovered rock units in the southern archipelago of Stockholm

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The bedrock of the southern archipelago of Stockholm contains some classical geological localities, most notably Utö with its iron deposit, well-preserved Svecofennian supracrustals and granitic pegmatites (Gavelin et al. 1976; Stålhös 1982), but also Ornö with its strongly sheared "banded series" outcropping along its western side. However, further east is a virtual geological "Terra incognita" that has, at least in part, apparently not been mapped geologically since Holst (1882).

The island of Fjärdlång, located E of Ornö and NNE of Utö, together with neighbouring islets and skerries, is marked as consisting of syn-orogenic Svecofennian granitoids on the digital bedrock map of SGU. However, during a visit some years ago, it was found to consist of metaturbidites similar to the greywackes on eastern Utö, but also some more massive units of possible volcanic or volcano-clastic origin, and monomict or polymict breccias. These rocks include rocks mapped as "helleflint gneiss" or "mica schist" as well as "red gneisses" by Holst (1882).

New detailed mapping of the island has revealed two fold phases and two metamorphic events, as well as numerous signs of incipient melting including pegmatitic veins and dykes (Högdahl et al. 2022). Further east, a NNE-trending belt of reddish felsic metavolcanic rocks occur, referred to as "red gneiss" by Holst (1882) and sampled by us on the islet of Marskär. This belt is apparently cut by a red granite intrusion mapped by Holst (1882) and sampled by us on the island of Villinge.

Three samples of the Fjärdlång supracrustals yield detrital zircon ages mainly between 1900 and 2060 Ma, similar to the detrital zircon data from Utö reported by Kathol et al. (2020). The red rhyolitic metavolcanic rock from Marskär yields a U-Pb zircon concordia age of 1900 ± 6 Ma, within error of the volcanism on Utö (1904 ± 4 Ma; Lundström et al. 1998), while the red granite on Villinge gives a virtually identical concordia age of 1898 ± 5 Ma.

The general NNE strike of the rock units suggests that the Fjärdlång supracrustals and the Marskär metavolcanites may represent two easterly branches of the well-known supracrustal units on Utö. These new discoveries and rediscoveries call for a more systematic regional mapping campaign of the outer part of the southern Stockholm archipelago.

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1865 Ma Svecofennian extensional magmatism in Nagu, SW Finland

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The Svecofennian orogeny in southern Finland is traditionally divided into two compressional stages, the 1.89-1.87 Ga (synorogenic) stage and the ca 1.84-1.82 Ga (lateorogenic) stage. The term "intraorogenic" that was introduced by Simonen (1980) is used to describe the poorly defined phase that occurred between these two, with some overlapping. Intraorogenic magmatism is typically bimodal and the mafic components show MORB affinities that imply extensional tectonics. During the last 20 years, an increasing amount of mafic intrusions (i.e. Kara et al. 2020 and references therein) of intraorogenic ages have been identified in the Late Svecofennian Granite and Migmatite zone (LSGM, Ehlers et al. 1993) in the Southern Finland Subprovince (SFS), continuing into both Sweden and Russia. Mature quartzites (Bergman et al. 2008, Lahtinen & Nironen 2010) occur in the same area. Parts of the BABEL (Korja & Heikkinen 2005) and FIRE (Lahtinen et al. 2009a) seismic profiles from the SFS and Bothnian basin region have been interpreted to reflect upwelling of mantle material in extensional sedimentary basins that were later subject to high-T low-P lateorogenic metamorphism.

The Kaiplot gabbro is situated on a number of islands and islets in Nagu in the southwestern archipelago of Finland. The outcrops occur as dykes as well as plutonic bodies and have been emplaced in at least two separate pulses. U-Pb dating (TIMS, zircon) gave an age of 1865±2 Ma, i.e. an intraorogenic age. Net-veining structures and incomplete mixing between the Kaiplot gabbro and a felsic magma is seen in places, a feature also described by Väisänen et al. (2012a) regarding slightly younger intraorogenic rocks in the nearby area.

The tholeiitic Kaiplot gabbro has Mg# of 62.75 to 37.05, with the most primitive samples being close to chemical equilibrium with the mantle. During transport and emplacement, both differentiation and assimilation of crustal material have taken place. The incompatible trace element signatures show that the Kaiplot gabbro is transitional between volcanic arc and back-arc basalt, and further imply depleted to slightly enriched MORB and back-arc basin basalt affinities. The Kaiplot gabbro confirms an extensional tectonic episode at around 1865 Ma.

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Lithotectonic map of Fennoscandia

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We present a coherent lithotectonic map for the onshore solid rock masses of Norway, Sweden and Finland. The map is largely the result of a first-order harmonization between the publicly available NGU, SGU and GTK national bedrock databases as they were in the year 2023. The map also builds heavily on - and complements - earlier tectonic synthesis of Fennoscandia, such as published by Stephens et al. (2020), Kohonen et al. (2021), Torgersen et al. (2021) and Lahtinen et al. (2023).

The purpose of the presented map is to increase consensus on terminology, to connect border-crossing units and tectonic boundaries, and hence to provide a joined-up tectonic framework that includes 2 billion years of geological evolution of Fennoscandia. Moreover, we desire that the lithotectonic map is treated as a dynamic framework that may change over time as new data and knowledge becomes available and new consensus is found through discussions and collaborations between the countries. Creating and refining the lithotectonic map by knowledge exchange will increase our understanding of the crustal evolution of Fennoscandia in space and time, but it also provides a reference for the harmonization of other national geological- and geophysical datasets. Not least, the map will serve the need to place the occurrences of energy- and mineral resources of the Nordic countries into a wider tectonic context.

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The Börön volcanic suite and the initial closure of the Bothnian Basin

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The supracrustal rocks of the Bothnian Basin in the Bothnia-Skellefte Lithotectonic Unit, central Sweden, are dominated by a several km thick sequence of metasedimentary rocks, mostly greywackes possibly originally formed as turbidites. The bedrock is deformed and metamorphosed at high grade, and intruded by younger rock units, e.g. c. 1.82 Ga old Härnö-type anatectic granites and 1.85–1.80 Ga Revsund suite granites. The latter also intrude the metasedimentary units along most of the western border of the basin. To the south the Bothnian Basin borders the 1.86–1.84 Ga Ljusdal batholith.

Within the sedimentary rocks of the basin there are volcanic units, mostly amphibolites, but less common also intermediate and felsic volcanic sequences. One of these is the Börön volcanic suite in the southwestern corner of the basin, in an area dominated by varieties of Revsund granites and partly covered by nappes of the Scandinavian Caledonides and units originating from the mid-Ordovician Lockne meteorite impact.

The Börön volcanic suite comprises locally well-preserved units where volcanic features such as agglomerates, layered ashes and pumice fragments can be recognized. In the east the rocks are affected by shear zones that probably are part of the Forsaån Shear Zone, which is a continuation of the regional-scale Storsjön-Edsbyn shear zone (Högdahl & Sjöström 2001). The suite ranges from basalt to rhyodacite in composition, with a weak trend of more felsic units towards the northwest. Major, minor and trace elements suggest formation in an island arc setting with continuous fractionation trends for most elements between 47 and 69 wt% SiO_2.

An ion probe U–Pb zircon age determination of a rhyodacite unit in the southeastern part of the suite yielded an age of 1882±3 Ma, which is within errors similar to a 1888±6 Ma age of a calc-alkaline volcanic unit in the tectonically emplaced Hamrånge syncline to the southeast of the Ljusdal Lithotectonic Unit (Högdahl & Bergman 2020).

The 1.88 Ga age and calc-alkaline island arc signature of the Börön volcanic suite in the southwest of the Bothnian Basin, together with the similar aged rocks of the Hamrånge syncline in the southeast suggest a common origin of the units, and we suggest that they represent remnants of an island arc formed during early convergence in the Bothnian Basin, which eventually led to the closure of the basin c. 20–30 m.y. later.

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The metamorphic evolution on Utö

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The bedrock of Utö in the outer part of the southern part of Stockholm archipelago comprises a well-preserved sequence of older Svecofennian supracrustal rocks metamorphosed and deformed during the Svecokarelian orogeny. Recent studies by our group have resulted in a more detailed knowledge of the formation and evolution of the bedrock, especially regarding the metamorphic conditions.

We divide the stratigraphy of Utö, from southeast to northwest, in a lower, middle and upper formation, where the boundary between the two first coincides with the lower boundary of the "leptites and hälleflintas" in the stratigraphy of Gavelin et al. (1976).

The lower formation begins with turbidites that suggest an upwards shallowing of the depositional environment. The turbidites are followed by a several hundred meter thick sequence of ignimbrites and layered tuffs, which at the top are gradually replaced by sandy and silty sediments deposited at shallow depths, or even in deltas or tidal flats. Metamorphism here is characterized by two generations of andalusite, one early together with cordierite, and one later with andalusite and garnet. Peak metamorphism was at rather high temperatures (540–580°C) but low pressures (≈3 MPa).

The middle formation is less exposed, and details of the stratigraphy are only seen along the northernmost tip of Utö. The unit is dominated by carbonates, both dolomitic and calcitic, intercalated with iron rich fine-grained sediments, maybe of volcanic origin. Individual beds range in thickness from decimeter-sized to some meters. A few less than meter-sized units of layered tuffs are also present. Furthermore, the old iron mine of Utö probably lies high up in the stratigraphy of the middle formation. So far, we have not been able to characterize peak metamorphism here, but retrograde metamorphism as seen as replacement of calcic pyroxene by calcic amphibole, and formation of a later generation of muscovite in skarns is evident. Metamorphic temperatures based on Ca/Mg equilibrium in calcite yield temperatures of 230–440°C, which probably reflects the fluid induced retrograde metamorphism.

The upper formation is separated from the middle by the Utö Shear Zone and is found on Stora Persholmen, Ängsholmen and Näsudden further to the southwest. The supracrustal units probably represent turbidites with a high amount of feldspar (10–40%). Units of possible volcanic origin are rare and differ from the rest of Utö in being more mafic in composition. The rocks of the Upper formation are more deformed and of higher metamorphic grade than the rest of Utö. Sillimanite is seen to replace andalusite and temperature estimates yield temperatures of 650–680°C. A later retrograde event is recognized as chlorite replacing biotite along discrete shear zones, probably as part of the Utö Shear Zone. Chlorite bearing units record metamorphic temperatures at 520–540°C

Our studies together with earlier petrographic works suggest three different metamorphic events on main Utö, one early high T–low P forming cordierite and andalusite. This was followed by a later event producing garnet and a second generation of andalusite at peak metamorphic conditions of 540–580°C. The third event is a fluid induced low temperature retrogression at c. 350°C. This is in contrast to the upper formation that records a different metamorphic history. Only one prograde event, at high temperature producing sillimanite, followed by a retrograde event, but still at elevated temperatures have been recognised. This suggest that the upper formation originally was formed far away from the rest of Utö's bedrock and emplaced in its current position after peak metamorphism but before intrusions of the pegmatites.

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Chalcophile geochemistry of the Ni-Cu-PGE mineralised 2.05 Ga conduits in the Karasjok Greenstone Belt, northern Norway

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The Karasjok Greenstone Belt (KGB) extends from the Norwegian coast in the north into Finland, where it is called the Central Lapland Greenstone Belt (CLGB). This belt represents one of the most substantial Palaeoproterozoic volcano-sedimentary formations within the Fennoscandian Shield (Hanski and Huhma, 2005). Within the CLGB, numerous ore bodies are present, particularly magmatic Ni-Cu-PGE deposits linked to a magmatic event around 2.05 Ga. Notable examples include the Kevitsa, Sakatti, Lomalampi and Hotinvaara deposits. These deposits are associated with komatiitic magmatism, resulting in mineralisations within both intrusive conduits and extrusive counterparts. However, past research indicates that the komatiites in the Karasjok region display lower concentrations of chalcophile elements compared to the Finnish belt segment (Fiorentini et al., 2011). This suggests that the melts equilibrated with sulphides en route, again implying a potential for unidentified mineralisations associated with the conduit system. In the Karasjok region, several smaller bodies, such as the Karenhaugen (c. 0.04 km^2), Porsvann (c. 0.3 km^2) and Gállojávri (c. 2.3 km^2) intrusions, exhibit anomalous Ni-Cu-PGE contents. Recent dating confirms the age of the Gállojávri and Porsvann intrusions to be around 2.05 Ga (Hansen et al., 2023; Orvik et al., 2022b). Petrogenetic modelling suggests that Gállojávri served as a conduit for local komatiites, a scenario likely applicable to Karenhaugen and Porsvann (Orvik et al., 2022a). In this study, we present chalcophile geochemistry for the 2.05 Ga intrusive bodies and whole rock S isotopes for the Gállojávri intrusion in the KGB. After adjusting for silicate fractionation, unmineralised rocks exhibit enrichment in chalcophile elements compared to mantle background values, indicating the potential of a prospective system. The Karenhaugen and Porsvann intrusions show enrichment with respect to mantle-normalised $(Cu/Pd)_N$ ratios, with medians of 0.20 and 0.16, respectively. In contrast, Gállojávri is slightly depleted with a median $(Cu/Pd)_N$ of 2.32. All intrusions show S/Se-ratio ranges below mantle values, but low S content and Se detection limits may affect the results. For the Gállojávri intrusion, whole rock $\delta^{34}S$ ranges from 1.5 to 4.0‰. The lower-than-mantle S/Se-ratios and mantle-overlapping $\delta^{34}S$-ratio of Gállojávri are challenging to reconcile with significant S addition from country rocks. However, high sulphide-to-silicate ratios (i.e., R-factors) may obscure contamination effects. In Cu vs. Pd plots, the intrusions follow two different trends. The Karenhaugen and Porsvann intrusions align with a trend suggesting formation from a mantle source initially enriched in Pd, while Gállojávri follows a trend indicating either a slightly depleted source or the removal of cotectic sulphides before emplacement. We favour the latter scenario, as it aligns with previous models suggesting significant lower-crustal fractionation before Gállojávri's emplacement. This suggests that the Porsvann and Karenhaugen conduits represent more efficient transport of enriched melt to the upper crust. Our findings highlight that small-scale intrusions with characteristics supporting a dynamic conduit-like system should be considered as potential exploration targets within the KGB.

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The well- and unknown Vetlanda sedimentary sequence

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The Vetlanda sedimentary sequence, formed by arkoses, greywackes and conglomerates, is located in southern Sweden and is surrounded by the 1808-1794 Ma generation of the Transscandinavian Igneous Belt (TIB 1a) in the north and the 1793-1769 Ma generation (TIB 1b) in the south (Salin et al. 2019). These rocks were thought to represent an older supracrustal unit intruded by the TIB (Småland) granitoids (e.g., Magnusson 1962, Röshoff 1975, Mansfeld et al. 2005). Another sedimentary sequence is located within the Malmbäck supracrustal formation northwest of Vetlanda (Appelqvist et al. 2009). This formation consists of 1796 Ma volcanic and volcaniclastic rocks as well as conglomerates surrounded by TIB 1b granitoids and was interpreted to belong to the TIB 1 by Appelqvist et al. (2009).

This research is based on field observations, petrological and chemical studies as well as preliminary U-Pb age determinations of detrital zircons from the sedimentary rocks in the Vetlanda and Malmbäck areas. The aim of this contribution is to show the similarity of these two sedimentary sequences and to suggest an interpretation of the depositional environment.

Both sedimentary sequences are composed of arkoses, greywackes and conglomerates. The arkoses and greywackes are dominantly poorly- to moderately-sorted and contain moderately-rounded quartz and/or feldspar grains in a groundmass of feldspar, quartz and biotite with minor opaque minerals. The conglomerates are composed of rounded and elongated lithic fragments (quartzite, K-feldspar granites and tonalites) embedded into a moderately-sorted groundmass, mostly composed of feldspar, biotite, quartz and opaque minerals. U-Pb zircon dating of an arkose at Sunnerskog (eastern part of the Vetlanda sequence) demonstrates a derivation from a source with the age of 1849±1 Ma.

Biotite and feldspar are not resistant for a long transportation. A large proportion of these minerals in the groundmass of arkoses and conglomerates, as well as quartzite fragments, is an evidence for a short distance from a source rock with a granitic composition, even if feldspar is not observed in the lithic fragments of some conglomerates. The homogeneous age of the Sunnerskog zircons is another evidence for a local source. Furthermore, the unsorted character of the sediments indicates a rather rapid sedimentation.

To conclude, a probable depositional environment for the studied sedimentary rocks is a shallow marine environment (e.g., a beach) close to a granitic source rock. This is consistent with the assumption that the Vetlanda and Malmbäck successions were not formed prior to the TIB emplacement. It is instead suggested that the 1808-1794 Ma TIB 1a was a significant source for these sediments, but the 1849±1 Ma zircon age at Sunnerskog indicates even more complex provenance pattern.

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Bedrock mapping, zircon U-Pb geochronology and Lu-Hf isotopes of the Archaean Kirkenes Gneiss Complex, Kola Craton

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The Kirkenes Gneiss Complex in the northwesternmost Kola Craton is a little-studied part of the Fennoscandian Shield. This master's project intends to supplement the current knowledge of this Archaean domain, including an increased understanding of both magmatic and metamorphic evolution and correlation between the various studied units.

The study area is located northeast of the town of Kirkenes, Northern Norway. Field work was conducted across units that earlier literature describes as the the Kirkenes Granitic Gneiss complex (Siedlecka et al. 1985), the metasupracrustal Jarfjord/ Kola gneiss (Siedlecka et al. 1985) and the Ropelv-type quartz monzonite/syenite (Siedlecka & Nordgulen. 1996). Sampled units include TTG gneisses, metasupracrustal gneisses, mafic and felsic intrusive bodies as well as mafic dykes.

Work conducted in the project thus far includes mapping and sampling, as well as zircon mineral seperation. Zircon has been gathered from a total of 27 samples and will be used for U-Pb geochronology and the Lu-Hf isotope analyses to constrain melt evolution and crustal growth. Further methods that will be applied include whole-rock geochemistry and thin sections for mineral identification. The first results are expected in November 2023.

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Subduction and loss of continental crust during the Mesoproterozoic Sveconorwegian Orogeny

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The Sveconorwegian Orogeny is characterised by tectonically bound units that record different metamorphic, magmatic and deformation histories, suggesting that they were separated by some unknown distance prior to orogeny. New U–Pb and Lu–Hf zircon data from a 1200 km-long NE–SW transect from Archaean to 1450 Ma rocks allow us to delineate the age and isotopic architecture of western Fennoscandia prior to the late Mesoproterozoic Sveconorwegian Orogeny. Age and Hf-isotopic patterns suggest that the units comprising the Sveconorwegian Province are both younger and isotopically more juvenile than expected for autochthonous crust that grew (south)westward, and most likely derive from areas at least 500 km west of their current location (i.e., west of the present-day Norwegian coastline). The Mylonite Zone appears to be the main structure delineating allochthonous Sveconorwegian units that record magmatism, metamorphism and deformation from 1140 to 930 Ma, from autochthonous Fennoscandian crust that only record tectonic activity after 990 Ma. New and compiled metamorphic age data suggest that the Mylonite Zone can be traced westward through the Western Gneiss Region, lining up with Sognefjorden in western Norway, an area also characterised by undated, east–west-trending, high-strain tectonic fabrics. The proposed westward continuation of the Mylonite Zone most likely accommodated several hundred kilometres of sinistral strike-slip movement. Eastward translation of crust must have taken place around 990 Ma, coinciding with a magmatic lull in the orogenic hinterland (Telemark unit) and high-pressure eclogite-facies metamorphism in the footwall to the Mylonite Zone (Eastern Segment). Following this relatively short period of compression, the entire orogen and its immediate foreland underwent extension lasting until at least 930 Ma. The nature and fate of the ca. 500 km of crust originally separating the autochthonous and allochthonous units remain elusive. There is no evidence of arc magmatism related to Benioff-style subduction of oceanic crust, and thus we propose an amagmatic Ampferer-style subduction comprising spontaneous subduction of thinned continental crust, as proposed for the Western Alps. Subduction of continental crust and associated radioactive heat-producing elements could also account for anomalously high temperatures in the lithospheric mantle under the Sveconorwegian Province, which cannot easily be accounted for by other mechanisms. Regional magnetic and gravity data suggest that the Sveconorwegian Province sensu stricto was part of a larger north–south trending orogen; however, evidence of this needs to be teased out from areas that are either covered by Palaeozoic Caledonian nappes or were heavily overprinted by Caledonian deformation and metamorphism. In this interpretation of the Sveconorwegian Orogeny, the Province itself may be an anomalous feature in an otherwise larger-scale orogen, the nature of which is not understood.

Archaean TTGs derive from mafic cumulates buried within the roots of proto-continents

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Large amounts of juvenile crust with tonalite-trondhjemite-granodiorite (TTG) composition were added to the continental crust during from about 3.5 billion years ago (Condie et al., 2005). As most Archean cratons, this episode of crustal growth is also clearly recorded in the Archean cratonic core of the Fennoscandian Shield, which locally preserves 3.5-Ga crustal fragments and contains a substantial exposure of Neoarchean TTG crust (Hölttä et al., 2008). The rise of TTG crust in the Archaean is classically attributed to the start of modern-style plate tectonics (Moyen & Martin, 2012), which would be consistent with great melting depths indicated by high La/Yb and Sr/Y. The meaning of such proxies is nevertheless debated (Kendrick & Yakymchuk, 2020) and so is the general petrogenetic setting of TTGs. Many other processes, including delamination and intra-crustal differentiation, have been proposed to explain TTG petrogenesis (e.g., Bédard, 2006; Kamber, 2015). Each of these to some degree explains certain compositional features of these rocks, but they cannot all be correct. Progress in this regard requires quantitative constraints on the composition of TTG parental melts, and thus a means to distinguish primary compositional features from those caused by crustal assimilation and fractional crystallization. In this study, we present a new way of investigating TTG petrogenesis using high field-strength element (HFSE) systematics.

The Nb concentrations and Ti anomalies of TTGs show the overwhelming effects of amphibole and plagioclase fractionation and permit the first clear constraints on the composition of primary TTG melts. These melts are uniformly incompatible element-poor and characterised by variably high La/Sm, Sm/Yb and Sr/Y, and positive Eu anomalies. Differences in these parameters are not indicative of melting depth, but instead track differences in the degree of melting and fractional crystallisation. The HFSE signatures of TTGs show that these melts derive from mafic plagioclase-cumulates that melted to different degrees in the presence of residual rutile and garnet. These cumulates resided in the roots of the overthickened proto-crust, which underwent partial melting as a result of being magmatically loaded and buried. The partial melting of these cumulates is part of a causal chain that explains the rise of TTG crust during the Archaean and links TTG magmatism to the formation of sanukitoids and K-rich granites in ancient cratons.

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A new web portal brings the Svecofennian geology of Landsort to life

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Landsort is an island and a small community in the outer archipelago of Stockholm, primarily known as a pilotage site for 500 years. The island is characterized by a rich maritime cultural history, a rich environment in the Baltic Sea, and an interesting Svecofennian geological heritage. But like all rural areas, this community also faces challenges; the population is decreasing, and community services are disappearing.

In 1998, local efforts were initiated to reverse this trend, with the ambition to create new jobs and activities. This has included work to develop the tourism industry, based on Landsort's unique features. A web portal has been created, www.visitlandsort.se, to guide visitors regarding the maritime cultural heritage, the Baltic Sea environment, and the geological heritage. The geological heritage of Landsort consists of spectacular 1.9-billion-year-old Svecofennian gneisses and amphibolites with massive epidote-quartz veins telling how metamorphic fluids flowed through them. The Svecofennian landscape of Landsort bears many marks of the last glaciation There are fault planes from historical earthquakes associated with postglacial rebound, raised beaches, glacial striations, P-forms and giant's cauldrons many of which testify to the advance and retreat of the ice sheet and the dramatic events from 11,600 years ago when the edge of the Baltic ice lake was right at Landsort. And in its eastern harbor, marks etched into the rock face provide a record that Landsort is still rising from the sea.

The purpose of the web portal is to help the visitor visualize the events that are Landsort's story. The work was started in 2020 in collaboration with researchers at the Department of Geological Sciences at Stockholm University. Factual information was presented as stories, which aimed to take the visitor back to the time when the geological events occurred. Alongside the stories, there are links to other information to provide interested visitors with opportunities for further knowledge and deeper understanding.

References

Webportal *www.visitlandsort.se*

Interaction between Svecofennian crust and rapakivi granites along the SW margin of the Wiborg Batholith, southern Finland

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The Wiborg Batholith is an anorthosite-gabbro-granite rapakivi complex that was emplaced into 1.89-1.91 Ga metamorphosed Svecofennian crust in an extensional tectonic regime. The igneous activity started with the emplacement of the 1640 Ma Häme dykes (Luttinen et al. 2022) and was followed by two granitic pulses (Vaasjoki et al., 1991), which are represented by 1635-1628 Ma zircons in alkali feldspar mega-crysts and c. 1628 Ma zircons in the granitic groundmass (Heinonen et al., 2017). Indium-bearing magnetite-sphalerite bodies occur at Pahasaari in the 1633 ± 5 Ma Verla granite in the NW margin of the batholith, but even more significant indium-rich polymetallic mineralization occur at Sarvlaxviken, in the SW margin of the batholith (Cook et al., 2011).

This study is based on comprehensive remapping, geochemical characterization, and U-Pb dating of the granites along the SW margin of the Wiborg Batholith. Sm-Nd isotope work and paleomagnetic studies are also underway. At present, we have identified an igneous geochemical evolution trend, from the 1628.2 ± 2.4 Ma primitive wiborgite (host to In-rich veins) to the evolved 1625.2 ± 2.4 Ma Mo-Be-Cu-As-Sn-bearing Marviken granite and 1625.3 ± 1.7 Ma Saltkilen granite dykes, the latter thus representing the last igneous expressions in the Wiborg Batholith and is considered to be the engine for the hydrothermal activity responsible for the polymetallic veins in the Sarvlaxviken area.

Our research has also revealed significant intriguing interactions between the rapakivi granites and the Svecofennian crust. Numerous Svecofennian fragments, ranging in size from < 1 mm^3 xenocrysts to > 100 km^3 xenoliths, occur in the batholith margin. The 1629.6 ± 4.6 Ma Stormossen granite hosts significant amounts of 1877.1 ± 6.2 Ma (Svecofennian) and 1804 ± 7.5 Ma (Late Svecofennian) zircon xenocrysts as well as abundant 10 x 50 m large fragments of Svecofennian granitoids and amphibolites, providing clear evidence for extensive assimilation of older crust into the Stormossen magma.

The Högbergsträsket mega-xenolith is even more spectacular. It is a 32 km^2 big, kidney-shaped body, equally shared between 1870-1907 Ma (Svecofennian) and 1636 Ma rapakivi components. This mega-xenolith descended and rotated c. 30-40° northwards, along an ENE-trending axis, into a later (1628 Ma) pulse of the rapakivi magma. In this way, a profile can now be studied, from the lower levels of the ancient magma chamber (1636 Ma wiborgites), via the Eskodalen granite into the highest levels; ignimbritic volcanic rocks with an ongonitic geochemical signature. The Eskodalen granite hosts several In-bearing magnetite-sphalerite bodies which show a NS-trending zonation with magnetite stringers at lower levels (at Bockmossen) and an increasing Zn- and In-rich hydrothermal overprint (at Getmossmalmen), close to the overlying ignimbritic volcanic rocks. This peculiar ore type bears a correlation with the Pahasaari magnetite-sphalerite bodies in the 1633 Ma Verla granite.

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Mapping of mafic dykes in the Archaean Kola craton in Sør-Varanger, and testing the applicability of in situ LA-ICP-MS Sm-Nd isotope analysis in apatite

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This master's project comprises two different goals aiming to: (1) increase our understanding of the evolution of the Archean Kola craton, and (2) test if in situ, LA-MC-ICP-MS analyses of Sm-Nd isotopes in apatite can serve as a proxy for whole-rock isotopic compositions.

The primary objective of the project is to map out the distribution of mafic dykes in the field and using drone magnetic surveys and aerial photographs, to determine if they can be classified into distinct geological groups based on orientation and relationship with their hosts gneisses. Whole-rock geochemistry and Sm-Nd isotopes will aid in this work and provide a basis for selecting samples for U-Pb zircon geochronology.

The secondary objective is method development and testing of in situ, LA-ICP-MS analyses of apatite Sm-Nd isotopes as a proxy for whole-rock isotopic compositions. The results from this method will be compared with results from whole-rock Sm-Nd isotope analysis conducted by TIMS and aims to find out if the Sm-Nd isotope analysis of apatite can serve as a reliable alternative to TIMS analysis. The testing will be carried out on samples from different origins: mafic intrusive rocks (Karasjok Greenstone Belt), mafic dykes (Sør-Varanger and the West Troms Basement Complex) and TTG gneisses (Sør-Varanger).

Rock samples were collected during a twelve-day field campaign. The samples are currently undergoing geochemical analysis and mineral separation for both apatite and zircon. The first results are expected in November 2023. The data will be used to correlate with mafic dykes in other parts of Fennoscandia and other Archaean cratons around the North Atlantic and constitute part of a larger geochemical and isotopic dataset from mafic dykes in Fennoscandia aiming at increasing our understanding of Fennoscandian mantle evolution. A positive outcome from the test of apatite Sm-Nd compositions will provide a new tool for easy access to isotopic data from zircon-poor rocks.

The tectonometamorphic evolution of northeastern Fennoscandia

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One of the defining geological features of northeastern Fennoscandia is the Lapland-Kola Orogen. Oriented N-NE, it spans a length of approximately 800 km. In Norway, it affects three main units (from west to east): the Karasjok Greenstone Belt, the Tanaelv Migmatite Belt and the Lapland Granulite Belt, extending across southeastern Finnmark, into Finland and Russia. The Karasjok Greenstone Belt consists of amphibolite-facies sedimentary and volcanic rocks, which represent a rift and passive-margin sequence. The Lapland Granulite Belt is interpreted as a metamorphosed nappe stack of sedimentary and arc volcanic rocks, which was thrusted southwestwards over the Karasjok Greenstone Belt, with the Tanaelv Migmatite Belt corresponding to a collisional melange. This configuration represents a significant inverted metamorphic gradient, with a temperature difference of over 300°C between the LGB and KGB across 20 km (Krill, 1985; Gaál et al., 1989; Cagnard et al., 2011). Furthermore, the metamorphic grade within the Karasjok Greenstone Belt increases eastwards towards the TMB contact, with a corresponding increase in the degree of recrystallization. While previous work (Marker, 1988; Barbey & Raith, 1990; Korja et al., 1996; Tuisku & Makkonen, 1999, Cagnard et al., 2011) argued that this variation is a result of heating from the overthrust Lapland Granulite Belt, the timing of this metamorphism is unconstrained and only a limited number of estimates regarding its intensive variables are available. The main objective of this project is to constrain the metamorphic history of the aforementioned units, focussing on their thermal–time evolution and the kinematics and timing of movements along bounding structures. The expected goal is a model that takes into consideration the geochronology of high-, medium-, and low-temperature minerals along with general investigations into the metamorphic petrology and structural geology of the units, which will enable the description of their pressure–temperature–time paths and cooling histories.

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Session 14
General geology: Open session

Session Chair:
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Dypingite as a series and its formation from serpentinite weathering

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Dypingite, $Mg_5(CO_3)_4(OH)_2 \cdot 5H_2O$, is one of the hydrous magnesium carbonate phases which also include lansfordite ($MgCO_3 \cdot 5H_2O$), nesquehonite ($MgCO_3 \cdot 3H_2O$), and hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$). Weathering of serpentinite by water and atmospheric CO_2 induces the formation of hydrous magnesium carbonates including dypingite (Power et al. 2013). Recently, dypingite has been found to be relevant for CO_2 sequestration (Ballirano et al. 2013) and water purification (Naqvi, 2014). However, the fact that its structure and formation in natural settings are still largely unknown hampers further applications of dypingite. Supported by the NATSORB project, this work collected hydrous magnesium carbonates from Dypingdal and the Feragen Ultramafic Body, Norway, to study the formation of dypingite, which contributes to refinement of dypingite structure, synthesis and environmental application of dypingite.

Deviations in most X-ray diffraction (XRD) patterns of dypingite compared to the first dypingite pattern in Raade (1970) has been ascribed to undefined "dypingite-like phases" (Hopkinson et al. 2012). In our samples, both dypingite showing the same XRD pattern as that in Raade (1970) and dypingite-like phases have been found. The former one is called dypingite *sensu stricto* (*s.s.*). Synchronous variation between structure parameters analyzed by XRD and molecular water contents measured by thermogravimetric analyses and Infrared spectroscopy is shown from dypingite *s.s.* via dypingite-like phases to hydromagnesite. Subsequently, humidity incubation experiment conducted under room temperature showed that high humidity (> 95%) induced phase transformation toward dypingite *s.s.*, whereas low humidity (< 23%) reversed the phase change direction, but failed to attain hydromagnesite. Therefore, dypingite *s.s.* and dypingite-like phases are a continuous series connected by reversible phase change. Dypingite *s.s.* as one endmember is the fully hydrated version, while on the other end is the minimally hydrated dypingite.

Hydrous magnesium carbonates encrusting serpentinite can be composed of three zones, which are moderately hydrated dypingite (Zone 1), nearly fully hydrated dypingite (Zone 2), and nesquehonite or lansfordite (Zone 3). In Zone 1, platy crystals of dypingite are perpendicular to the serpentine surface, whereas in Zone 2, some dypingite crystals grow in similar way on surface of serpentine fragments but also as radiating morphology. The $\delta^{13}C$ values well distinguish dypingite in Zone 1 from that in Zone 2. Values of Zone 2 are in the same area of those in Zone 3. Accordingly, the dypingite in Zone 2 might be transformed from nesquehonite or lansfordite or precipitated in one type of weathering fluid. The dypingite in Zone 1 is proposed to be formed directly from another fluid.

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The war in Ukraine - its impact on scientific collections, scientists and their research

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Swedish governmental institutes have recently been required to present crisis plans for evacuation of collections and items of national heritage importance. Within Natural Science collections, the type specimens are the most prioritized specimens and calculations have been made for the evacuation time in case of war.

Russia's invasion of Ukraine had a profound impact on the country's research institutes and museum collections. Information and experience from Ukrainian institutes are of crucial importance for crisis and evacuation plans for Swedish collections and science data.

Since the beginning of the full-scale invasion, as reported by the Ministry of Culture and Information Policy of Ukraine, a total of 63 museums and galleries have been affected in Ukraine: 22 units were destroyed and 41 damaged. The following institutes in Kyiv were damaged by missiles the Khanenko Museum, the Taras Shevchenko National Museum, the Kyiv Art Gallery, the National Science and Natural History Museum of the National Academy of Sciences of Ukraine and others. Of great importance is the illustration and digitization of important specimens. Museum employees have been saving museum collections since the first days of the full-scale war. For security reasons, the storage locations of historical and architectural monuments saved from Russian aggression are not disclosed. Restoration of destroyed and damaged cultural monuments at the state level will begin after the end of the war. Museums and cultural monuments are now being conserved to prevent further destruction. For example, the Chernobyl radiation-ecological biosphere reserve requires de-mining operations; the national reserve "Khortytsia" in Zaporozhye is currently under constant shelling; the biosphere reserve "Askania-Nova" named after F.E. Falz-Fein in the Kherson region is located in the zone of temporary occupation. Restoration of museums requires significant financial investment, so museums are looking for patrons.

Many scientists were forced to leave their homes and move to other parts of Ukraine or abroad. Others joined the army to fight, or died in war or were captured. Also, due to everyday problems created by the war, some scientists both abroad and in Ukraine cannot begin full-fledged scientific work.

Many international foundations and organizations initiated grants and scholarships to support Ukrainian scientists. Sweden has taken a leading role in this respect. The Swedish Foundation for Strategic Research, The Wenner-Gren Foundations, Royal Swedish Academy of Sciences, The Knut and Alice Wallenberg Foundation, The Marianne and Marcus Wallenberg Foundation and The Marcus and Amalia Wallenberg Foundation, among others, announced special grants for Ukrainian scientists who came to Sweden.

It is not clear how long the war in Ukraine will last and we do not know what the outcome of the war will be, so we are looking further towards finding the best solution for building the capacity of, and securing employment for, Ukrainian scientists into the future. Further, the experiences held by our Ukrainian colleagues are an invaluable source for Sweden´s strategic work with crisis management.

Triassic and Jurassic of Sweden – fauna and flora in a disturbed ecosystem

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The Triassic–Jurassic transition is in Sweden marked by a change from lithologies dominated by coals and dark, organic-rich mudstones in the pre-ETE successions, to light grey to whitish silt- and sandstones for the post-ETE. Facies changed from continental in the uppermost Triassic, to marginal marine in the Hettangian, locally enriched in iron ooids, in the Sinemurian. The Swedish Museum of Natural History hosts large collections of plants from these Rhaetian–Hettangian successions of southern Sweden. Detailed taxonomical investigations of these assemblages have been carried out over the last centuries contributing to its prominence by the many type specimens of foliage and cones.

Here we complement the thorough systematic work on these floras, with a major study assessing the plant diversity and abundance across the End-Triassic event from multiple localities from southern Sweden. The initial results reveal a major change, from the diverse and varied floral assemblages hosted in the Rhaetian coal-bearing deposits, to the lycophyte and fern-dominated interval within the mudstones overlying the coals. The post-extinction Jurassic floras are highly dominated by *Nilssonia*, *Sagenopteris* (Caytonia-plant) and *Podozamites*. This dramatic change in the flora, also expressed in the palynological record is most probably linked to the volcanic activity in the Atlantic volcanic province, where short term volcanic winter caused darkness and cooling leading to demise of vegetation, before the onset of high CO_2 conditions with a new flora emerging. The following transgression is traced in the marine fauna, mainly represented by bivalves in successive monospecific assemblages. Other evidence of the marine environment are the and trace fossil, shark eggs, foraminifera and in the Sinemurian, sparse ammonites.

Fracture-driven magma degassing pathways in intruding rhyolitic magma

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Degassing efficiency during the emplacement of silicic magma can determine the eruptive potential. Effusive lava domes are coupled with localized degassing through transient fractures near the walls of the conduit (Holland et al. 2011), whereas explosive eruptions are a result of bulk magma fragmentation. Complex interplay between viscous and brittle processes is likely occurring in magmas close to the viscous-brittle transition even in intrusive settings, but evidence of such relationships can be easily overprinted or erased either via viscous healing or by post-emplacement fluid alteration. Here we present excellently preserved mechanical deformation features grading from viscous into brittle in the Sandfell laccolith, Eastern Iceland. Building on work by Mattsson et al (2018), we mapped the area and categorized each outcrop on a deformation scale of 1-5, 1 being purely viscous flow banding and 5 being breccia. The intermediate categories are as follows: 2) 'vesicle trains,' where the higher porosity flow bands have undergone continuous shear, stretching and aligning the vesicles parallel to the shear direction. 3) 'Fracture bands' (small/simple), clearly brittle tensile fractures confined to a planar band, interpreted as the initial flow band plane. The outcrop fell under this category if fracture bands contained only one fracture set and/or were <5 cm in thickness. 4) Fracture bands (large/complex), similar to category 3 except more than one fracture set is present and/or fracture band is >5 cm thick. We measured anisotropy of magnetic susceptibility (AMS) of coherent Sandfell rhyolite to determine magnetic fabric, and coupled these data with structural measurements of magma flow and fracture bands along with the categories of deformation. Porosity/permeability measurements were taken on coherent and flow-banded samples, and micro-CT scans were made of fracture band blocks to quantify fracture connectivity. Mapping results show clusters of dominantly-brittle and dominantly-viscous deformation features throughout the laccolith. Permeability of coherent rhyolite was below the detection limit, while along a flow band permeability was 2.05×10^{-14} m^2. Micro-CT results show strong preference of permeable flow along fracture lengths, with minor connectivity between main fractures. This exemplifies the increase of permeability with continued deformation from viscous to brittle. We suggest that during early laccolith growth stages, degassing occurred within flow bands. Continued inflation-induced shearing stretched and joined vesicles within the flow bands together, increasing permeability. Magma pore pressure increased from volatile exsolution and coupled with the accumulation of inflation stresses in the magma. Eventually, the tensile strength of the magma was overcome by these stresses, and tensile fractures propagated outward from the edges of the flow band. These fracture bands provided highways for fluids to move through, eventually escaping the laccolith entirely or remaining in the fractured rhyolite. Continued inflation deformed areas of the magma further after it had crossed the brittle transition, brecciating the magma. Based on our interpretations, the abundance of these features throughout the rhyolite (~80% of the exposed volume) would have effectively degassed the magma body, and as a result it remained below the pressure threshold required to trigger an eruption. The documentation of fracture bands in other intrusions and lavas with different compositions and crystallinities leads us to propose that this process takes place to some degree in all silicic magmas undergoing shear.

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Session 15

Structural geology and tectonics: Open session

Session Chair:
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Structures and magmatism associated to a triple junction in Traill Ø, East Greenland

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The Late Eocene–Oligocene post-breakup magmatism of the North Atlantic Igneous Province (NAIP) (Fig. 1), is represented by sub-volcanic intrusions associated with a NE-SW oriented magmatic lineament, the Werner Bjerge Rift (WBR), extending for more than 100 Km from eastern Traill Ø to Werner Bjerge in East Greenland (Fig. 1). In the same region, strike-slip post-breakup faulting is documented along N-S trending faults belonging to the Loch Fyne Fault Zone (LFFZ), extending more than 300 Km from Traill Ø up to the north. The NW-SE trending, East Jan Mayen Fracture Zone (EJMFZ) offshore East Greenland, represented the northern boundary of the Jan Mayen Micro Continent during the Eocene–Oligocene, and extended westward, toward Traill Ø (Fig. 1). The LFFZ together with the WBR and the EJMFZ, were active during the Late Eocene–Oligocene and intersected at a 120º angle in eastern Traill Ø, typical for triple junctions. These trends are interpreted to represent the tectonic elements of a Fault-Fault-Ridge triple junction in East Greenland reactivating old structures inherited from the Caledonian Orogeny and from multi-stage rifting episodes that characterized the East Greenland basin system. Age and geochemistry of the magmatism in the WBR suggest that the Traill Ø triple junction was generated by new plate tectonics configuration and not by a mantle plume. The alkaline magmatism of the WBR initiated at Kap Parry while left-lateral strike slip faults were active and interconnected along the N-S trending LFFZ. The oceanic extension was oriented NW-SE and the EJMFZ, representing the northern crustal boundary of the Jan Mayen Micro Continent, accommodated left-lateral movement associated to the spreading along the Mohns ridge. The same strike-slip movement along the EJMFZ was responsible for tectonic inversion in the Vøring basin. Several triple junctions in the Northeast Atlantic Ocean were interpreted using geophysical data while, this paper, shows the onshore geological evidence of deformation and magmatism associated to a triple junction, highlighting the importance of inherited structures during breakup and their response to stress variations during plate tectonic modifications.

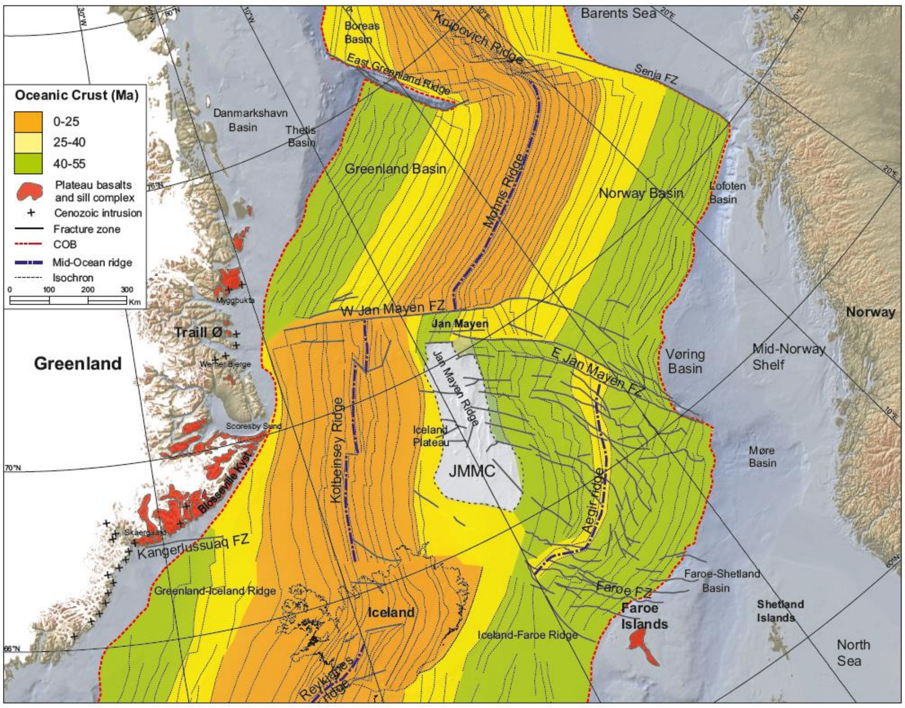

Figure 1. Northeast Atlantic Ocean magnetic anomalies, fracture zones, and gridded age of oceanic crust, showing onshore basalts and magmatic intrusions associated with the NAIP. JMMC-Jan Mayen Micro Continent.

Assessment of the porosity and density structure of complex impact structures based on their strain distribution

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Data from three impact structures in crystalline rocks were collected for the study:

- The complex *Ries* impact structure in south-west Germany with data from a 1.2 km deep drill hole in the mega breccia ring basin and its crystalline basement compiled in Pohl et al. (1977).

- The *Puchezh Katunki* complex impact structure in western Russia with data from an over 5 km deep drill hole in crystalline rocks in its central uplift published in Masaitis and Pevzner (1999).

- The *numerically modelled complex crater* in Collins et al. (2004) where the strain distribution is presented as accumulated strain, or bulk strain. The strain model was calculated for a homogenous target with granite properties. Three strain regimes can be seen – A far reaching belt of dispersed low strain (A), a concentric low strain belt (B), an upper high-strain hyperbolic contained volume (C) and a deep hemispheric contained volume (D) of outward and downward decreasing strain.

The strain distribution with depth is in a subsequent step combined with the porosity – depth distribution as measured in the deep drill holes of the Ries and Puchezh Katunki impact structures. The strain distribution of the model crater can then, via the porosity distribution, be translated to the density distribution related to the impact structure. For comparison of data from different sized impact structures, depth values are normalised by division with the respective transient crater diameter. This in turn has to be estimated from presently measurable parameters that can be related to a common surface: The pre-impact surface of the model crater providing the strain distribution and the reconstruction of the pre-impact surface of the two complex impact structures that are the data source for porosity.

The obtained density distribution differs considerably from conventional thinking as it was found that an upper common density region is characteristic for the whole collapsed crater interior, including the mega breccia ring basin and the central uplift. The high strain region contributes 90 % of the gravity anomaly of –12 mGal in the Dellen impact structure, for which the new approach was tested. At 80 s after impact the formed melt is still liquid; in a final crater the melt and the fall back suevite have to be modelled separately (grey shaded top part of the strain model). The concept of accumulated strain in a hemispherical volume can be applied for simple craters, where the high strain region of the collapse phase not occurs, to account for a radially downward and outward decreasing remaining porosity and the associated density contrast.

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The discovery of a regional scale strike-slip fault in northern Sweden through re-evaluation of potential field data

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The national airborne magnetic datasets acquired by the geological surveys in the Nordic countries constitute very important data sources for regional scale structural mapping. These data are of particular importance for structural interpretations due to low degree of bedrock exposures in many areas. Despite most of these data have been publicly available for decades, new data analyses reveal important information of hitherto unrecognized large-scale structures in the Fennoscandian Shield. This is exemplified by a recent discovery of the regional scale Norrbotten brittle strike-slip fault in northern Sweden with a length >250 km and apparent offset of 51.2 km. The fault extends northwards through Finland and possibly to the Caledonian Front in northern Norway. The discovery implies that geological maps need to be revised.

To validate and support the hypothesis of the fault, several other data types are included. They are:

- Multi-variate classification of magnetic gradient tensor data
- The Bouguer gravity field and derived gradient data
- Inspection of airborne gamma-ray and VLF data
- Geological field observations and structural measurements
- Early Holocene faulting and present-day seismicity along the fault
- A joint three-dimensional classification of crustal scale magnetic susceptibility, density, and electrical conductivity models
- Partly continuity of geological units across the fault after application of shift to mapped geological units.

Identification of faults and in particular estimation of fault displacements is in the ideal case based on a visual matching of well-defined markers. A simple restoration of the anomaly pattern on one side of the fault provides the estimate of displacement provided that a match between one or preferentially several anomalies is obtained. The anomalies are in this manner used as a simple barcode in the matching procedure. An initial interpretation based on pattern recognition was followed by visual inspection of short wavelength anomalies to quantify the displacement. An apparent horizontal displacement of 51.2 km is proposed for the discovered fault. In Sweden, the fault strikes N-S from Karesuando at the Swedish-Finnish border in the north to the Archaean-Proterozoic boundary marked by the Luleå-Jokkmokk Zone (c.f. Mellqvist *et al*., 1999).

The strikingly linear and straight character of the proposed fault implies a timing later than mapped ductile deformation events dated to 1.80–1.78 Ga (Bauer et al. 2022). We tentatively suggest the timing to coincide with the post-orogenic collapse at the latest stages of the Svecokarelian orogeny (approx. 1.76–1.70 Ga; Korja et al., 2006).

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The significance of initial fabric during deformation

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The initial fabric of sedimentary rocks is influenced by the mode of deposition of the sediments. In this contribution, we study the impact of mode of deposition on deformation using analogue modelling. It is a common practice to prepare sand-box models by sieving the sand or pouring with scraping individual sand layers. In this study, we compare the two methods by building models with mixed magnetite with quartz sand and measuring the anisotropy of magnetic susceptibility (AMS) on small samples taken from the two models. Preparing layers by sieving creates an initial fabric (S_0) that is similar to a sedimentary (aggradation/fall out) fabric in nature. In contrast, preparing layers by pouring and scraping produces an aligned initial fabric with oriented grains parallel to the scraping direction (Fig. 1). Such aligned fabric can be compared to sediments deposited in fluvial environments such as rivers, turbidites or eolian dunes.

During shortening of both types of models (Fig. 1), simulating a fold-and-thrust belt, the grains were aligned mainly in association with the evolving structures (folds and shear zones). However, a pervasive/penetrative fabric developed throughout the compacted part of the foreland away from individual structures (Fig. 1b). The orientation and magnitude of this penetrative fabric (S_1) differs throughout the model and depends on the initial fabric (S_0) and the amount of shortening. Nevertheless, the intensity and orientation of the penetrative fabrics developed in a "sieved" versus "scrapped" model are roughly comparable (Schöfisch, 2023).

We conclude that applying magnetic fabric analyses to sand-box-models provides insights into 1) penetrative (invisible) strain in contractional domains, and 2) influence of the initial anisotropy on any superimposed tectonic fabric (Schöfisch, 2023).

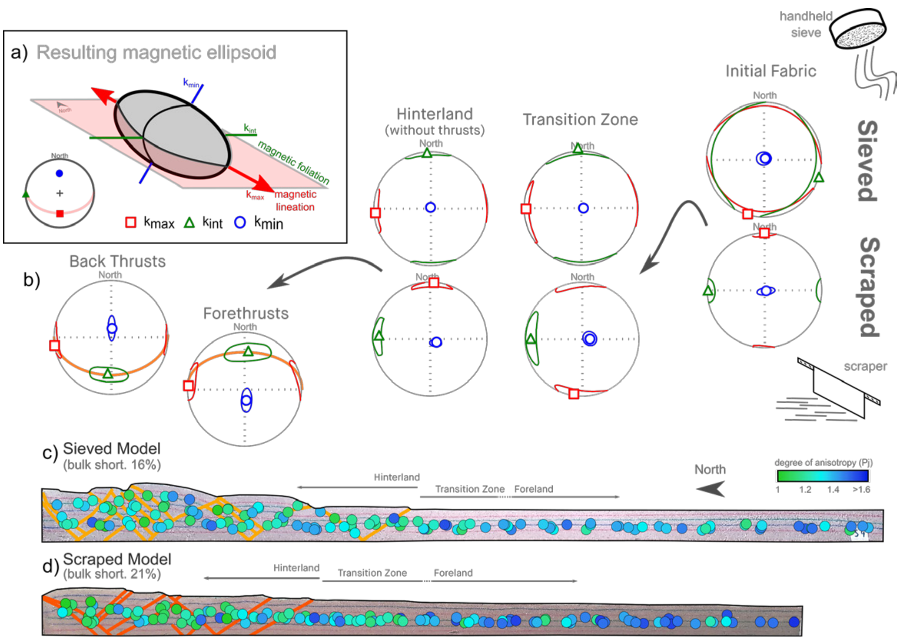

Fig. 1: a) The resulting magnetic ellipsoid with principal axes from magnetic fabric measurements of a sample. b) Principal axes realignment for different areas within the models that are associated with increasing deformation. c) and d) Distribution of the degree of anisotropy ($P = k_{max}/k_{min}$) for each model.

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Early Paleogene rift-to-drift transition at the NE Atlantic – new insights from rift propagation and paired extension-compression

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The breakup at the northeast Atlantic at ca. 54 Ma has long been considered a direct result of the Paleocene continental rifting (Faleide et al. 2008, Gernigon et al. 2020). This notion, however, poses a question on how the northeastern tip of the rift accommodated tensile strain prior to the formation of the sheared margin (Senja Fracture Zone, or SFZ). Our recent study (Wong et al. 2023) indicates that the Paleocene continental rift propagated northeastward – a scenario does not require a long-living, regional-scale transform fault between Greenland and Eurasia.

Our detailed reconstruction of the tectono-magmatic elements of the Paleocene rift shows trends of propagation comparable to analogue model results (Schmid et al. 2022) – along-axis development of magmatism, and migration of tectonic faulting inward and towards its tip (a horst-and-graben system, or H&G) at the SW Barents Sea. Being truncated by the SFZ, the H&G is of pre-breakup origin and is abutted by a coeval V-shaped anticline (VA) bounding the Tromsø Basin. Together, the H&G and the VA represent a paired extension-compression (PEC) of rotational kinematics (Hey et al. 1980, Martin 1984) and signify forward projection of the rift's rotational driving force during the termination of the propagation.

Overall, the early Paleogene evolution of the NE Atlantic can be summarized by a 3-stage model. During rift initiation in early Paleocene (Stage 1), boundary faults started to develop along the Greenland-Norway shelves while magmatism dominated the Faroe-Shetland region (ca. 63 - 59 Ma). In late Paleocene and early Eocene (Stage 2; ca. 58 - 55 Ma), the rift propagated northeastward and was eventually stalled by an elevated mafic-ultramafic body at the Barents shelf (Fichler and Pastore 2022). With its pivot of rotation fixed, the rift's rotational kinematics started to create PEC structures (the H&G and the VA) and dissipated the along-strike force component during this process. The sudden domination of the axis-perpendicular component then drove orthogonal extension, which promoted breakup and the development of sheared margin (Stage 3, ca. 54 Ma), as exemplified by the strong parallelism of the C24n.3n chrons at the two ends of the Norwegian-Greenland Sea (Gaina et al. 2017).

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Session 16
Petrology: Open session

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Metamorphic zoning in plagioclase from the Caledonides recording transient events

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In recent years, special types of chemical zonation in plagioclase have been observed in lower crustal rocks. Two microstructural types can be differentiated: 1) Anorthite-rich plagioclase arranged in a network pattern in intact, more albite-rich plagioclase, which has been termed "complex feldspar" by Mukai et al. (2014). 2) Polygonal plagioclase with asymmetric rims of higher anorthite content. Because an increase in anorthite content is the opposite of what would be expected from fractional crystallisation, Soda et al. (2020) termed this "reversely zoned" plagioclase. What is striking is that the original intermediate plagioclase composition, where it is preserved, is split into two new ones. Versions of these plagioclase types have been described from the Bergen Arcs in Western Norway (Kaatz et al., 2022; Mukai et al. 2014, Petley-Ragan et al. 2021) and Vesterålen in Northern Norway (Soda et al., 2020), both part of the Scandinavian Caledonides. In all cases, the development of the plagioclase seems connected to deformation and fluids. However, differences in secondary phases and grain morphologies point to slightly different origins and/or developments. Two main mechanisms for their formation have been suggested: exsolution and grain boundary migration (Mukai et al. 2014, Petley-Ragan et al. 2021) and two-stage metamorphism during which intermediate plagioclase reacts to Ab-rich plagioclase and secondary phases (Kaatz et al. 2022), which are later backreacted to An-rich plagioclase (Soda et al. 2020).

Here, we investigate early stages of such plagioclase microstructures in detail, using examples of lower crustal rocks from the southern part of Lofoten. Here, the plagioclase is almost free of inclusions, except for local concentrations of aluminosilicate needles. Microstructurally, there are gradual transitions from needle-type in the host rock to polygonal type in cm-scale shear zones. Using microstructural and compositional data (acquired by electron microprobe analysis) combined with local equilibrium thermodynamic modelling, we show that two-stage metamorphism under changing pressure conditions is a plausible explanation for the plagioclase zonation, and that such zonations can be the only remaining records of metamorphic events. With data from transmission electron microscopy and electron backscatter diffraction, we further elucidate the deformation conditions and the microstructural evolution of the plagioclase. Initial reaction was probably focused at high-stress areas in a deforming rock. The polygonal microstructures likely developed by grain boundary migration induced by gradients in both dislocation density and chemistry.

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Neoarchean synkinematic metamorphic peak in the Isua supracrustal belt (West Greenland)

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The Isua supracrustal belt in West Greenland represents some of the best preserved Eoarchean geology worldwide, and as such, the area is critical for investigating the early Earth. We present petrological data and seven Lu-Hf-garnet-amphibole-whole-rock ages obtained from a single garnet-hornblende-mica-schist sample from the Isua supracrustal belt. Garnets grew during prograde metamorphism towards regional amphibolite-facies peak conditions and a mylonitic folitation formed during and after garnet growth. Garnet crystals show typical prograde zoning with no visible traces of a relict garnet generation. They do show various degrees of retrogression. While some crystals are perfectly euhedral with only minor chemical alteration along cracks, others are elongated in the foliation and either grew in this shape or were deformed. Six garnet splits were separated from crushed single crystals and one from the crushed bulk sample. Individual 3-point garnet-hornblende-whole-rock ages scatter between 2.603 ± 0.018 Ga and 2432 ± 0.059 Ga for single garnets. The garnet split from the bulk sample defines an age of 2.463 ± 0.031 Ga, the data point farthest from the regression line for all data points (2.551 ± 0.074 Ga, MSWD = 25). We interpret this data to indicate partial retrogression of a Neoarchean garnet population not significantly older than the oldest obtained three-point age. Well-preserved garnet zoning, regional peak temperatures well below the closing temperature of the Lu-Hf system, and the small scatter of Lu-Hf ages preclude an interpretation of the observed metamorphism and deformation as being Eoarchean in age.

Compositional controls on the rinkite-(Ce)-nacareniobsite-(Ce) solid solution series

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The minerals rinkite-(Ce) ($(Ca_3Ce)Na(NaCa)Ti(Si_2O_7)_2(OF)F_2$) and nacareniobsite-(Ce) ($Ca_3(Ce)Na_3Nb(Si_2O_7)_2(OF)F_2$) are isostructural (Camara et al., 2011; Sokolova & Hawthorne, 2008) and form a solid solution series (Vivalva et al., 2013). As intermediate compositions are produced by substitution of Nb for (Ti+Zr), we report compositions as the rin#, which is calculated as (Ti+Zr)/(Ti+Zr+Nb) (in apfu/apfu). In the Ilímaussaq Complex (Gardar Province, South Greenland), most of the solid solution series is represented. On the intrusion-wide scale, high rin# compositions are represented in the earliest pulaskites (rin#$_{0.88\text{-}0.90}$) and kakortokites (rin#$_{0.63\text{-}0.75}$) and become increasingly low in rin# as crystallization progresses, such that late lujavrite contain dominantly nacareniobsite-(Ce) (rin#$_{0.18\text{-}0.35}$; Rønsbo et al., 2014). In our new data set, three lujavrite samples contain nacareniobsite-(Ce) (rin#$_{0.28\text{-}0.42}$) and three naujaite samples contain rinkite-(Ce) without zonation (rin#$_{0.37\text{-}0.71}$). In addition, two naujaite samples have homogenous rinkite-(Ce) cores (rin#$_{0.60\text{-}0.67}$) with relatively thin overgrowths of nacareniobsite-(Ce) (rin#$_{0.23\text{-}0.34}$). Finally, one naujaite sample shows complex zonations of at least three types: (1) The most abundant type of zonation yields a rounded core of intermediate composition (rin#$_{0.3\text{-}0.6}$) with multiple inclusions of a eudialyte-group mineral and pectolite. The cores are mantled by inclusion-free rinkite-(Ce) (rin#$_{0.7}$). Finally, grains are overgrown by a thin rim of nacareniobsite-(Ce) (rin#$_{0.2\text{-}0.4}$) which is genetically related to small, late-stage nacareniobsite-(Ce) needles. (2) In another type, the rinkite-(Ce) mantles are themselves zoned and yield two distinct compositions. (3) Finally, some grains show extremely complex patchy zoning patterns of irregularly shaped areas of distinct compositions.

We interpret the general trend of decreasing rin# in rinkite-(Ce)/nacareniobsite-(Ce) in the Ilímaussaq Complex as a consequence of progressively decreasing rin# in the magma. Similarly, we interpret thin overgrowth of nacareniobsite-(Ce) on rinkite-(Ce) grains in naujaite as reflecting the progressive magma evolution in trapped interstitial melt. The zoning pattern of intermediate-rin# cores in high-rin# mantles in naujaite is related to the co-crystallizing eudialyte-group minerals with relatively Nb-rich and Ti-poor cores, relative to rims. We suggest that the initial crystallization of relatively Nb-rich rinkite-(Ce) could be caused by local depletion of TiO_2 and ZrO_2 in a diffusional boundary layer. This stage is then followed by partial resorption of the core and overgrowth of Ti-rich rinkite-(Ce). The study highlights the complex distribution of economically important elements such as REE, Y, Nb, Zr and Ta, and the importance of understanding the petrogenesis of their host rocks.

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Session 17
Mineralogy – new insights and future opportunities

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Swedish ericssonite-group minerals

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The ericssonite group of minerals (EGM; Sokolova et al. 2018) includes ericssonite and "orthoericssonite", $BaMn_2(Fe^{3+}O)[Si_2O_7](OH)$ (Moore 1971), ferroericssonite, ideally $BaFe^{2+}{}_2Fe^{3+}(Si_2O_7)O(OH)$ (Kampf et al. 2011) and zinkgruvanite $Ba_4Mn^{2+}{}_4Fe^{3+}{}_2(Si_2O_7)_2(SO_4)_2O_2(OH)_2$ (Cámara et al. 2021). These are Fe^{3+} disilicates, which are closely related to seidozerite supergroup minerals (SGM; Sokolova & Cámara, 2017). The later encompasses about 50 mineral species and polytypes, all characterized by TS (titanium silicate) blocks (or HOH blocks) in the structural framework. EGM have also an HOH block as the main structural unit, with Mn^{2+} and Fe^{2+} being the dominant cations in the O (octahedral) sheet of the HOH block and Fe^{3+} being the dominant cation at the [5]-coordinated sites along with Si_2O_7 groups of the H (heteropolyhedral) sheets. SGM are divided into four groups based on the Ti content and the topology and stereochemistry of the TS block: in the rinkite, bafertisite, lamprophyllite, and murmanite groups, Ti (+ Nb + Zr + Fe3+ + Mg + Mn) = 1, 2, 3, and 4 apfu, respectively. The presence of HOH blocks in both the EGM and the SGM would lead to place the in the same supergroup. In fact, Moore (1971) described ericssonite and "orthoericssonite" (now ericssonite-2*O*) as "minerals of the lamprophyllite group". In addition, the two Ti disilicates yoshimuraite, $Ba_4Mn_4Ti_2(Si_2O_7)_2(PO_4)_2O_2(OH)_2$ (a bafertisite-group mineral; McDonald et al 2000) and innelite-1*A* $Ba_4(Na_2M^{2+}Ti)Ti_2(Si_2O_7)_2[(SO_4)(PO_4)]O_3(OH)$ (with M^{2+} = Mn, Fe^{2+}, Mg, Ca; a lamprophyllite-group mineral; Sokolova & Cámara, 2017) share in common with zinkgruvanite the insertion of SO_4/PO_4 groups between two HOH blocks, i.e. at the I block. Yet, some structural and chemical differences are required to classify them into a separate group: all minerals of the bafertisite and lamprophyllite groups have Ti (+Nb) in the H sheets; in the bafertisite group, the O sheet is composed of Mn or Fe^{2+} octahedra; in the lamprophyllite group, the composition of the O sheet is generally Na_3Ti apfu. In ericssonite, ferroericssonite and zinkgruvanite, the O sheet is composed of Mn or Fe^{2+} octahedra, as in the bafertisite-group minerals, but the topology of the HOH block is the same as in the lamprophyllite-group minerals. Thus, ericssonite and ferroericssonite do not contain the combination of features that is characteristic of either the bafertisite group or the lamprophyllite group. Ericssonite, ericssonite-2*O* and zinkgruvanite are very rare and were first described from Swedish localities (Långban in Filipstad, Värmland County, and Åmmeberg, in the municipality of Askersund, Örebro County). Ericssonite have been also described in the Hijikuzu mine, in the Iwate prefecture (Japan), whereas ferroericssonite have been described so far only in Eastern Fresno County, California (U.S.A). Many of the members of the seidozerite supergroup come from the region of the Kola peninsula. The similarities and differences in topology between these two groups of minerals will be discussed.

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New insight into jarlite and jørgensenite, two rare Sr-fluorides from Ivigtut, South Greenland

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The Ivigtut cryolite deposit in South Greenland is known for its wealth of rare fluoride minerals, among which the rarest are all Sr-minerals. Five of these (acuminite, bøggildite, bøggvadite, jørgensenite and stenonite) have never been found outside Ivigtut.

Jarlite, $Na_2(Sr,Na)_{14}(Mg,\square)_2Al_{12}F_{64}(OH)_4$, was first described as a new species from Ivigtut by Bøgvad (1933) and its structure solved by Hawthorne (1983). The element distribution in the structure was found to be Na in the fully occupied octahedrally coordinated, *Na1*-site, and three fully occupied Sr-sites with varying coordinations. The partly occupied octahedrally coordinated *Mg*-site is corner-sharing with the two adjacent *Na1*-sites. The partial occupancy of the *Mg*-site is required to maintain charge balance. Jørgensenite is isostructural with jarlite, but the *Mg*-site is now fully occupied by sodium creating a second sodium site (*Na2*) (Hawthorne & Burns 1997). There are only two structure refinements of these minerals and there are several unanswered questions including, 1) is the *Mg*-site in jarlite is really partly vacant 2) is Ba randomly distributed between the three strontium sites or ordered and 3) what is the maximum Ba content in these minerals. To answer some of these questions, a systematic study was carried out on jarlite-group minerals from Ivigtut. To explore possible chemical and structural variations within these species, samples from different paragenesis were selected for chemical and full crystal structure analyses.

A series of full crystal structure analyses were carried out and showed that *Mg*-site in jarlite is most likely full as mixed between Mg and Na. The resulting surplus charge is compensated by the mixed substitution of K and Na into the Sr-sites. This study revealed that jørgensenite is more abundant than currently believed as only one out of eight structure solutions correspond to jarlite. The structure refinements also revealed that there is a systematic increase in unit cell volume as the amount of both Na and Ba increased. In fact, some samples have such levels of Ba that preferentially enters the *Sr2*-site, that this site becomes dominated by barium rather than strontium, and hence should be considered a new species. This requires the establishing of a formal nomenclature, which should be called the Jarlite-Group. We will present new data on jarlite group minerals and discuss the crystal-chemical features of the species and the establishment of a Jarlite-Group.

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Magmatic or hydrothermal epidote?

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Epidote is a common mineral in the Rolvsnes granodiorite and associated granitoids in the northern parts of Bølmo island, W Norway. It is useful as an indicator of the extent of early hydrothermal alteration, as the green discoloration of the granodiorite is largely connected to epidote replacing calcic amphibole and biotite and sericitization plagioclase. Macroscopically, epidote occurs as veins cutting all rock types, a pervasive alteration assemblage of the granodiorite, and in miarolitic cavities in granites. Microscopically, epidote occurs together with albite and muscovite as replacement of calcic plagioclase cores, weakly zoned overgrowths on euhedral titanite and allanite, patchily zoned with small titanite inclusions, epidote-quartz symplectites commonly associated biotite, and euhedral inclusions in plagioclase and K-feldspar phenocrysts. With the exception of one grain with >20 wt% MnO, the major element composition varies from endmember epidote to clinozoisite, mostly with Fe/(Fe+Al) ratios between 0.25 and 0.35. Clinozoisite is mostly observed in zoned alteration products of plagioclase. Only a weak correlation between host rock and major element chemistry is observed, with epidote in granites being slightly more Fe-rich than in granodiorite. The minor element vary distinctly with microtextures. Epidote from miarolitic cavities may have >5wt% SrO, and the euhedral inclusions in plagioclase have up to 2 wt% MnO. One epidote grain from the granodiorite has an REE-rich core, an REE-poor overgrowth with sharp contacts towards K-feldspar, and a subsequent zone of epidote-quartz symplectite. The two inner growth zones are comparable to the reports of magmatic epidote from the nearby Drøni monzogranite (Torgersen & Jansen 1987). The occurrence of magmatic epidote is compatible with the pressure estimates from Al-in-hornblende barometry at 400-450 MPa and moderate to high *f*O2. However, the textural evidence indicates that if epidote crystallized from a melt, it is late in the crystallization sequence. The amount of epidote in the samples correlate with the extent of breakdown of amphibole and biotite, and quartz inclusions in biotite resulting from breakdown of amphibole crosscut the border to epidote, indicating that the vast majority of epidote in the samples is the result of hydrothermal replacement of primary minerals.

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Super- and subsolidus processes in the Rolvsnes granodiorite recorded by titanite

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Titanite has a range of uses as a geological tracer mineral. It can incorporate significant amounts of Nb, Y, and REE into the crystal structure, has a (near-)magmatic closure temperature of the U-Pb isotopic system, a defined relationship with Zr content and temperature, and distinct alteration products, making it a potential geochronothermometer in addition to an indicator of melt fractionation, metamorphic recrystallization, and fluid infiltration. In the Rolvsnes Granodiorite and associated granitoids at Bømlo Island, Western Norway, titanite is observed as euhedral crystals in the matrix and K-feldspar phenocrysts, as inclusions in epidote, and overgrowths of Fe-Ti-oxides. Preliminary U-Pb ages of the granodiorite around 460 Ma are within the uncertainty of reported zircon ages from 463-467 Ma (Scheiber et al. 2016). Zr-in-titanite thermometry (Hayden et al. 2008) using the calculated pressure from Al-in-hornblende of 400 Ma, gives temperatures from 710 to 740° C, similar to the Zr saturation temperatures (Crisp & Berry 2022) of ~740-750° C from the same samples calculated using the same pressure and $X_{H2O} = 0.05$.

Titanite found as inclusions in epidote is likely crystallized due to Ti excess during replacement of amphibole or biotite by epidote. Titanite inclusions are characterized by low Mn and Nb, <0.05 and <0.015 wt% oxides, respectively, compared to typical levels of ~0.15 wt% MnO and <0.5 wt% Nb_2O_5 in the granodiorite. Titanite in a titanite-chlorite-epidote-ilmenite cluster in a granite sample is strongly zoned and host up to 5 wt% Nb_2O_5 and up to 1 wt%. Titanite partly replaces ilmenite, and the zoning may be the result of redistribution of Y and Nb from ilmenite. The relationship between the cluster and the granite is unclear, but it may be an altered mafic xenolith.

In all samples with observable carbonate veins, titanite is altered to rutile and quartz +/- calcite, and in samples exposed to significant low temperature alteration, smectite is the main alteration product, in addition to TiO_2 mineral(s) and quartz. This shows that titanite not only records the high temperature crystallization, but is also useful to identify low temperature fluid influx.

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The high temperature, low-pressure phase transitions of crystalline silica

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The transitions of the high temperature, low-pressure phases of silica are based on the work by Fenner (1913). When determining the inversion point between quartz and tridymite at 870°C±10°C Fenner used a flux, sodium tungstate (Na_2WO_4) to accelerate the rate of transformation (Fenner, 1913). The incorporation of sodium tungstate has led to much debate on the validity of tridymite as a pure silica phase. Several scientists have shown the stabilization of tridymite through phase transitions requiring the presence of either impurities or a mineralizer (Flörke 1956, Holmquist 1961, Stevens et al. 1997). Despite this, the phase relations, and the temperatures for the inversions between quartz, tridymite, and cristobalite by Fenner remain the most cited in the literature (Heaney et al. 1994, Stevens et al. 1997).

The understanding of the phase relations of the crystalline high temperature, low-pressure SiO_2 phases and the effects of impurities are of most relevance to industrial processes such as high-purity quartz or silicon production. This research aims to increase the understanding by investigating the effects of impurities and particle size on the high temperature, low-pressure phase transitions of crystalline silica. This has been achieved by heating three different powdered quartz materials with varying purity and PSD in the stability range of tridymite at 900°C to 1500°C with holding times of one, three, and eight hours. The Internal Standard method as explained in Madsen et al. (2011) has been used to assess the role of amorphous silica on the phase transitions. Qualitative phase analysis with X-ray diffraction and Differential Thermal Analysis has shown no stabilization of tridymite in either quartz materials with a purity of 99.3, and 99.9%. The quartz materials transition directly from quartz to cristobalite through an intermediate amorphous phase. The temperature of the transition is found to be 300°C lower for a quartz material with 99.3% purity, compared to the quartz material with 99.9% purity. The finer particle materials display a full conversion to cristobalite at a higher rate than the coarser particle materials.

It is concluded that tridymite cannot form through high temperature phase transformations in crystalline silica according to the silica phase diagram without the presence of a sufficient amount of large cations. Further, the temperature and the rate of the phase transition between quartz and cristobalite are dependent on the purity and the particle size of the silica.

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The minium mineral group

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Compounds with the general formula MX_2O_4 (X = ion with a lone electron pair; As^{3+}, Sb^{3+}, Bi^{3+} or Pb^{2+}), with tetragonal crystal symmetry, are intensely studied by material scientists because of potential functional properties, e.g., as ferroelectrics (Bennet & Rabe 2012). The principal space group is $P4_2/mbc$, with unit-cell parameters a = 8–9 Å and c ~ 6 Å. In the crystal structure (e.g., Zemann 1951), the 2 to 4-valent M atoms are coordinated by 6 O atoms in distorted (axially elongated) octahedra, which connect via trans-edges to form rutile-like ribbons along the c-axis. The X atoms form trigonal XO_3 pyramids, which are linked via corners to form zig-zag $(XO_2)_n$ chains. The lone-pair electrons of the X atoms protrude into tunnels created by four neighboring parallel chains.

Minerals belonging to this type are trippkeite ($Cu^{2+}As^{3+}{}_2O_4$) and schafarzikite ($Fe^{2+}Sb^{3+}{}_2O_4$), that were previously included in the “trippkeite group”. Minium, $Pb^{4+}Pb^{2+}{}_2O_4$, is an isostructural mineral, and since the compound is known from antiquity (mentioned by Pliny the Elder and others), it deserves priority as a group name. The minium group was recently established by an IMA decision (23-C). Kusachiite, $Cu^{2+}Bi^{3+}{}_2O_4$, used to belong to the old “trippkeite group”, but is not strictly isostructural: the Cu^{2+} ion has 4-fold (square planar) coordination to O, and Bi occurs in BiO_4 polyhedra (Boivin et al. 1976). Apuanite, $(Fe^{2+}Fe^{3+}{}_2)(Fe^{3+}{}_2Sb^{3+}{}_4)O_{12}S$ and versiliaite, $(Fe^{2+}{}_2Fe^{3+}{}_2)(Fe^{3+}{}_2Sb^{3+}{}_6)O_{16}S$ (Mellini & Merlino, 1979) are direct structural derivatives but not counted to the minium group because of mixed anion compositions (introduction of extra S atoms to balance Fe^{3+} in the octahedral ribbons).

In the course of examining undescribed fissure minerals from the Långban Mn-Fe deposit, in the collections of the Swedish Museum of Natural History, two new members of the group have been discovered: igelströmite ($Fe^{3+}[Sb^{3+}Pb^{2+}]O_4$; IMA2021-035), derived from schafarzikite via the coupled heterovalent substitution $Fe^{2+} + Sb^{3+} \rightarrow Fe^{3+} + Pb^{2+}$; and manganoschafarzikite ($Mn^{2+}Sb^{3+}{}_2O_4$; IMA2022-129), the Mn analogue of schafarzikite. They occur on open fractures in fine-grained hematite ore, together with calcite, barite, nadorite, serpentine, mimetite, rhodochrosite and other minerals. The late-stage mineral formation postdates brittle deformation of the ore bodies, at relatively low temperatures (< 200°C) and close to atmospheric pressure conditions. Chemical, structural and spectroscopic data have been collected for the new minerals and will be presented.

The abundance of synthetic structural equivalents to the group suggests that additional natural members could exist. For new species, it is recommended to adhere to the existing minerals for root names, based on the X atom content, and add prefixes for elements substituting at M sites. As an example, isostructural $CoAs_2O_4$ would be named “cobaltotrippkeite”.

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Untold stories of the Veramin mesosiderite

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The rare stony-iron meteorites known as mesosiderites have an enigmatic origin. Only seven witnessed falls have been reported to date. The Veramin meteorite (mass c. 52 kg; Ward 1901) that according to tradition fell in Persia in 1880 A.D. in the vicinity of Veramin (Varamin, Tehran Province) belongs to this category. By using the historical method and scrutinizing the scientific literature and other written sources, we have clarified some inconsistencies with respect to details of the fall. A mineralogical examination of a meteorite sample was also carried out.

The primary source for information about the meteorite fall and samples subsequently distributed to foreigners was the Shah of Persia and his courtiers. The meteorite got its current official name in writing, "Veramin", by Brezina (1881). This designation has no support in Iranian sources. A key document is a rediscovered cardboard label that belongs to the main mass of the meteorite, preserved in the Golestan Palace, Tehran. It was the subject of perusal by Westerners like Sven Hedin and Henry Augustus Ward before 1900, but not interpreted correctly and later fell into oblivion. The place of the event indicated is Booghin (a.k.a. Buqin, lat. 35°35'N, long. 50°38'E), a small area in the historical Zarand district, located a linear distance of c. 100 km NW from Varamin. Members of the nomadic Shahsevan-e Baghdadi tribal confederacy, who had winter settlements in the neighbourhood, are mentioned as eyewitnesses of the fall. The cardboard text is, however, in error as regards the timing, translated from the Hijri lunar calendar as April 18, 1881. In accordance with other local sources and international publications, the correct year is 1880 A.D., coinciding with the Turkic zodiac year, *luu yil*, mentioned. The period February to April that year is most probable, in agreement with the yearly movement of pastoral tribesmen before May to summer pastures far away from the impact area.

Texture and mineral composition of a verified meteorite sample, from the collections of the Swedish Museum of Natural History, are in agreement with previous descriptions (e.g., Powell, 1971). Main components are iron (kamacite), enstatite, anorthite and forsterite. The occurrence of chromite, troilite and tetrataenite in the specimen is also confirmed. Grains of keplerite [$Ca_9(Ca_{0.5}\square_{0.5})Mg(PO_4)_7$] to 0.5 mm, identified by of microchemical analysis and Raman spectroscopy, occur contiguous to kamacite and anorthite. There is evidence that mesosiderites contain intermediate merrillite–keplerite members, where some variation (due to Na loss) is ascribed to the degree of reheating. Infrared spectroscopy measurements of polished crystal fragments of enstatite in the region 6,000–2,000 cm^{-1} showed no bands related to a hydroxyl component. Annealing experiments under H_2 atmosphere were conducted at 100 kPa and 700°C, which however failed to produce a hydrous component (detection limit ~5 ppm H_2O). It can be concluded that the environment of formation was essentially "dry", analogous to what has been found for pyroxene in the HED (Vesta clan) meteorites. On weathered surfaces thin encrustations of eskolaite occur. The only potential source of Cr in the meteorite is chromite, which however, is very resistant to weathering. It is more likely that the sample is affected by treatment with a Cr-rich compound, e.g., Cr_2O_3 used as an abrasive.

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On the ore mineralogy of the Bi-Te-rich Enåsen Au-Cu deposit, central Sweden

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A recent SGU project focused on the Enåsen deposit (Bergman et al. 2022) in northern Gävleborg county, central Sweden, has included detailed studies of its ore assemblages. Some results were recently presented by Jonsson & Pieslinger (2022), as we interpreted abundant, complex, symplectitic sulphide-sulphosalt-telluride intergrowths and associated ore minerals to represent unsuccessfully quenched ore melts that had formed through metamorphogenic (partial?) melting of the pre-existing (meta-)epithermal ore. Notably, the melting temperatures of ore mineral assemblages can be decreased through the presence of so-called low-melting-point chalcophile elements, i.e., As, Au, Bi, Hg, Sb, Se, Sn, Tl, Te, Cu and Pb (e.g., Frost et al. 2002, Mavrogenes et al. 2013), of which several are abundant in the Enåsen ore. Surprisingly, several ore minerals reported by Nysten & Annersten (1984) have not been observed at all or only sparingly so during this study (e.g., willyamite, löllingite, cobaltite and Sb-tellurides, see below). We take this as an indication of a broad mineralogical zoning in the deposit. In the studied sulphide-dominated assemblages, chalcopyrite is predominant, but pyrrhotite can dominate locally and pyrite is variably abundant together with (lesser) sphalerite, the latter characteristically with small-scale “chalcopyrite disease”. Bornite is less common, more so idaite (c. Cu_5FeS_6), while digenite and covellite may replace earlier Cu sulphides. Arsenopyrite, characteristically euhedral, occur in only a few studied samples, as does molybdenite. Of sulphosalts, tennantite-tetrahedrite (mainly As-dominated, locally Ag- and/or Te-bearing) minerals are most abundant, mainly as anhedral aggregates or inclusions, but also in intergrowths with tellurides, locally native gold, and other ore minerals. Stannite (Cu_2FeSnS_4) and mawsonite ($Cu_6Fe_2SnS_8$) typically occur as anhedral aggregates, sometimes together, associated with bornite, while anhedral bournonite ($PbSbCuS_3$) has been noted. Rare cobaltite (CoAsS) occurs as minute crystals. The most common tellurides are Bi-dominant, often with significant Se contents and typically exhibiting stoichiometries close to variably Se-substituted tellurobismuthite [c. $Bi_2(Te,Se)_3$] to kawazulite (Bi_2Te_2Se), whereas additional Bi-Te-dominant phases have also been identified (e.g., pilsenite and a tsumoite-like mineral). The Cu tellurides rickardite (Cu_7Te_5 alternatively $Cu_{3-x}Te_2$) and vulcanite (CuTe), were first observed during this project and often occur intergrown in complex assemblages with Cu sulphides, sulphosalts and other tellurides as well as native gold. The gold is most commonly observed in telluride-rich ore samples and is Ag-bearing and may contain significant Hg. Additional tellurides include altaite (PbTe), frohbergite ($FeTe_2$) and minor Au-Ag-tellurides including hessite (Ag_2Te) and a muthmannite or montbrayite-like phase (Au-Ag-telluride), while the unknown Au-Sb-telluride (possibly corresponding to pampaloite, AuSbTe), tellurantimony (Sb_2Te_3) and Bi-Sb-telluride reported by Nysten & Annersten (1984) have not been encountered. Overall, a large proportion of the ore minerals at Enåsen occur in texturally and structurally late positions that suggest ore mobilisation into brittle structures, a feature consistent with an evolution including syn-metamorphic ore anatexis.

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A new Zr-Ti-silicate related to rosenbuschite from the agpaitic rocks of Norra Kärr, southern Sweden

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A new member of the seidozerite supergroup and rinkite group with the ideal formula $Na_6Ca_6Zr_2Ti_2(Si_2O_7)_4O_2F_6$ has been discovered at Norra Kärr. The new mineral is triclinic (P-1) and occurs macroscopic pale yellow to straw yellowish radiating prismatic laths in a matrix mainly composed of albite, microcline, arfvedsonite and minor aegirine, along with accessory phases such as nepheline, mosandrite-(Ce), catapleiite and analcime. It exhibits a pale green to yellowish green fluorescence under short wave UV-light. The new mineral is closely related to rosenbuschite, ideally $Na_6Ca_6Zr_3Ti(Si_2O_7)_4O_2F_6$ via the homovalent substitution $Zr^{4+} \rightarrow Ti^{4+}$ on the M5a site, and to kochite, $Na_6Ca_4Mn_2Zr_2Ti_2(Si_2O_7)_4O_2F_6$ through 2Mn → 2Ca on the M1b site. An empirical formula derived from WDS and single crystal XRD (on the basis of 36 anions) is: $(Na_{4.84}Ca_{0.84})_{\Sigma 5.68}(Ca_{5.76}Y_{0.22}REE_{0.02})_{\Sigma 6.00}(Zr_{1.69}Mn_{0.18}Ca_{0.07}Fe_{0.05}Mg_{0.01})_{\Sigma 2.00}(Ti_{1.86}Zr_{0.09}Nb_{0.05})_{\Sigma 2.00}(Si_{2.01}O_7)_4(F_{5.65}O_{2.35})_{\Sigma 8.00}$.

The Norra Kärr alkaline complex is a classical locality of agpaitic rocks in southern Sweden, which was first described by Törnebohm (1906). Agpaitic rocks are peralkaline igneous rocks that are defined by their content of complex volatile-bearing Zr–Ti–HFSE silicate minerals, such as eudialyte group minerals, catapleiite and rosenbuschite, which occur instead of common minerals like zircon and titanite. The complex is approximately 0.5 by 1.5 km at the surface and consists of different varieties of peralkaline silica-undersaturated syenites, which intruded and caused fenitisation of the surrounding granitic bedrock at 1.49±0.01 Ga (Sjöqvist et al. 2017).

The specimen that instigated the current investigations was collected by Lage Karlsson in the 1990s in the northern part of the complex, near the western contact to the granite. A closer re-examination of similar material in the collection of the Swedish Museum of Natural History resulted in the recognition of additional samples of the new mineral. One of these very rich specimens was almost certainly collected by Axel Hamberg and investigated by Törnebohm (1906) in his pioneering work on the Norra Kärr complex. These samples originate from a domain in Norra Kärr that contains large rounded "lakarpite" and "pulaskite" enclaves surrounded by strongly foliated fine-grained "grennaite".

The new mineral does not occur in association with eudialyte-group minerals. Our new observations are consistent with those made by Adamson (1944) and Sjöqvist et al. (2013) and confirm that the "lakarpite" in the western part of the complex is devoid of eudialyte group minerals, the absence of which could be an important factor in the formation of this new mineral. It is the fourth seidozerite supergroup mineral confirmed from the Norra Kärr alkaline complex after mosandrite-(Ce) (Sjöqvist et al. 2013), jinshajiangite (Holtstam 1998) and rosenbuschite (*s.s.*; Törnebohm 1906).

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Vavřínite (Ni_2SbTe_2) and gold from the Palaeoproterozoic Lainijaur Ni-Cu-Co deposit in Malå district, northern Sweden

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During the Swedish government project "Secondary Resources", which aimed to develop classification methods for mine waste and other secondary mineral resources, vavřínite (Ni_2SbTe_2, Laufek et al. 2007) and gold were discovered in a polished section made from a mineralized sample taken from the waste rock dumps at the historical Lainijaur Ni-Cu-Co mine in Malå district, northern Sweden (coordinates E685632, N7240713). The deposit is hosted in a gabbro intrusion and was mined for nickel and copper between 1941 and 1945, yielding c. 100 kt ore, with 2.2% Ni, 0.9% Cu and 0.1% Co (Grip 1961).

Microscope examination followed by micro-Raman spectroscopy and mineral chemical analyses by energy-dispersive spectrometry (EDS) on a scanning electron microscope, confirmed the find of vavřínite. The empirical formula as established with EDS is $Ni_{2.04}Sb_{0.88}As_{0.17}Te_{1.92}$. X-ray powder diffraction data obtained from the bulk matrix of the sample (non-opaque fraction) shows, in order of abundance, albite, calcite, clinoamphibole, chlorite and biotite. The main ore minerals in the sample are nickeline (NiAs) and gersdorffite (NiAsS). Vavřínite occurs mainly as euhedral lath-shaped crystals up to 200 µm long, occurring in direct contact with pyrrhotite, gersdorffite, gold (alloy of Au with c. 30 atomic % Ag) and calcite. Gold forms subhedral grains up to 130 µm. Other associated minerals are chalcopyrite, sphalerite, ilmenite and chromian magnetite. Ilmenite occurs both as exsolution lamellae in magnetite and as separate subhedral grains. Diffuse chemical zoning is observed in the Fe-Co bearing gersdorffite.

Vavřínite is the only known mineral species in the ternary Ni-Sb-Te system, and Lainijaur is one of few localities in the world where it has been observed. It is the only telluride mineral found at the deposit so far, and the first described occurrence of vavřínite from Sweden.

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An unusual epidote supergroup mineral: A solid solution containing the new (OH)-analogue of dollaseite-(Ce)

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In a fragment of a skarn rock from the Malmkärra iron mine, Norberg, Västmanland (Sweden) containing the fluorbritholite-(Nd) holotype (Holtstam et al. 2023), an unusual mineral belonging to the allanite group has been found. Besides fluorbritholite-(Nd), the associated minerals are calcite, dolomite, magnetite, lizardite, talc, fluorite, baryte, scheelite and gadolinite-(Nd). The mineral was investigated with electron microprobe, single crystal X-ray diffraction, vibrational (Raman and FT-IR) and Mössbauer spectroscopy. One crystal was annealed at different temperatures from 500 to 700°C, in 50°C steps. Structural refinements, along with quantitative chemical data, suggest the following cationic populations for the structural sites: $A1 = Ca_{0.96}REE^{3+}_{0.03}Mn_{0.01}$; $A2 = REE^{3+}_{0.99}Ca_{0.01}$; $M1 = Mg_{0.40}Al_{0.32}Fe^{3+}_{0.26}Fe^{2+}_{0.02}$; $M2 = Al_{0.98}Fe^{3+}_{0.02}$; $M3 = Mg_{0.72}Fe^{2+}_{0.18}Fe^{3+}_{0.10}$; $T1,2,3 = Si_{2.93}Al_{0.07}$, leading to a total positive charge of 24.63. The presence of divalent iron is in fairly good agreement with Mössbauer data, and it is confirmed by a significant shortening of the $\langle M3\text{-O}\rangle$ distance, compatible with Fe^{2+} oxidation induced by heating in air (Bonazzi & Menchetti 1994). The occurrence of a considerable amount of divalent cations at both *M*1 and *M*3 sites requires more than one monovalent anion per formula unit. In the dollaseite group minerals, where *M*1 and *M*3 are dominated by divalent cations (Armbruster et al. 2006), charge balance is achieved through the $F^- \rightarrow O^{2-}$ substitution at the O4 site. The lack of fluorine in the present mineral suggests that charge neutrality could be achieved through the presence of additional H^+ (about 0.4 atoms per formula unit, apfu), which could also explain unusual peaks observed at 3580 and 3594 cm^{-1} in Raman and FT-IR spectra, respectively. Another O···O contact suitable for a hydrogen bond could occur between O10 and O2 (Gatta et al. 2012); however, only one independent proton site could be located, with O10 as donor and O4 as acceptor. According to Varlamov et al. (2019), a number of epidote minerals seem to have more than one hydroxyl group pfu, although Raman spectra of the studied samples did not allow them to estimate the exact content of OH groups due to strong luminescence and background noise at wavenumbers > 2000 cm^{-1}. In conclusion, it is reasonable to describe the composition of the mineral from Malmkärra as a solid solution between three members, *i.e.*, dissakisite-(Ce) (32%), ferriallanite-(Ce) (28%), and the (OH)-analogue of dollaseite-(Ce) (40%), a still undescribed end-member.

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Session 18
Metasomatism

Session Chairs:
Matthias Konrad-Schmolke,
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Extreme enrichment of Arsenic and Antimony during formation of Ni-Cr-rich jasper and quartzite from serpentinized peridotite

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Alteration of serpentinised peridotites of Highland Border Complex in Scotland take place in two steps. Listvenite-like dolomite-quartz rocks are formed by addition CaO and CO_2 at constant MgO and SiO_2 involving a mass-increase of ca 140 %. Stage-two involves dissolution of dolomite evinced by the abundant pores and rhombohedral-shaped grains of quartz to form Cr- and Ni-rich jasper and quartzites. Formation of the jasper-quartzites involve a mass-reduction of ca 80%. The listvenite-like and jasper-quartzite rocks have enrichment in the fluid mobile elements Ba, Sr, Cs, As and Sb. The As is present in the Aluminium Phosphate-Sulphate group of minerals formed during alteration of Cr-spinel. Cr-spinel also alters to porous hematite and ferrihydrite with patches containing up to 5 wt% As_2O_3. Enrichment of As, related to alteration of chromite, is previously unknown from natural rocks, but strongly resembles efficient methods used for remediation of this potential toxic element. Formation of quartzite and jasper from peridotite and their common presence as pebbles both in the Devonian Old Red conglomerates, in the Highland Border Complex and in Devonian Basins in the Scandinavian Caledonides, highlights their importance and potential for provenance- and tectono-stratigraphic correlations.

Beyond Beauty: Chronicles of the world's oldest rubies from Greenland

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Constraining the mechanism of corundum(ruby) formation during Mesoarchaean metasomatism of mafic-ultramafic rocks in the Ujaragssuit Nûnat Complex, SW Greenland

The Ujaragssuit Nûnat Complex (UNC) in SW Greenland is an extraordinary geological terrain featuring of igneous and metamorphosed mafic-ultramafic rocks with layers and large pods of chromitite, in a vast expanse of Eoarchean orthogneiss and Mesoarchean granitoid sheets. These rocks offer a glimpse into Earth's formative stages, spanning a remarkable timeframe from approximately 4.1 billion years ago (Coggon et al. 2013) to 2.95 billion years ago (Sawada et al. 2023), encompassing much of our planet's early evolution. This large period is also considered by a large group of scientists to be the time of initiation and evolution of plate tectonics on Earth eventually making it habitable as we know today (Cawood et al. 2022 and references therein). Notably, the rocks from UNC exhibit distinct signatures of polymetamorphism and metasomatism, occurring after their initial emplacement, as evidenced by their intricate mineralogy, including the formation of corundum, which require unique physico-chemical conditions.

This study, for the first time, investigates corundum-bearing rocks from UNC to unravel the complex post-emplacement metamorphic and metasomatic history. Our findings result from an integrated analytical approach encompassing petrography, micro-textural analysis using micro-XRF, mineral chemistry, and thermodynamic phase equilibria modeling (*Perple_X*) using effective bulk rock composition. Our study unveils a sequence of metamorphic and metasomatic events: (a) initial metamorphism of mafic rocks to amphibolite facies conditions, (b) subsequent K^+ rich fluid infiltration associated with granitoid melt infiltration at ca. 2.95 Ga (Sawada et al. 2023) leading to desilication and decalcification of calcic plagioclase and amphibole, creating conditions conducive for the local crystallization of corundum (ruby) crystals within the geochemically "disturbed" metasomatic rock and (c) low-temperature retrogression event possibly at a later stage resulting in the formation of minerals such as chlorite, pumpellyite. Additional tests of isopleth thermometry is being carried out to further narrow down the exact range and P-T path of these rocks. These results will enhance our understanding of the tectonic history (possibly burial and exhumation cycles) of the North Atlantic Craton, spanning from 3 billion years ago from now and onward.

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The microstructural record of high-pressure modulated deserpentinisation

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Aqueous fluids released during dehydration of a subducting slab largely affect the volatiles cycling at convergent margins. It has been recently proposed that high-pressure (HP) serpentine dehydration (deserpentinisation) can be promoted by the coeval influx of reducing external fluids (i.e., modulated deserpentinisation) that modify the serpentinite intrinsic redox conditions. Here we investigate this new model based on field relationships, microstructures and petrology of Cerro Pingano ultramafic massif (Betic Cordillera, S. Spain). Detailed mapping of this massif shows the transformation of HP antigorite (Atg-)serpentinite, through chlorite (Chl-)serpentinite to Chl-harzburgite, which, until now, had only been described in Cerro del Almirez (Padrón-Navarta et al. 2023 and references therein). In Cerro Pingano, the transition can be traced across a ~50 cm wide reaction front marked by the appearance of chlorite first and then by the disappearance of antigorite. The Atg-serpentinite shows a gently NW-NWW dipping foliation and Chl-harzburgite a weak compositional layering with the same orientation, both obliquely cut by the reaction front, steeply NW dipping.

Antigorite has a strong Crystal Preferred Orientation (CPO) with $[001]_{Atg}$ perpendicular to the foliation. Randomly oriented, euhedral tremolite overgrows this fabric. Similarly, olivine in Chl-harzburgite has a low-strain appearance with a CPO characterized by $(010)_{Ol}$ perpendicular to the layering, consistent with a macroscopic topotactic relationship $(001)_{Atg}||(010)_{Ol}$. Orthopyroxene and tremolite show $(010)_{Opx/Tr}$ perpendicular to, and $[001]_{Opx/Tr}$ defining a girdle within the layering plane. Magnesite —present in some Chl-harzburgite samples— has a CPO of [0001] parallel to $(010)_{Ol}$. The transition from Atg-serpentinite to Chl-harzburgite is associated with a relative decrease of $Fe^{3+}/\Sigma Fe$ (from 0.73 to 0.23), consistent with infiltration of reducing external fluids during the coeval dehydration (Padrón-Navarta et al., 2023). Chl-harzburgite samples are also enriched in C (496 - 1601 µg/g) compared to the Atg-serpentinite precursor (<120 µg/g). This trend explains the occurrence of magnesite in harzburgites (< 6 vol.%) and the lack thereof in serpentinites. Textural equilibrium of magnesite within the assemblage Ol + Opx + Chl + Tr + Mgs + Mag indicates it was formed by fluid-rock interaction and was stable at peak conditions, a unique feature of Cerro Pingano compared to other prograde Chl-harzburgite examples. Furthermore, tremolite in Atg-serpentinite contains low Na+K content (~0.05 apfu), but shows increasing Na+K content from transitional lithologies to Chl-harzburgite (up to 0.20 apfu, with invariant Na/K ratio).

The structural analysis suggests that the reaction front at Cerro Pingano does not follow structural discontinuities, nor does it propagate along the rock fabric. The correlation of antigorite CPO (Atg-serpentinite) with olivine, orthopyroxene, tremolite, and magnesite CPOs (Chl-harzburgite) suggests that the Chl-harzburgite fabric is inherited from Atg-serpentinite or was obtained during dehydration, but is not a result of dynamic recrystallization. However, while these features can be attributed to *in-situ* dehydration, the changes in bulk chemistry (enrichment in magnesite) indicate interaction with an externally derived aqueous fluid, possibly originating from graphite-bearing metasediment host rocks.

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From high-T hydrothermal alteration to near-surface weathering – the alteration history of the Rolvsnes granodiorite, W Norway

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The Rolvsnes Granodiorite, comprising the major extent of the northern part of Bømlo Island, Western Norway, has been proposed to be an onshore analogue to the weathered basement rocks at Utsira High hosting significant petroleum resources. A total of 205 meters of core in three boreholes was collected crosscutting both fault zones and apparently tectonically undisturbed rocks. Four distinct lithologies were identified in the drillholes: A medium-grained (grano-)diorite, a range of biotite granites, a porphyritic granite, and aplites/pegmatites. All rock types display evidence of hydrothermal alteration as either pervasive discoloration or more localized veining. Early propylitic alteration of the granodiorite is easily observed macroscopically as distinct greening, caused by primary amphibole being replaced by epidote, and calcic plagioclase cores being altered to epidote+muscovite+quartz. The extent and transition of the alteration steps can be observed in the hyperspectral logs. A second generation of epidote can be observed as 1-2 mm veins crosscutting all lithologies. With decreasing temperature and/or higher fluid/rock ratio, biotite is altered to chlorite. Late infiltration of carbonic fluids is evident from calcite veins cutting former alteration types, and ankerite/Fe-rich dolomite + Fe-oxide veins associated with open fractures.

The clay mineralogy is dominated by smectite and kaolinite, and several meter long sections of the drill cores are near or completely disintegrated from drilling and core handling due to the high smectite content. Kaolinite and smectite may occur together as alteration products, but in open fractures kaolinite is found as infilling in vugs and fractures lined with quartz or associated with the Fe-carbonates, with little or no smectite. This indicates that during late fluid circulation in the faults, kaolinite was precipitated directly from the fluid, and that smectite in the smectite-rich zones was a part of a low temperature pervasive alteration event.

K-Ar dating of the clay-rich alteration zones from this and former studies show a large range of ages, with the ages of the finest (<0.1 µm) fraction ranging from 31 Ma to 281 Ma. The oldest ages are likely mixed or inherited from early events, but apparent clusters around 30-50, 110-140, 200-210, and 265-280 Ma may provide indications of periods of low temperature alteration.

Microfabric evolution during metasomatism and deformation, exemplified by the nodular sillimanite gneisses (Bamble lithotectonic domain, South Norway)

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Proterozoic foliated and nodular sillimanite gneisses from the Bamble lithotectonic domain, South Norway, are analysed to unravel their microfabric evolution with mineral reactions during metasomatism and associated deformation. The nodules form cm-scaled spherical to ellipsoidal sillimanite-quartz aggregates that locally grade into foliated sillimanite gneisses. Independent on their fabric, they record incomplete breakdown reactions of biotite and K-feldspar recorded by muscovite lamellae and associated Fe-oxide needles in biotite and by muscovite-quartz aggregates after K-feldspar. Muscovite is partly replaced by sillimanite. Based on immobile Al, the nodular gneiss forming reactions give excess K, Mg and H_2O that may leave the nodular gneiss to form a metasomatic agent and caused regional metasomatism (scapolitisation) in the surrounding rocks. Quartz in the foliated gneisses shows a pronounced shape but no marked crystallographic preferred orientation. There is no indication of major strain accumulation by quartz dislocation creep. Muscovite shows lobate phase boundaries to quartz, which is interpreted as reaction fabric, from the breakdown reactions of K-feldspar and biotite. The nodular and sillimanite gneisses formed during metasomatic mineral reactions, where major elements K, Mg and H_2O leave the rock and an Al-rich metasomatic restite remains. We suggest that the metasomatism involved a molar volume loss, where reactions forming muscovite, quartz and sillimanite occurred by incongruent dissolution-precipitation creep at low stresses forming the nodular and foliated gneisses. Our study demonstrates that metasomatism with chemical rock changes and mass transfer associated with incongruent dissolution-precipitation contributed to the observed reaction and deformation microfabric.

Modelling the global water cycle – the effect of Mg-sursassite and phase A on deep slab dehydration and the global subduction zone water budget

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Numerous geological, petrological, and geophysical processes depend on the abundance, distribution, and transport of water between the Earth's surface and its interior. Especially important is the role of the hydrated lithospheric mantle in cold subduction zones, where the amount of water transported into the deeper mantle is determined by the stability of the hydrous phases. Stability of these hydrous phases is controlled by the chemical composition, initial hydration intensity and thermal structure of the subducting slab, as well as the thermodynamic properties of the hydrous phases in the subducting slab.

To investigate the global water transport in subduction zones, we implement different published thermodynamic data for the two dense hydrous magnesium silicates (DHMS) Phase A [$Mg_7Si_2O_8(OH)_6$] and Mg-sursassite [$Mg_5Al_5Si_6O_{21}(OH)_7$] in a global set of 56 subduction zone thermal patterns (Syracuse et al., 2010) in a gridded two-dimensional thermodynamic forward model, taking into account the migration of fluids within the slab. The model is based on a combination of MATLAB and Perple_X, which uses Gibbs energy minimisation to calculate amounts of stable phases and coexisting fluid. This provides a tool to quantify and compare the effects of different thermodynamic databases, thermal and geometric patterns of subduction zones, and chemical compositions on the water budget in the subducting slab.

Our results show that, beyond the breakdown of Lawsonite, mafic and sedimentary rocks play a minor role for the globally subducted water budget. The absolute amount of deeply subducted water in subducted ultramafic rocks as well as the different dehydration patterns and the migration of fluids within the plate strongly depends on the intensity and depth of the initial slab mantle hydration and the Clapeyron slopes of the dehydration reactions of phase-A and Mg-sursassite. The global amount of deeply subducted water for different investigated models varies between 8×10^8 Tg/Ma and 1.4×10^9 Tg/Ma. In subduction zones with an intermediate temperature structure, the differences span several orders of magnitude. Depending on the choice of the thermodynamic data set the globally subducted water modelled with a 2 wt.% H_2O hydrated 12 km slab mantle is equal to subduction of the entire Earth's surface water in 1 to 1.7 billion years.

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Basement fracturing and weathering on- and offshore Norway, the BASE projects

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Crystalline basement highs currently represent geological exploration and knowledge frontiers in Norwegian marine territories. Until recently, the potential for hydrocarbon plays hosted therein has received little consideration and investment, both in the UK and Norway[1] (for a review). However, recent, remarkable discoveries in fractured and weathered basement not only offshore SW Norway (Utsira High, e.g. Tellus East, Rolvsnes; www.npd.no), but also west of the Shetland Islands (Rona Ridge, e.g. Lancaster Field; www.hurricaneenergy.com), have shown the great potential for new resources in these uncon- ventional plays in which the reservoir is a crystalline rock affected by dense, natural networks of hydraulically conductive fractures. In the updated ocean strategy[2], the Norwegian government guarantees a profitable production of hydrocarbons by maintaining a predictable framework that includes regular licensing rounds giving the industry access to new exploration areas. Crucial for a safe, innovative, and cost- effective exploration of basement highs offshore Norway (including the Barents Sea), thus becomes a sound understanding of the geological and geophysical characteristics of the exploration blocks, which is only possible if integrated with in-depth studies from onshore analogues. To this end, BASE will establish an integrated, multi-disciplinary platform specifically focussing on the genesis, characteristics, age and landscape development of fractured and weathered basement on- and offshore Norway. A crucial element toward the success of the BASE project will be the availability of recently recovered basement wells drilled on the Norwegian “strandflat” from the North Sea to the Barents Sea, whose preliminary analysis shows remarkably similar geological features to those of the basement blocks drilled as potential reservoirs for hydrocarbons in the offshore domain (Figure 1).

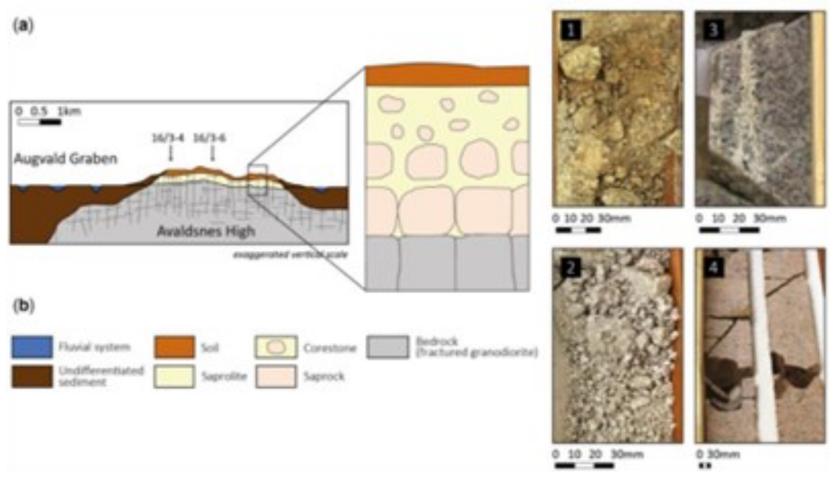

Figure 1: Conceptual model for exemplified basement plays offshore SW Norway (Avaldsnes High, Utsira)[1,3]. Left: (a) Exposed basement high during times of intense chemical weathering. (b) Schematic regolith mantle lithologies. (Right) Core photographs of weathered (1-2) and fractured basement rocks (3-4) offshore.

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Fluid pathways and fluid-rock interaction mechanisms during high pressure metasomatism

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Metasomatic rock transformations are among the few petrological processes that have a significant social impact. For example, element enrichment in surface-near rocks can lead to the formation of ore deposits or cause an unwanted concentration of elements harmful to human health. Despite their importance rate controlling processes during metasomatism are not very well understood in detail, i.e. the intra-crystalline and surface kinetics of the reactant, the inter-crystalline element transport as well as the surface kinetics at the product mineral. There is still an ongoing debate about quantification of all of these rate controlling parameters in metasomatic rocks. However, the observation that natural constraints on metasomatic mineral reaction rates span over a range of up to nine orders of magnitude indicates that each of these processes might be rate-controlled by different mechanisms that can be active at the same time. Recent developments in analytical techniques allow for the observation of element exchange during mineral reactions down to the nano-scale, which yielded new insight into rate-controlling processes and led to the discovery of entirely new reaction pathways among solids and fluids.

We present examples from natural rocks, which clearly indicate that:

(1) lattice defects, such as dislocation walls in the reacting mineral, induced during metasomatic reactions, allow for very fast intracrystalline element transport and very high dissolution rates of the reactant,
(2) reaction induced transient and interconnected porosity enables effective element transport during rock transformation,
(3) the formation of an amorphous transport medium during mineral reactions, that is thermodynamically decoupled from an inter-crystalline aqueous solution, leads to enhanced element transfer between reactant and product, and
(4) re-polymerization of that amorphous phase at the product surface further enhances the crystallization rate during metasomatism.

All of these observations indicate that metasomatic mineral reactions might follow different pathways with different reaction rates, which might be much more effective and faster than previously thought. It is noteworthy that subduction related low temperature/high pressure rocks are the most valuable sources of information about metasomatic reaction pathways as peak temperatures experienced by these rocks are sufficiently low to allow for the preservation of reaction textures, whereas high fluid fluxes and peak pressures allow for large chemical potential differences hence still invoking mineral reactions.

Fault-controlled, kilometre-scale fluid-rock interaction in a late-orogenic setting: insights from C and O isotope profiles from Lismore, Scotland

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The Isle of Lismore is located off the west coast of Scotland, adjacent to the regional SW-NE striking Great Glen Fault (GGF) that cuts through the entire Scottish mainland. Metalimestones of the Lismore Limestone Formation dominate the bedrock and are interlayered with minor metapelites, all deposited during the Neoproterozoic Era and metamorphosed at greenschist facies conditions during the Grampian phase of the Caledonian Orogeny at ca. 470 Ma (Treagus 2013). The GGF formed in the late stages of the Caledonian Orogeny at ca. 430 Ma and is constituted by a ca. 3 km wide fault zone with a ca. 300 m wide zone of principal displacement at its centre (Stewart et al. 2001).

Field observations and samples were collected along a ca. 2 km long profile perpendicular to the GGF. Veins of calcite, ankerite and quartz were observed. Vein density was estimated from field photographs and show a general decrease from ca. 11% at 0.6 km distance from the centre of Loch Linnhe, the approximate centre of the GGF, to ca. 4% at 2.3 km distance, indicative of fluid infiltration from the GGF and probably decreasing fluid fluxes with increased distance from the GGF. The proportion of ankerite is largest close to the GGF and could indicate mass transfer of Fe, in addition to Ca and CO_2, during fluid infiltration.

Stable isotope analyses of vein samples show an increase in $\delta^{18}O_{VSMOW}$ from ca. 16‰ to 19.9‰ with increasing distance from the GGF. Wall rock samples show similar trends with isotopic shifts of 16.0 to 20.2‰ for $\delta^{18}O$ and ca. 2‰ to 7‰ for $\delta^{13}C_{VPBD}$. These isotopic shifts are attributed to fluid-rock interaction caused by vein-channelled fluid infiltration from the GGF and represent fluid:rock ratios of up to F/R = 43. $\delta^{18}O$ and $\delta^{13}C$ correlate for most wall rock samples ($R^2 = 0.65$), which strongly argues for modification of isotopic ratios by fluids and implies pervasive fluid-rock isotopic equilibration by channelled fluid flow to at least 2 km distance from the GGF. Only samples collected >2.3 km from the GGF show possibly retained primary sedimentary $\delta^{13}C$ signatures, at which point fluid-rock interaction may have been less pervasive.

Chromatographic modelling (see Lewerentz & Skelton 2018, and references therein) of the three isotopic datasets yields three independently estimated, within-error-agreeing time-integrated fluid fluxes of ca. 100 to 1,000 $m^3 \cdot m^{-2}$ for vein-controlled fluid flow away from the GGF. For the wall rock data, the oxygen and carbon isotope fronts are located at 155±40.2 m and 76.4±34.1 m from the GGF, respectively. The lag between the carbon and oxygen isotope fronts is used to estimate the X_{CO2} of the fluid to 0.17–0.69, assuming a binary H_2O-CO_2 fluid. Based on results from the chromatographic modelling, field measurements of vein spacing, as well as assumptions for chemical diffusion in the pore fluid ($D_c = 3.07 \cdot 10^{-10} – 9.82 \cdot 10^{-11}$) and porosity for deformation-controlled intermittent movement of close-spaced cracks ($\phi = 10^{-3} – 10^{-4}$), the timescale of fluid flow is estimated to 100 – 100,000 years. This implies time-averaged fluid and carbon fluxes of 0.001 to 0.1 $m^3 \cdot m^{-2} \cdot yr^{-1}$ and 1 – 10,000 mol $C \cdot m^{-2} \cdot yr^{-1}$ (0.044 – 440 kg $CO_2 \cdot m^{-2} \cdot yr^{-1}$), respectively.

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H_2O budget and high-pressure re-equilibration in polycyclic rocks: a case study from the Dora-Maira Massif (Western Alps)

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During metamorphism, aqueous fluids favour mineral-chemical re-equilibration, acting both as a reaction catalyst and a chemical component in hydrous minerals. During subduction of the oceanic and continental crust, fluid-present conditions are maintained thanks to the break-down of hydrous minerals along an up-pressure (P) up-temperature (T) P–T path. However, a more complex fluid evolution may occur in the case of recycling of a continental crust already metamorphosed during a previous orogenic cycle. This polycyclic crust may be already dehydrated before being subducted. Therefore, its re-equilibration during subduction requires interaction with external fluids: a process that may occur prior or during subduction.

In this study, we estimate the H_2O budget in polycyclic metapelites from the Dora-Maira Massif (Western Alps) and we investigate its role in high-pressure (HP) re-equilibration. A pre-Alpine amphibolite-facies foliation is preserved within a kilometre-scale domain where the Alpine deformation was weak. The amphibolite-facies pre-Alpine minerals are statically replaced by Alpine HP minerals. Polycyclic garnet displays evidence of growth and dissolution. The first garnet generation is pre-Alpine (dated at ~ 324 Ma; Nosenzo et al. 2022) and grew during the amphibolite-facies metamorphism. A second garnet generation grew during the Alpine cycle at ~ 21 kbar ~ 550 °C. Microtextures suggest that pre-Alpine garnet was partially dissolved before the growth of Alpine garnet. Thermodynamic modelling indicates that the rock H_2O content (H_2O bounded in the mineral assemblage) at the peak pre-Alpine amphibolite-facies conditions was not sufficient to develop the observed Alpine mineral assemblage (g-ctd-ph-gl-ru). This suggests that a stage of re-hydration of a minimum of 0.7–1.0 wt% H_2O occurred after the peak pre-Alpine conditions and either before or during the Alpine HP overprint. In the low-strain domain, fluid infiltration may have occurred along anastomosed decimetre-scale shear zones during the late pre-Alpine evolution at LP-LT conditions, as suggested by field, microstructural and geochronological data (Nosenzo et al. 2023).

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Effect of volume changes on style of mineral reactions during mixed-volatile infiltration in ultramafic-mafic rocks from the Reinfjord lower crustal field laboratory

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This study demonstrates how the response of ultramafic lithologies to infiltrating H_20-CO_2 fluids depends on the primary mineralogy. This has major implications on fluid flow through the lower crust and upper mantle as mineral reactions control the permeability and rheology. The studied samples are from the hanging wall of a 2 kilometer-long transtensional shear zone in the Reinfjord Ultramafic Complex (RUC), part of the Seiland Igneous Province (SIP) in Northern Norway.

Fluid-rock interaction surrounding shear zones is highly variable and depends on bulk rock compositions. Thermodynamic modelling demonstrates that mineral reactions involving hydration and carbonation differ between dunitic rocks and the pyroxenitic dykes which intersect them. Alteration of dunitic rocks results in the formation of dominantly magnesite-anthophyllite-talc and talc-magnesite assemblages causing approximately 12% volume expansion. This results in a sharp reaction front contacts with the host rock. When the alteration zones cross the dunite-pyroxenite boundary the associated alteration has a more gradual boundary towards the unaltered rock and the alteration zone widens by approximately 40%. In contrast to the simpler dunite alteration assemblage, the pyroxenetic dykes are altered to a complex mixture of cummingtonite-anthophyllite, magnetite and chlorite. Additionally, orthopyroxene is completely pseudomorphed by a mixture of cummingtonite and magnetite, whereas olivine xenocrysts are partly preserved and surrounded by a magnesite-anthophyllite assemblage. Other, open cavity-like areas are filled by chlorite, amphibole, and Mg-MgCa carbonates, indicating volume reduction during alteration of the pyroxene.

Accordingly, dunite alteration effectuates a significant volume expansion, and are therefore only altered locally during seismic creep events. The pyroxenites are near volume neutral throughout interaction with the same fluids, and are thus more homogeneously altered. The formation of chlorite in hybrid compositions, such as the dykes in the lower crust, may create weak permeable zones that are consequently exploited as pathways for fertile mantle fluids and will hence also be the locus of ore bearing fluids moving to the upper crust. Increased understanding of fluid mediated metamorphism increases our current knowledge on fluid flow and strain localization in the lower crust.

Session 19

Marine geology records of Quaternary to late Holocene changes in North Atlantic Ocean circulation with a special reference to Arctic and North European climate

Session Chairs:
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Marit-Solveig Seidenkrantz,
Department of Geoscience, Aahus University
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Post-glacial fluctuations in ocean currents and their impact on the environment of the Eastern Nordic Seas

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Although the overall patterns of Atlantic Water (AW) inflow into the European Arctic during the post-glacial are well known, our understanding of regional climate changes and the behaviour of AW current and subsequent environmental responses are less well established. In particular, there is only limited knowledge on the development of ocean currents since the last deglaciation. Here, we present a multiproxy record from two high-resolution sediment cores retrieved from the eastern Nordic Seas: new data from core OCE2022-KV02-GC from Kveithola Trough and from previously published core OCE2019-HR7-GC from southwestern Svalbard shelf (Devendra et al., 2023). These locations are situated in a highly dynamic frontal area influenced by different ocean currents and local water masses. The cores are positioned beneath the Norwegian Current and the West Spitsbergen Current, which transport heat and salt into the Arctic Ocean. We reconstruct the paleoceanographic forcing of the prevailing water currents on climatic conditions and associated environmental changes during the post-glacial period by means of foraminiferal assemblages, sea ice biomarkers, stable isotopes, and various sedimentological parameters. Further, we reconstruct the surface and bottom water temperatures using alkenones and Mg/Ca. Our reconstruction documents an significant influx of sediment-laden meltwater to the western Barents Sea margin during the Bølling–Allerød interval (~14.6–12.7 kyr BP) originating from the melting Svalbard-Barents Sea ice sheet. This was followed by a sudden decrease in meltwater discharge and relatively high sea ice concentration during the Younger Dryas (~12.8–11.7 kyr BP), as evidenced by benthic $\delta^{18}O$, sea ice biomarkers and foraminiferal faunal composition. The earliest part of the Holocene was characterized by large temperature variability, including the Preboreal Oscillation (PBO). We observe extensive sea ice cover at the southwest Svalbard shelf during the PBO, although this signal was not recorded in the OCE2022-KV02-GC core. In general, similar warm environmental conditions were observed during the early Holocene, with the period between ~9.5–7 kyr BP characterized as the warmest part of the Holocene in both records. This interval is also associated with high surface water productivity and an enhanced AW influx that drove strong erosive activity at the bottom. After 6.5 kyr BP, the eastern Nordic Seas were characterized by a dynamic environment with cold and unstable conditions that persisted until 3.5 kyr BP. Again, the strengthening of AW current was observed since ~3.5 kyr BP, especially in OCE2022-KV02-GC core, similary in OCE2019-HR7-GC core, but since ~2 kyr BP.

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The influence of source waters on the Holocene nutrient cycle in the Labrador Sea: A multiproxy approach of stable isotopes

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In the Labrador Sea, hydrographic and biogeochemical conditions are sensitive to climate variability. Accelerated warming and melting of sea ice today reduce the seasonal sea ice cover and increase primary productivity (Chan et al., 2017). The amount of productivity is closely coupled to nitrate and dissolved silicic acid (dSi) delivery to the area (Harrison et al., 2013). High nitrate, compared to dSi, is delivered from the North Atlantic via the Irminger Sea, while Pacific waters delivered via the Canadian Archipelago are higher in dSi than nitrate (Torres-Valdés et al., 2013) and have distinctively heavier isotope signatures (Giesbrecht et al., 2022).

To investigate how primary productivity was influenced during the Holocene, we analyzed nitrogen isotopes ($\delta^{15}N$) of sediments and silicon isotope ($\delta^{30}Si$) compositions of diatoms. Based on an extensive data set from surface sediments of the entire Labrador Sea record, influences of the water mass signatures or nutrient utilization on the recorded isotope composition were studied. The $\delta^{15}N$ signatures closely mirror the water column signal, as nitrate utilization is complete, suggesting that sediments can be used to trace changes in the source signature of nitrate and the admixture of the source waters. Additionally, two downcore records were studied, from the NE Labrador Sea, in the pathway of Atlantic waters, and from the NW Labrador Sea, where Pacific and Atlantic waters are mixed. These records indicate similar $\delta^{15}N$ values of 7‰ before 7 kyr BP, followed by a decrease to 4.5‰ in the NE and a much slighter decrease to 6.5‰ in the NW over the mid and late Holocene. The $\delta^{30}Si$ values of diatoms ($\delta^{30}Si_{diatom}$) are only available from surface sediments of the Labrador Shelf and a core from the NW Labrador Shelf. Here, dSi is also nearly entirely used by summer (>90%), reflecting the differences in the $\delta^{30}Si$ of source waters. Our downcore record from the NE Labrador Shelf indicates a decrease of $\delta^{30}Si_{diatom}$ that reflects either an increase of light Atlantic-derived waters or a lighter Pacific-derived source.

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Investigation of contourites in the south-western maritime area of the Faroe Islands

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Contourites are essential for understanding the modern bottom current processes and , palaeoceanography. Using the software, Petrel, all public availabe offshore 2D reflection seismic data has been used to find and map contourites in the southwestern maritime area of the Faroe Islands. Six types of recent contourite drifts have been found in the study area, of which elongated mounded drifts are the most common. Maps are shown that illustrate the location of the contourites. The bottom current pattern has been found passing, among others, the Faroe Bank Channel, the Faroe Bank, the Faroe Bank Channel Knoll, the Wyville Thomson Ridge, the Ymir Ridge, the Sigmundur Seamount, the Bill Bailey Bank, the Lousy Bank and the Johannes Rasmussen Trough. Additionally, future studies would benefit from an improvement in the categorization of contourites.

Multi-century reconstruction of environmental conditions in Lurefjorden, Norway

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Benthic foraminiferal assemblages are identified to reconstruct changes in environmental conditions over the last few centuries in Lurefjorden, a western Norwegian fjord. From ca. 1970 until present days the relative abundance of *Brizalina skagerrakkensis,* an efficient bio-indicator for organic matter fluxes*,* is enhanced relative to the preceding time interval. Hence, our results suggest that there is an increase of the organic matter within the Lurefjorden basin in the last 50 years. Over the same period, there is also an increase in the absolute abundance of agglutinated species, indicating lower oxygen concentration in the water. A lowering of the oxygen concentrations may have taken place as a response of a greater oxygen consumption caused by a higher organic matter supply in the water column. Accoridng to Aksnes (2009), Lurefjorden was subject to an increased freshening of Norwegian coastal waters (NCW), which has led to a decrease in sunlight penetration into the water column, affecting the oxygen levels and the behavior of marine life within the basin, between 1935 and 2007. Furthermore, we used diversity indices to study the ecological status of the area, showing significant growth in diversity, abundance, and richness within the benthic foraminiferal community over the past 50 years. Our observations highlight that an increase in the input of organic matter over the last century has led to a change in the benthic foraminifera community in the Lurefjorden basin.

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Unravelling massive meltwater events: Fennoscandian ice sheet and its potential role in North Atlantic Heinrich events

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The Baltic Sea-Skagerrak region displays strong connections with North Atlantic climate during recent glacial-interglacial cycles. However, a detailed assessment of this linkage has been hindered by the lack of continuous, high-resolution paleoclimate records from the Baltic region. Sediment cores collected during IODP Expedition 347 have begun to fill this need; located adjacent to the Fennoscandian Ice Sheet (FIS) during the latest deglaciation, these cores provide an ultra-high resolution record that may reveal insights into environmental changes during this dynamic time period.

Our study focuses on deglacial benthic foraminiferal stable oxygen and carbon isotopes, trace elements, and species assemblages from IODP Site M0060, located close to the Island of Anholt in the Kattegat, covering the period approximately 17.6-13.3 thousand years ago (ka BP). At this site, three distinct deglacial phases were identified. Firstly, a significant rapid freshening event occurred around 17.5 ka, associated with the proximal ice margin. Subsequently, two relatively smaller freshening events transpired around 17 ka and 16.3 ka.

Between 17.6 and 15.5 ka, the environment exhibited fjord-like characteristics with strong vertical stratification, limited bottom-water ventilation, and sea-ice formation, leading to a salinity decrease of approximately 10 units. Between 15.5 and 13.3 ka, the environment became more saline, warmer, and better ventilated, beginning even before the Bølling-Allerød period. These recorded meltwater releases are suspected to be driven by fluctuations in the FIS. Notably, the freshening events at approximately 17 and 16.3 ka closely resembled large $\delta^{18}O$ excursions from the North Atlantic and Nordic Seas, suggesting that these events were not localized but instead affected extensive regions. We will discuss the potential links to Heinrich Event 1 and other larger hydrographic events.

Recent insights into the radiocarbon dating of Arctic Ocean sediments

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Radiocarbon dating of planktic and benthic foraminifera forms the backbone of most late Quaternary paleoclimate reconstructions. In the Arctic Ocean, radiocarbon dates become particularly important because of the limited usefulness of oxygen isotope stratigraphy caused by strong fresh water overprint on the isotope signal, as well as the scarcity of calcareous micro- and nannofossils. However, recent studies have high-lighted several problems with the commonly accepted radiocarbon dated chronostratigraphies from the central Arctic Ocean. In particular, Wollenburg et al. (2023) demonstrated that authigenic calcite overgrowth can make radiocarbon ages several thousand or even tens of thousands of years older, and they argue that this bias can offer an alternative explanation for the apparent widespread hiatus observed in many Arctic cores for the MIS 2 interval. However, the study overlooks the effect of deep-reaching bioturbation. The producers of trace fossils such as *Zoophycos* have been shown to pipe surface material deep down into the sediment, resulting in age errors of several thousands of years (Leuschner et al., 2002; Löwemark and Werner, 2001).

In fact, the depth interval where Wollenburg et al. (2023) finds the largest discrepancies in the radiocarbon ages coincides with an interval rich in *Zoophycos*. It is therefore likely that at least some of the offset in age between radiocarbon ages influenced by authigenic calcite and the presumed true age of the sediment can be explained by downwards piping of younger foraminifera from the (paleo)sea floor. This would mean that while radiocarbon ages of the MIS 2 interval likely are too old, the offset might not be as large as postulated by Wollenburg et al. (2023).

Another, maybe more important implication from their study is that it is not enough to select the best preserved foraminifera when radiocarbon dating sediment. These pristine foraminifera may actually represent “fresh” specimens piped down by *Zoophycos*, providing an alluring source of foraminifera for dating and proxy measurements in a sediment else dominated by heavily altered tests. Consequently, before sampling of foraminifera for radiocarbon dating, it must be established that the sediment interval is free of deep reaching burrows. This is best done by consulting X-ray radiographs.

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Abrupt arctic climate change: Stadial to interstadial climate change in the Fram Strait and connections to the eastern Nordic Seas

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At unprecedented resolution we investigate the nature of the cold Greenland Stadial (GS) 9 and warmer Interstadial (GI) 8 in the Fram Strait, the gateway between the Nordic Seas and the Arctic Ocean. Sea ice was present throughout GS9, however, polynyas occurred regularly. During the interstadial, seasonal sea ice prevailed. Proxies of ice transport reflects the changes in sea ice, with higher productivity and more ice rafted material deposited at times with less sea ice. The transitions between stadial and interstadial conditions are characterised by cold, fresh water and a maximum sea ice extent.

The new reconstructions of ice, ocean and climate are seen in context of ice, ocean and climate of an eastern Nordic Seas transect as seen in multi-model output from three transient glacial GCM simulations (NorESM, CESM, MPI-ESM) and high-resolution reconstructions. There is consistence between the reconstructions and NorESM model results with respect to sea ice extent, subsurface ocean temperatures and ocean atmosphere heat release during the stadial to interstadial transition. The combined results show that ocean-atmosphere-sea ice processes and dynamics are strongly coupled during GS9 and GI8.

Session 20
Geoscience for offshore wind and marine infrastructure

Session Chairs:
Benjamin Bellwald,
Norwegian Geotechnical Institute
Katrine Juul Andresen,
Department of Geoscience, Aahus University
Verner Brandbyge Ernstsen,
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Chalk: an updated stratigraphy and insights into periglacial weathering profiles, offshore windfarm, UK

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Understanding geological variability of the subsurface is key to the successful development of offshore windfarms and associated infrastructure. In particular, in sites with shallow bedrock, it is critical to identify weathered bedrock and to map the boundary between weathered, residual soils and competent, structured bedrock. In this study we focus on the Chalk offshore the UK continental shelf, where the depth to bedrock ranges from outcropping at the seabed down to over 100 meters below seabed. Through the Middle and Late Pleistocene, much of upland and lowland Britain were covered by successive ice sheets that extended out onto the continental shelf. As the ice sheets advanced and retreated, the Chalk bedrock experienced weathering, fracturing and erosion associated with repeated freeze-thaw cycles under periglacial conditions (Johnson et al. 2023). This weathering can alter the structure, strength and geotechnical behaviour of the Chalk which must be characterised during site investigations. With different areas experiencing different levels of weathering and some Chalk units being more susceptible to weathering than others, the resulting weathering profiles are highly variable and challenging to predict. Using high-resolution 2D seismic data and sediment cores recovered from boreholes to ground-truth the ground model, we evaluate the impact of glacial processes on Chalk bedrock at an offshore windfarm site in the Southern North Sea. We present an updated stratigraphy of the Chalk, using onshore analogues to classify the lithology of the Chalk from the Cenomanian to the Campanian and to compare how weathering varies across the stratigraphy as well as spatially. With a multidisciplinary approach integrating geological, geophysical and geotechnical data, we construct a ground model that characterises the extent of weathering in the Chalk bedrock at type localities. Our study highlights how geological observations and geophysical mapping contribute to offshore site investigations, providing site developers and geotechnical engineers with information on soil-type and behaviour.

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Interpreting X-ray images of sediment samples for offshore site investigations

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Offshore site investigations collect a large number of soil samples, commonly sealed in tubes or in wax to preserve the natural moisture content. There is increased interest in running X-rays and CT scans on these samples before geotechnical testing to confirm the sample material, assess the sample quality and to identify material or structures that could have undesirable effects on advanced laboratory tests, such as large gravels. After geotechnical engineers use the X-ray images to specify tests, the images are given a second life by geoscientists looking for evidence of depositional environment and deformation structures that reveal details of the geological history of a site.

In this case study, we evaluate X-ray images from an Offshore Wind Farm site investigation and highlight the benefits to both geotechnical engineers and geoscientists. We acquired X-ray images (radiographs) at three angles: 0°, 45° and 90°, to give a complete, high-resolution view of each sample. We present images of a diverse catalogue of Quaternary sediments, with depositional environments including marine, glaciolacustrine, subglacial and more. Details such as laminations, variations in density, and the size, shape and frequency of gravel all provide clues on depositional environment that geoscientists can use in the development of conceptual ground models.

X-ray imaging, along with CT scanning, is a valuable, non-destructive testing method providing information on sample quality and origin. While geophysical and geotechnical data can be integrated to create quantitative ground models, the geoscientists' contribution in developing the conceptual ground model is perhaps the most fundamental.

Examples of the impact of formerly glaciated terrains on marine infrastructure projects in the North Sea and in the Baltic Sea

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Examples of the impact of formerly glaciated terrains on marine infrastructure projects in the North Sea and in the Baltic Sea

Since 2016, Clinton Marine Survey has worked with large-scale windfarm surveys in various northern-European waters for some of the most influential wind energy companies. Being formerly glaciated terrains, the settings of these survey sites vary, and therefore bring their own challenges into the planning and progress of marine infrastructure projects.

Here we present a few examples out of context, which show some of our most interesting geological findings. For example, glacially polished bedrock outcrops in the North Sea yielded backscatter values lower than the surrounding sand, which brought unexpected challenges into cable dredging there. Relatively recent mass-flow deposits in the Baltic Sea highlights the importance of taking geohazard risks into account when planning geological and conducting marine infrastructure projects. Finally, an extensive system of paleo-channels in a ca. 40 m sediment record covering the last two glaciations under a flat and muddy seabed is another example highlighting the impact and importance of formerly glaciated terrains on marine infrastructure projects of today.

Paleogeographic reconstruction of the Peon area in the Northern North Sea: Implications for ground conditions

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The North Sea is a pivotal area for offshore windfarm development. Within the Norwegian Channel, with depths varying from 200-700 m, six different fields (Vestavind A-F) have being delimeted as areas of interest. This region, however, was shaped by multiple avances of the Norwegian Ice Stream throughout the Quaternary, which affected sediment composition and distribution – directly impacting ground conditions.

Sub-bottom profilers and ultra-high-resolution 2D seismic are standard geophysical dataset for subsurface characterization. In the Northern North Sea, extensive 3D and HR3D seismic data enable regional insights, including paleogeographic reconstructions. For this study, 3D seismic data, including P-cable data, from the shelf and slope, is used to reconstruct the paleogeographic conditions in which the sediments infilling the Northern Norwegian Channel were deposited. High-amplitude reflections were mapped and seismo-geomorphological analyses were caried out, using amplitude extractions and spectral decomposition, and combined with well information.

The interpretation is focused on two main areas on the shelf: i) around of the Peon gas discovery where we have a good control of the paleo-environments for the last ~0.5 Ma, and ii) on the outer shelf northwest of Peon, where parts of the deposits can be directly correlated to the deposits of the North Sea Fan on the slope. The Peon area is characterized by nine units, spanning from the Upper Regional Unconformity (URU) to the seabed (Bellwald et al., 2022). The 50 m thick Peon sandstone is deposited directly over the glacial unconformity is lenticular in shape and has previously been interpreted as an outwash fan, deposited at the ice margin (Bellwald et al., 2022). Further ice-sheet oscillations were responsible for depositing the eight overlying units of harder tills and softer glaciomarine sediments. In the reflections limiting the units of the overburden, there are abundant pockmarks, as well as iceberg ploughmarks and glacial lineations. Shallow seismic anomalies and high-amplitude reflections above the reservoir level indicate migration and accumulation of gas within the overburden.

Northwest of Peon, the equivalent package is generally thinner, but a few reflections can be correlated laterally. On the same stratigraphic level as the Peon sandstone, there is another lense-shaped deposit (potentially another outwash fan), interpreted till units and a deep erosive channel. The channel is roughly 30 km long, starting 20 km from the shelf break and eroding into the slope. Its head is only ~60 ms below the seabed and is characterized by a series of stacked high amplitude reflections, around 800 m wide and under 40 ms deep. It gets progressively wider and deeper towards the shelf break, reaching up to 6 km wide and 400 ms deep. The infill of the structure is heterogeneous, with chaotic and semi-transparent units at the base and some more continuous high amplitudes towards the middle and top. Those continuous reflections can be mapped within the channel and into the North Sea Fan on the slope, where a network of channels can be seen transporting sediment and meltwater deeper in the basin. The channel morphologies change rapidly upward (within ~150 ms time window), from densely spaced, anabranching channels to more isolated and meandering occurrences.

The different till units pose a challenge for the foundation of wind turbines, due to the horizontal and vertical variable soil conditions and possible overconsolidation of the material by repeated ice activity. Soft clays, on the other hand, will not provide sufficient stability for marine infrastructure, and further act as weak layers for slope failure on the paleo-shelf environment.

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SEEP ecology – a multiproxy approach to establish a seabed ecological baseline in the North Sea prior to human activities in the subsurface

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The SEEP and SEEP ecology projects were established to generate a preproduction and syn-production baseline which can distinguish between absence of hydrocarbons (HC), natural seepage, and environmental impacts related to HC exploration and production by a multiproxy approach. However, the results from these two studies focusing on seepage, can also be used to establish a seabed ecological baseline in the North Sea prior to human activities in the subsurface. This ecological baseline for the benthic fauna and microbial communities is therefore also very relevant for discussing the impact of offshore wind and marine infrastructure to determine the environmental health of the seabed pre/post human activities.

To develop a methodology for an ecological baseline we use three key communities of microbes, bivalves and benthic foraminifera that have widely differing roles in the marine ecosystem.

The microbial community reveal the presence of HC degrading microbes, and analyses can distinguish between omnipresent guilds, guilds that are associated with natural seepage of hydrocarbons, and guilds that are associated with polluted sites. The bacterial community responds fast and reveals current conditions.

The bivalves are long lived filter feeders that deposit pollutants from the benthic and planktonic environment in their shells. They are important in the marine food web and useful in reconstructing the palaeoecology of the environment, since the bivalves are present in the oldest part of the marine beds in the sediment cores from the study dating back at least 8000 years. Trace elements analysed of the bivalve shells will provide us with information on past pollutants and gas seepage in the environment.

Benthic foraminifera are small, well preserved, diverse and widely distributed in marine sediments and are therefore excellent candidates for the study of both past and recent ecological conditions. The different benthic foraminiferal species have adapted to distinct environments with changing oxygen and food conditions. Further, studies have shown that some species thrive during methane release events. Hence, establishing an endemic benthic foraminiferal fauna for seep environments in the North Sea will aid our identification of past and present seepage to the seafloor.

Automatic boulder detection and boulder field properties: Techniques and practical applications

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The demand for surface and sub-surface detection of boulder fields is growing. Boulder fields properties acquired from satellite images help to understand the development of extraterrestrial bodies. Similar studies on Earth are useful for offshore spatial planning (e.g., wind farms, platforms, pipelines) and ecosystem research. However, most offshore areas lack high-resolution non-confidential bathymetric and acoustic imagery data to apply and evaluate boulder detection techniques. In our project, we examine a large boulder field (~2 km^2, >10 thousand a meter-size boulders) in the Altai Mountains ("Stone Garden"), which provides an ideal location to test different techniques and design robust detection/analysis workflows. Using this quantitative analysis, the study also aims to understand the origin of the Stone Garden. Two main hypotheses are now under consideration claiming either Altai mega-floods or glacier as the main transport agents. During the 2021 field campaign, we applied structure-from-motion photogrammetry to UAV photography data collected over the Stone Garden to compute a high-resolution (13 cm/px) digital surface model (DSM) and orthophoto imagery mosaic (6 cm/px). Our study involves two major parts: (i) boulder detection and outlining, and (ii) analysis of boulder population properties.

Three methods were used for boulder detection: (1) Deep learning technique to analyze high-resolution orthophoto images of the area (Prieur *et al.*, 2022a, 2022b); (2) Advanced combination of standard GIS methods and manual tuning of DSM and orthophoto images; (3) Numerical recognition of topographic singularities on DSM. The analysis of boulder sizes demonstrates identical power-law distribution (Clauset *et al.*, 2009) for all three methods with power-law exponent between 3 and 4. This dependence breaks for boulders smaller than ~2-3 m in effective diameter. This defines the completeness of the detection only for boulders of larger dimensions (2-10 m), if no additional geological mechanism exists that removes average size boulders (0.5-2.5 m) from the area.

While analyzing individual and statistical properties of detected boulders, we pay special attention to potential difference between traditional, planar (2D, obtained from images), and volumetric (3D) properties estimations. Benefiting from available high-resolution DSM, we use additional characteristics of boulders (such as height, volume, asymmetry, etc.) in the analysis of the field. This way we can illustrate potential errors of image-based (2D) analysis of boulder fields. Applied to the Stone Garden, we demonstrate differences in average boulder size depending on elevation. Orientation of elongated boulders is not well-defined statistically, but major axes tend to be orthogonal to the average topographic trend. We also develop DSM-based methods to detect boulders characterized by distinct stoss slope, which allows us to build a map of the distribution of stoss slopes orientation.

The combination and comparison of different methods increases the analysis robustness. The three methods in our study show comparable boulder detection results. We also developed routines for in-depth analysis of statistical and individual properties based on DSM. Offshore areas without acoustic imagery data can also benefit from these workflows.

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Clay Tectonics: investigating the influence of clay tectonic deformations on offshore windfarm development on the Belgian Continental Shelf

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In the coming years, a new zone for offshore windfarms (285 km^2, up to 3.5 GW capacity) will be developed on the Belgian continental shelf (BCS), in the Southern Bight of the North Sea. The substrate in this so-called ”Princess Elisabeth Zone” consists of a thin Quaternary cover (locally only a few to < 1 m thick) overlying Early Eocene Ypresian clays, which are part of the Kortrijk Formation. Clay tectonic deformations, manifesting as polygonal fault networks and diapiric structures, have been reported to occur in this formation since the 1980s (Henriet et al. 1983, Henriet et al. 1988), yet, they have so far received little attention in the context of offshore infrastructure works on the BCS. New acoustic measurements in the Princess Elisabeth Zone, using very-high-resolution parametric sub-bottom profilers, have now revealed the style and intensity of the deformations in unprecedented detail, readily highlighting the potential risk to the design, installation and operation of the newly planned windfarms. This instigated the ”Clay Tectonics” project (2023-2025), which aims to address the problem through the integration of geophysical measurements, geological analyses and geotechnical simulations. This presentation will outline the project’s rationale and strategy, and provide preliminary results from the geophysical measurements performed during the first year of the project.

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Characterization of glacial and interglacial deposits in the German North Sea from the integration of CPT and UHR MCS wind farm data

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The North Sea plays a key role in the development of offshore wind, and especially in the past years it has seen a rapid expansion of such projects. The suitability for the development of wind farms in this area relies on a combination of favorable conditions such as relatively shallow water depths, a strong wind regime and short distances to shore. Nevertheless, various construction challenges need to be taken into consideration. The North Sea was predominantly shaped by extensive glaciations during the Quaternary (Huuse & Lykke-Andersen 2000). A complex geological evolution including repeated ice stream activity, sediment transport and erosion processes, as well as diverse depositional environments interacting with older regional features has resulted in highly heterogeneous conditions in the shallow sub-seafloor. Foundation types for offshore wind turbines and installation depths generally depend on the geotechnical characteristics of the encountered sediments, which are intrinsic to their depositional environment. Thus, geophysical and geotechnical data from windfarm development areas is valuable for a better understanding of the overall geological setting and the expected deposits in these areas, which helps significantly in creating dependable subsurface models. In the German sector of the North Sea, regional high-resolution seismic data has been typically very limited. However, in the last years with the onset of offshore wind expansion, site characterization datasets gathered on behalf of the Federal Maritime and Hydrographic Agency have become available to the public and consequently, high-resolution puzzle pieces have been added to a growing overview of the shallow geology in the area.

Fraunhofer IWES was the geophysical contractor for these datasets and over the last years has been integrating regional geological findings from wind farm areas in the western German North Sea sector. For this contribution three windfarm sites were selected for an integrated analysis of Ultra-High Resolution Multi-Channel Seismic (UHR MCS), Cone Penetration Testing (CPT) and borehole data. The initial geological analysis of these datasets (Ramboll & BSH 2022 a,b,c) was used to identify and compare similar structural features present in the surveyed area as well as the main seismostratigraphic units that can be followed throughout the region. The encountered sedimentary sequence includes Neogene to Early Pleistocene sand deposits, which have been incised by N-S and NW-SE trending tunnel valleys from the Elsterian glaciation. These valleys are often filled with glacial sediments, subsequent fluvial, lacustrine or even marine deposits (Coughlan et al., 2018). Soft Holsteinian interglacial sediments were interpreted to overlay these valleys and have been partially eroded by minor Saalian glacial valley incisions. Lateral variations over short distances among the encountered deposits were identified, and typical geotechnical values for risk-prone units (i.e., fine-grained layers and tunnel valleys) were constrained. It is shown that the data integration of large, surveyed areas together with a regional understanding of the geological history allows a comprehensive interpretation and aids in further predictions about neighbouring areas concerning the geotechnical character of specific deposits.

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The geological evolution of the Norwegian shelf during the Quaternary

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Over large areas of the Norwegian continental shelf more than 1000 m of Quaternary sediments exist. The depositional history of these sediments is an important context for understanding the geotechnical properties of the sedimentary units in the sub-surface. We summarise the large-scale history of the North Sea (52-62°N) and the mid-Norwegian shelf (62-68°N). The central and southern North Sea basin (52-59°N) was infilled by mainly fluvial and distal-marine sediments, whereas the northern North Sea Basin (59-62°N) was infilled mainly by glacial processes (e.g. glacigenic debris flows). The large coverage of 3D seismic data has allowed for a much better understanding of the sedimentary environment and examples of this will be shown.

The mid-Norwegian shelf was built out by glacigenic processes during the Quaternary, and the shelf edge has been moved up to 150 km towards the west. The basin was filled in by a series of prograding wedges mainly of glacial origin. On top of these units, flatlying till units were deposited during the last few glaciations, commonly separated from the underlying units by one or several unconformities. The lithology of these layers is generally fine-grained, mainly clay and silt, but with sporadic clasts up to boulder size. Several large slides have occurred from the shelf break and down the continental slope.

A geological characterization of the Sørlige Nordsjø II offshore wind site, southern North Sea

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Shallow subsurface and seabed deposits in previously glaciated marine areas are highly heterogeneous, representing a range of glacial and post-glacial environments and processes including glacitectonism, over-consolidation, fluvial and lacustrine deposition, and transgression. These heterogeneities are often linked to variations in geotechnical properties, with important implications for the design and installation of offshore wind infrastructure, and for data acquisition strategies.

Here, we present an integrated geological characterization of the Sørlige Nordsjø II offshore wind site, located in waters of 50-70 m depth along the southern border of the Norwegian North Sea. We focus on the evolution of the area's depositional setting during the Late Quaternary period and its implications for offshore wind development. We also integrate interpretations from a marine geological dataset acquired in 2022 with legacy 3D seismic data and a review of the current understanding of the southern North Sea's complex glacial history.

Five main geological units within the shallow subsurface, summarized within a preliminary conceptual geological model, are identified: 1) homogeneous and layered marine sands covering most of the site, with patchy distribution and coarser-grained deposits in the east, 2) buried, layered channel deposits containing organic material and possible associated shallow gas, 3) buried, stiff glacilacustrine clay deposits, 4) a buried, layered, glacitectonized unit incised by tunnel valleys, with a sandy marine infill, and 5) mounded glacial tills and glacitectonized deposits containing boulders, exposed to shallowly buried in the east. Salt diapirism and gas migration were also found to be important potential geohazards at the site.

3D seismic attribute maps were found to be a powerful aid to understanding the distribution and genesis of seismic facies identified on 2D high-resolution sub-bottom profiles. This type of data integration is an under-utilized methodology for generating detailed preliminary ground models, which can inform more cost-effective site survey and early foundation concept planning at geologically complex offshore wind sites.

Tools for understanding shallow gas in the Danish North Sea

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The shift from oil and gas to renewable energy poses a series of new challenges related to offshore infrastructure. For abandonment of Oil and Gas platforms and the introduction of subsurface carbon storage, baseline conditions regarding methane/CO2 seepage is crucial in order to mitigate leakage and to understand whether any seepage has a natural or anthropogenic origin. So far, the reservoir geology and water column has been monitored but only little attention has been given to the shallow subsurface, how it has been influenced by hydrocarbon production, and to which degree the geology facilitates or inhibits fluid migration. In order to monitor and evaluate future leakage of hydrocarbons to the marine environment, it is crucial to understand the natural seepage through the seabed both locally at platforms and regionally. For CCS, understanding the shallow subsurface is equally important as monitoring cannot be confined to the water column alone.

The aim of the SEEP project is to develop a Danish North Sea baseline for methane seepage in the shallow subsurface, near oil and gas platforms and in areas without any hydrocarbon production. Applying such a baseline will facilitate identification of anthropogenic seepage and help recognize the potential local environmental impact associated with abandonment.

Combining shallow seismic data with deep industry seismic data, provides a first approximation of the likelihood that seepage is natural, and has aided in pointing out positions for later coring. The next step is to integrate the geophysical results with sediment core analyses including facies analysis of cores, occurrence, distribution, geochemistry and age of bivalves and foraminifera related to restricted gas influenced environments, studies of the chemical and isotopic composition of the dissolved gas in the pore water, as well as the community-composition of gas-degrading bacteria.

This integrated approach will provide a solid model for gas distribution, frequency and origin, as well as impact on the environment in the shallow subsurface.

Here we present the different tools that are used to define a baseline, including results and examples from geophysical mapping (both multibeam echosounder and seismic data), faunal and ecological variations, geochemistry and geomicrobiology.

Multi-sensor core logging of shallow seabed sediments for subsea power cable design: a North Sea case study

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Accurate characterisation of shallow seabed sediments is a vital step for the design and installation of subsea power cables. Current industry practice is to collect sediment samples with vibrocores and to conduct cone penetration tests (CPTu) at points along the cable route. While CPTU tests give continuous profiles with depth, laboratory testing of sediment samples is required to ground truth the results, particularly in complex geological environments such as the North Sea.

In this study, we review results from an Offshore Wind Farm site investigation in the southern North Sea with a focus on relationships between Multi-Sensor Core Logger (MSCL) data and results of geotechnical index testing. We evaluate data on a range of materials including sand, soft marine clay, over-consolidated clay, peat and gyttja from the Quaternary formations Holocene, Botney Cut, Bolders Bank and Swarte Bank, in addition to structureless chalk of the Cretaceous (Cameron et al. 1992).

We used the MSCL apparatus by Geotek Ltd to measure attenuated gamma density (analogous to bulk density), P-wave velocity, magnetic susceptibility, electrical resistivity and natural gamma on sediment samples at 1-cm intervals. We compare and explore relationships between MSCL data and geotechnical properties including electrical resistivity and thermal conductivity, natural gamma and grain size/clay content, and magnetic susceptibility as an indicator of stratigraphic unit.

The most critical parameter for cable design is thermal conductivity, with lower thermally conductive sediments such as peat posing the highest risk towards overheating cables. Thermal conductivity measurements are typically taken with a needle probe at discrete intervals and are sensitive to sample preparation methods which can alter saturation ratio (Tucker et al. 2023). We propose that an empirical relationship between thermal conductivity and electrical resistivity can be used to derive continuous profiles of thermal conductivity, while other MSCL measurements such as attenuated gamma density and P-wave velocity, provide supporting information on soil type, sample quality and saturation ratio.

In large offshore projects, data from different locations are routinely grouped together into stratigraphic units with similar geotechnical properties to reduce the amount of laboratory testing required. Sediments of the same provenance and mineralogy are reliably correlated with measurements of magnetic susceptibility (e.g., Gehman & Kelly. 2001). In addition, as natural radioactivity is concentrated in silts and clays compared to sands, natural gamma can be used as an indicator of grain size/clay content.

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Understanding tunnel valleys in the North Sea: a 200-year history of enigmatic subglacial landforms

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Tunnel valleys are kilometre-scale elongate depressions formed beneath ice sheets, and are present extensively across NW Europe including in the North Sea, where they are found buried and at seabed. Much debate surrounds the nature of formation of tunnel valleys and their relationship to Quaternary ice sheet dynamics; this talk summarises how our understanding of tunnel valleys reflects changes in the data available to examine them, how they relate to the evolution of our understanding of the glacial history of the North Sea, and what implications this has for the offshore wind and marine industry.

Open seabed tunnel valleys in the North Sea (e.g. Silver Pit) were known by fishermen for hundreds of years, and surveyed by the British Navy in the 1800's; they were first described scientifically by de la Beche (1834, p.109) as "trough-like cavities" in an otherwise "great tract of plain" and formed as 'cracks' by upward bending of strata. Scientific understanding of tunnel valley formation developed alongside the glacial theory of geology in Europe, although the suggestions that the North Sea offshore tunnel valleys were subglacial in nature was not made until the 1950's (Robinson, 1952). From the 1960's, the seabed tunnel valleys were imaged in 2D seismic data, with much debate regarding their origin as fluvial, tidal, or glacial. In the 1970's, further 2D surveys revealed the existence of extensive networks of buried tunnel valleys at a number of stratigraphic levels across the North Sea, although the nature of the widely spaced 2D data precluded an understanding of the planform geomorphology of the tunnel valleys.

Since the 1990's, 3D seismic data has been used to image the subsurface of the North Sea; thousands of tunnel valleys reaching hundreds of kilometres in length are buried beneath the North Sea, and 3D seismic data highlights their extent and complexity. Tunnel valleys are critical to understanding the glacial history of the region – in size, they are the most significant Quaternary landforms preserved in the North Sea, and confirm unequivocally the existence of ice sheets extending across the North Sea area during this time. Furthermore, by imaging the planform geometry of the tunnel valleys, 3D seismic and gravity data revealed the complex networks of tunnel valleys are formed by cross-cutting 'generations', which, in turn, has led to further questions regarding their formation, evolution, and critically, relationship to Quaternary ice sheet dynamics (Stewart et al. 2013; Ottesen et al. 2020). More recently, high-resolution 2D and 3D seismic data has revealed further detail of tunnel valley infill and the complexity of their formation over time; the presence of landforms, such as crevasse-squeeze ridges and eskers, within tunnel valley fill, shows the North Sea tunnel valleys may be formed and modified within a variety of depositional environments, and very quickly, in the order of hundreds or thousands of years (Kirkham et al. 2021, 2022).

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Session 21
Geophysics: Open session

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Gravity surveying onshore Svalbard: forward modeling and data integration

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The Svalbard archipelago forms the northwestern edge of the Barents Shelf and exposes a complex geological history. The Pre-Caledonian basement rock of Svalbard consists of three distinct provinces separated by NNW-SSE trending long-lived tectonic lineaments. Svalbard is well-known for its outcropping geology, but the subsurface geometry and density structure is less well-known. To constrain these, we have investigated and integrated various data sets sensing different physical parameters in the subsurface. These include regional magnetic and gravity data, 2D seismic profiles and newly acquired onshore gravity data along 346 km of profiles across Spitsbergen. Specifically, we focus on the geophysical signature of one of the major fault zones, the Billefjorden Fault Zone (BFZ), and the emplacement of Lower Cretaceous magmatic bodies related to the High Arctic Large Igneous Province (HALIP).

Potential field data (i.e. magnetic and gravity) can help to constrain the subsurface geometry due to their sensitivity to variations in magnetic susceptibility and density, respectively. Preliminary interpretations linking the anomalies to geological features were previously described in Skilbrei (1992). We improved this first-order understanding of the regional potential fields trends by applying filters to the aeromagnetic and gravity compilations, allowing edge and depth detection as well as visualizing long wavelength trends.

In April 2022, new high resolution gravity data were collected along seismic lines acquired in the 1980s-1990s as part of petroleum exploration onshore Svalbard. Along seven profiles in central Spitsbergen, 260 data points were acquired with a cumulative length of 346 kilometers (Rylander & Sterley, 2022). After performing a quality control of the data, these were used in combination with the aeromagnetic grid as input observations for forward modeling of five key profiles on Spitsbergen. The gravity data are consistent with the pre-existing regional grid and each other.

The regional trends show positive anomalies in magnetic and gravity along the BFZ associated with a relatively shallow source, likely related to uplifted metamorphic basement. Below central Isfjorden, a deep and long-wavelength magnetic anomaly was situated with no coinciding gravity counterpart. In this region, we interpret HALIP-related igneous sills on 2D seismic data and outcropping igneous rocks on the shore. However, the magnetic anomaly depth and signal suggested the need for a deeper situated source.

To quantify the subsurface density structure, we conducted forward modeling on five roughly E-W trending profiles. The basement topography of the profiles was able to explain most of the gravity anomaly trends, linking them to an elevated basement along the BFZ. The three profiles within the extent of the Isfjorden anomaly required large susceptibility contrasts in the subsurface to match the magnetic data. As profiles further south did not require an intra-basement susceptibility heterogeneity to match the data, we favor a scenario with a local magmatic body. The potential field data analysis and forward modeling provided us with more constraints on the subsurface geometry and density structure of Svalbard.

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Analysis of radiation transport effects on passive remote sensing of SO_2 from the Bárðarbunga fissure eruption at Holuhraun, Iceland

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Measurements of the emission rate of magmatic volatiles provide important information about the geochemical and geophysical state of erupting volcanoes. Sulfur dioxide (SO_2), a reliable indicator of the presence and rise of magma at shallow levels, is commonly measured using remote sensing techniques from ground or space. This is usually achieved through the use of optical techniques that measure the absorption of diffuse solar radiation in ultraviolet bands. A recognized source of uncertainty in these types of measurements is radiative transfer, because scattering in hazy atmospheres and the volcanic plume itself can produce a variety of optical paths, and not a single path through the column, which is the key assumption of operational data retrieval schemes.

The eruption of the Bárðarbunga fissure in Holuhraun, central Iceland, in 2014-2015 provided a dramatic example of this situation. The eruption was responsible for the emission to the atmosphere of at least 9.6 Mt of SO_2, quantified through the use of several techniques, in particular differential optical absorption spectroscopy (DOAS). The exceptionally large amount of gas, relatively low levels of natural ultraviolet radiation at high latitudes, and the common occurrence of haze, dust, and clouds posed a challenge to the analysis of remote sensing data. Using a new method for the analysis of radiative transfer effects, we present a new assessment of the emissions from this eruption, which remains the largest source of SO_2 from volcanoes in the last decade.

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Reykjanes Peninsula unrest 2020–2023, Iceland: Deformation history of multiple volcanic systems

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There are several distinct volcanic systems on the Reykjanes Peninsula (RP) in SW Iceland: Reykjanes, Svartsengi, Fagradalsfjall, Krýsuvík, Brennisteinsfjöll, and Hengill, with Fagradalsfjall being least developed. All the systems on the RP except Brennisteinsfjöll have shown signs of volcanic unrest in the past years and decades. We review here the course of events in the ongoing unrest with focus on volcano geodesy. During 2020-2023, localized deformation and seismicity have "ping-ponged" between different systems on the RP. Three uplift episodes occurred at Svartsengi during 2020 and one in May 2022. One subtle deformation event occurred further west on Reykjanes in 2020. Inflation at Krýsuvík occurred during the summer of 2020, after about a decade of subsidence.

To date, three eruptions have occurred at Fagradalsfjall: in 2021, 2022, and July 2023. Each eruption has been preceded by a dike intrusion, often intertwined with complex patterns of faulting, near-surface fracturing over wide areas, and creep along segments of the plate boundary. An additional dike intrusion in December 2021 did not breach the surface. The largest earthquakes during the unrest were M5.65, accompanied by a myriad of earthquakes. The dike growth has spanned days to weeks; furthermore, small dikelets accompanied new vent openings during the 2021 eruption. The dikes were emplaced in the brittle crust, above ~8 km depth, spanned several decimeters in thickness. Co-eruptive deflation was observed in 2021, however, the other eruptions were much smaller in volume, with little co-eruptive deformation. Following the 2021 eruption immediate re-inflation was observed, but the deformation pattern was more subtle following the 2022 eruption, with increased inflation rates in the ~month before the July 2023 eruption. Inflation rates resumed in late 2023. The Fagradalsfjall dikes and associated seismicity released locally a great amount of stored plate-tectonic stresses. However, stress increased locally in several locations, affecting both future earthquakes and possibly locations of future dikes and eruptive vents.

The detailed deformation observations and modeling for the unrest period have revealed complex interactions of tectonics and magmatism across several volcanic systems, highlighting the usefulness of volcano geodesy.

Application of 2D and 3D mUHRS surveys on Mjösa lake, Norway. A first-of-its-kind 3D survey on a lake

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A bridge crossing Norway's largest lake, the Mjösa lake, is being constructed, and therefore offshore geophysical site investigations was needed as a part of the pre-investigations. The survey area consists of two bridge layouts, a northern and a southern, where a final position will be determined based on the findings of the pre-investigation.

The lake lies in a deep incision into the Pre-Cambrian bedrock, with steep sloping rock walls at the sides of the lake, creating difficulties for seismically mapping of the bedrock and subsurface units, due to the possibility of extensive side reflections. To reduce the effects of side reflections a combination of 2D and 3D mUHRS (Multi-channel Ultra High Resolution Seismic) was applied, making it possible to acquire high resolution data with a penetration depth of more than 60 m below lakebed. Normally a large vessel setup would be needed to conduct these types of offshore investigations, however, this was not an option due to the many tunnels on the highway leading to the lake and the small port facilities. Therefore, a first-of-its-kind catamaran barge was built that could support the heavy equipment and at the same time easily manoeuvre in the lake.

The acquired UHRS data showed to be almost free from side reflections and revealed a deep bedrock incision infilled with various glacial formations and recent lakebed deposits. It was possible to identify 10 different units deposited on top of the bedrock. The oldest unit was interpreted as a moraine formation deposited during the latest glacial advance, Weichsel. The moraine was found across the survey area, but was notably seen in the shape of a large mount in the central part of the lake in the southern area, stretching N-S. The remaining units consisted of glacial and late glacial meltwater deposits and marine to lacustrine deposits of sand and clay. Along with the geological interpretation a large-scale boulder-investigation was conducted in a 30m radius around the potential pillar positions. The investigation yielded 47 boulders picked in the sizes ranging from 0.8-7.8 m horizontally and 0.5-1.8 m vertically.

The interpretation yielded a geological history of an incised glacial valley that was infilled first with moraine and later with meltwater sand and silt from the retreating Weichsel ice sheet. An example of a delta deposit was recognized in the meltwater units and was proposed to come from the Moelv river in the southern part of the area. In the postglacial period, during the Holocene transgression, the setting became marine where sand and silt was deposited. During the rise of the land resulting from the previous pressure from the ice, the area was lifted to its current setting as a freshwater lake, and lacustrine deposits of clay and organic materials were deposited. Two propositions for the N-S running moraine mount were given: either it could be an Esker deposited in the middle of the large glacial incision or else it could be a medial moraine formed due to a large bedrock mount found just to the north of the moraine feature. The boulders identified in the units were located using both migrated and unmigrated data, and the approximate sizes of them could be assessed in the 3D dataset.
The study showed that 2D mUHRS and 3D mUHRS investigations can be applied and are highly suitable for offshore lake investigations in remote areas. A detailed 3D model was created including the interpreted units along with the 47 boulders and the well logs. This highly visually intuitive way of displaying data provided a basis for better collaboration between the different disciplines involved in this large construction project.

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Initiating Fennoscandian seismic hazard map

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Fennoscandia is largely a low seismicity intraplate region, with elevated seismicity associated with the passive margin of the North Atlantic and intraplate structures aligned with it. As seismicity is low, seismic hazard is low and thus the usage for national or Fennoscandian seismic hazard maps has been limited to large energy infrastructures. Recently, a new European level Seismic Hazard Model (ESHM20; Danciu et al., 2021) has been compiled. Because seismicity is limited in Fennoscandia and most of the earthquakes are below the cut-off magnitude value of M_w3.5 for the model, the hazard predictions in Fennoscandia are based on rather sparse data. Seismic hazard maps are used to define building codes, and seismic hazard is becoming a more important parameter in planning of new types of energy facilities such as geothermal and Small Modular nuclear Reactors (SMR) in urban areas. It is thus important to obtain realistic estimates of seismic hazard, based on statistically sufficient data. An increase regional hazard would increase construction costs of critical infrastructure projects.

The Nordic seismological observatories are engaged in developing a Fennoscandian seismic hazard model using a larger earthquake dataset. The project is using data and seismic source zones compiled for national projects and assembled into joint Nordic models in a series of workshops and meetings. We will present seismic source zones and the first hazard calculation results. The results are compared to ESHM20.

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3-D magnetotelluric survey of a Miocene-Quaternary volcanic province in NW Svalbard

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The Woodfjorden-Bockfjorden area in northwestern Svalbard hosts the world's northernmost onshore thermal springs, three extinct Quaternary volcanoes and extensive Miocene basalts that overlie an uplifted Devonian sedimentary basin. The thermal springs and volcanoes are located along a major fault system. The magnetotelluric (MT) method is known as an efficient tool for studying crustal structures in young volcanic areas. The resulting electrical resistivity models inverted from MT data provide valuable information about deep mineralization, subsurface fluids, and temperature distribution.

As a part of multi-disciplinary geoscience expedition in July 2023, we conducted the first semi-regional three-dimensional (3-D) MT survey covering an area of about 20x20 km, to enhance our understanding of the crustal structure underlying the volcanic landforms and active thermal springs. This knowledge aids the characterization of the magmatic plumbing system in the crust, which is crucial for understanding the Late Cenozoic evolution of the mantle-derived basaltic volcanism in this area and its relation to the seafloor spreading in the adjacent Arctic and northeastern Atlantic oceanic basins. The broadband MT data were acquired at 9 sites positioned within the Devonian sedimentary basin, and 3 sites within the Mesoproterozoic basement near the Quaternary Sverrefjellet volcano. The stations were installed mostly on smooth terrain, such as alluvial fans and marine terraces. For simultaneous data recording, we utilized two MT instruments. These instruments were equipped with horizontal coil magnetometers and pairs of LEMI non-polarizing electrodes deployed with a dipole length of about 50 m. The time series data of electrical and magnetic fields were acquired with a sampling frequency of 20 Hz, and a night burst recording of 1000 Hz using the EarthData recording unit. Initial inspection of the recorded time series indicated good data quality.

We employ the robust estimation of the magnetotelluric impedance tensor using a multi-variate processing technique. To map the subsurface electrical resistivity distribution, we will combine the new impedance tensor data with several existing broadband MT measurements in the vicinity of the Quaternary eruptive center and invert the combined dataset using ModEM, a well-tested 3-D MT inversion code. Joint interpretation of the 3-D resistivity model with other collected geoscientific data (geological maps, digital outcrop models, petrological and geochemical data) will shed light on the subsurface distribution of geothermal fluids, faults and crustal architecture of the Miocene-Quaternary volcanic province in NW Svalbard.

Recent unrest (2021–2023) at Askja volcano, Iceland

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Unrest began in July 2021 at the Askja volcano in the Northern Volcanic Zone of Iceland. Its most recent eruption, in 1961, was predominantly effusive and produced ~0.1 km^3 lava field. The last plinian eruption at Askja occurred in 1875. Geodetic measurements between 1983-2021 detail persistent subsidence of the Askja caldera, decaying in an exponential manner. At the end of July 2021, inflation was detected at Askja volcano, from GNSS observations and Sentinel-1 interferograms, which continued until September 2023. The inflation episode can be divided into two periods. An initial period until 20 September 2021 when geodetic models suggest transfer of magma (or magmatic fluids) from within the shallowest part of the magmatic system, potentially involving silicic magma. A following period when one source of pressure increase at shallow depth can explain the observations, modeled as a sill with uniform opening.

D-REx project in Fennoscandia

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The D-REx project addresses the ERA-MIN Joint Call 2019 “Raw materials for sustainable development and the circular economy”, topic 1: “Supply of raw materials from exploration and mining”. Formation and concentration of metals into economic mineral deposits requires a combination of processes operating at different scales. Mineral deposits are themselves a small part of a very large geological context, the so-called mineral system, which further includes an often deeply seated source for fluids, a source region for metals, an energy source for driving hydrothermal circulation, pathways for the migration of enriched fluids, a depositional mechanism responsible for the formation of the deposit and a fluid outflow. The primary objective of the D-REx project is to improve the identification of previously unrealized endowed regions. Historically, efforts to understand mineralized systems have focused on the near surface identification and evaluation of individual resource bodies using shallow imaging techniques. The manageable logistical requirements and small environmental footprint of magnetotellurics coupled with its broadband depth sensitivity (from 10s of meters to 100+ kilometres) are making it an increasingly important and powerful tool for geophysical studies with multiple depth scales of interest. For these reasons magnetotellurics is the primary new geophysical data set collected in D-REx. We have collected regional datasets at three prospective areas in Sweden, Norway and Finland to generate the regional and deposit scale models needed to identify the deeper footprints of metal concentration. The D-REx approach shade the light on the early earth history and processes responsible for the concentration of metals in the current uppermost crust of the Fennoscandian shield.

Variations in rock strength and P-wave velocities in a natural CO_2 leaking fault zone

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Accurate detection and characterisation of faults using seismic methods is critical for waste storage (e.g. CO_2, nuclear, landfills), tunnelling, and geothermal energy projects. In this study, we present unconfined compressive strength (UCS) and velocity measurements taken on core samples retrieved from the Little Grand Wash Fault, Utah, USA, a natural CO_2-leaking fault zone, to assess variations in rock strength and velocities. Together with detailed geological logging, optical petrography and CT-image analysis, we identify evidence for historic fluid flow along the fault zone and associated mineralisation. Furthermore, elastic wave velocity measurements were made during the UCS tests to detect microstructural changes and cracking within the samples during loading and evaluate if fault zone rocks exhibit different failure behaviour than rocks outside of fault zones.

Samples including Jurassic sandstones of the Summerville Formation and Brushy Basin member of the Morrison Formation were recovered from shallow (9m) boreholes on the footwall and hanging wall sides of the fault zone. Reference sandstone samples of the Morrison Formation (Salt Wash and Brushy Basin members) were collected 70km from the fault zone, away from the influence of fault-associated fluid flow.

Compared to the off-fault samples, samples from the fault zone have lower porosities and correspondingly higher densities, UCS and P-wave velocities, which is attributed to calcite cementation of historic CO_2 flow along the fault. The Brushy Basin sandstones in the hanging wall damage zone show the most pervasive calcite cementation, while the Summerville Formation sandstones in the footwall show varying compositions of hematite and calcite cement. There is a trend of increasing calcite cement and increasing P-wave velocities closer to the fault core, consistent with previous studies (Smith et al. 2022).

During the UCS tests, observed increases in P-wave velocity under increasing stress are associated with the closing of pre-existing microfractures which stiffens the rock matrix. With further increasing stress, new microfractures form, causing identifiable changes in the P-wave signal that can be used to forecast the rock failure (e.g. Zotz-Wilson et al. 2019). To determine minute changes in velocity within the samples, we applied coda wave interferometry to the raw waveform data recorded at regular intervals during deformation under uniaxial compression. This analysis is highly sensitive to changes in velocity and the formation of microcracks, resulting in a more precise determination of the stress threshold for damage.

Our results highlight the variations in strength and elastic wave velocity that can be found within fault zones and how the failure of recemented fault zone rocks compares to off-fault samples. Laboratory based investigations of fault zone rocks can support seismic interpretations (e.g. Liberty et al. 2022) and identifying changes in wave velocity may contribute to seismic-based subsurface monitoring of stress changes and rock failure.

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Decades of deflation of the Askja volcano, Iceland, prior to ongoing inflation

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The Askja volcano in Iceland is located at the subaerial part of the North American – Eurasian plate boundary. The activity is dominated by basalt but with occasionally rhyolitic explosive eruptions. The volcano hosts four nested calderas, the largest is 50 km^2 in size and the most recent formed during and following rifting episode and explosive eruption in 1874–1875. Following this, seven basaltic eruptions have taken place, with the most recent 1961. Crustal deformation measurements started in 1966 with a levelling profile which was extended to 1.2 km in 1968. Yearly measurements have been carried out on the profile, except for a ten-year gap 1973–82. The profile is mostly aligned in a radial manner outwards from the 1875 caldera. The leveling shows subsidence (1968–70), uplift (1970–72), subsidence (1983–2021) and uplift since August 2021. Extrapolating the uplift in 1970–72 and the following subsidence suggests a change in 1974. The subsidence rate had an exponential decay from 1983 until August 2021. Geodetic modelling considering a spherical pressure source within a uniform elastic halfspace, using combination of levelling, GPS and InSAR data, infers pressure decrease within a magma body at about 3.0 km depth. Using the height difference between the closest and most distant benchmarks, the amount of subsidence in the center can be determined. Such an approach suggests 2.4 m of subsidence 1983–2021. This translates to a subsurface volume change of about 0.1 km^3. The subsidence is suggested to relate to contraction of a cooling magma body. If a basaltic magma body cools and de-gasses a volume reduction can eventually be up to 10–14%. This would require involvement of a >1km^3 basaltic magma reservoir. It is possible the magma system under Askja has a magma body of rhyolitic composition and can contract to a larger extent. Rhyolitic magma at shallow depth in the crust would be more hazardous than basalt, and the next eruption at Askja could be explosive if a rhyolitic magma body is involved.

Investigating NYF-type Pegmatite deposits in Tysfjord, Norway, using ground geophysics

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GREENPEG (2020-2024) is a project funded by the European Union under Horizon 2020, with the primary goal of developing comprehensive exploration tools for identifying lithium-rich pegmatites and high-purity quartz deposits using a variety of methods. The main aim is to establish a sustainable exploration toolkit for small-scale, high-quality ore deposits (<5 million m^3) to reduce the EU's dependence on critical raw material imports (Müller et al. 2022). The project has chosen three demonstration sites in Europe, including Tysfjord in northern Norway, known for its production of high-purity quartz from NYF-type pegmatites.

The Geological Survey of Norway (NGU), one of the thirteen partners in the GREENPEG project, has been tasked with evaluating the effectiveness of ground geophysics in various locations at Tysfjord. Until now, only a few attempts have been made to apply Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) in pegmatite exploration (e.g., Oyonga et al. 2015, Patterson & Cook 2002). However, by using these methods along with a careful consideration of local geological conditions and the petrological-mineralogical structure of the targeted pegmatite and its host rocks, it has been demonstrated that GPR and ERT can provide valuable results for near-surface exploration of pegmatites within crystalline rock formations.

ERT profiling has shown a distinct contrast between pegmatite and its host rock, with highly resistive clusters appearing when the host rock is deformed (e.g., at the Jennyhaugen site) or as conductive layering when the pegmatite itself is mylonized (e.g., at the Håkonhals site). In contrast, GPR profiling has offered insights into the geometric features of the pegmatite deposit, revealing a variety of reflectors that help, among other things, to delineate the base of the pegmatite at depths where ERT resolution is limited. Moreover, GPR has been instrumental in establishing a correlation between the presence of pegmatite and low reflectivity, particularly in cases such as the Jennyhaugen site where profile coverage is sufficiently dense. These findings confirm that ground geophysics can serve as an effective and sustainable approach for mapping and characterizing buried pegmatites. However, it's important to note that detecting pegmatites using ground geophysics can be challenging due to the reliance on generic dielectric and geoelectric properties that are not specific to pegmatites, such as low/high resistivity and/or low reflectivity.

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Session 22
Geoscience education – Investigation of teaching and learning

Session Chairs:
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Improving geoscience education: how course and student representatives work at University of Oslo, Norway

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In pursuit of even better teaching and learning, a variation of course and student representatives are tried out at Oslo University's Department of Geosciences. This project, led by the Centre for integrated Earth science education, iEarth, involves students and lecturers joining forces to improve how courses are taught and learnt.

Whereas lecturers are subject experts in the courses they teach, the students are experts on their own knowledge, what they find particularly challenging, engaging and interesting. Students also tend to have more up-to-date and diverse experiences with teaching methods, thanks to the many different courses they take.

In this project we are therefore trying to invite and improve collaboration between teachers and students from both the teacher´s and student's perspectives. Our course representatives do not only gather student data and report it to lecturers, they focus on engaging their peers in conversations about teaching and learning in the course they are taking as well. Based on these conversations they discuss the course with the lecturer(s).

At the core of the project is the belief that teaching and learning must be continuously adapted to the context and the participants, and that improving teaching and learning therefore must be a "we" project, not an "us-and-them" project. We also work towards continuous course development that addresses issues during, and not after the course. We believe that our project can strengthen student motivation by increased ownership and influence of their own learning. Our iEarth student representatives support the course representatives, e.g. by organising meetings to share good ideas and address challenges. Here, we present the project and our experiences, along with a short video recently made to introduce our project to students and teachers in courses.

Building global capacity for the observation of volcanic and atmospheric change through Situated Learning

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Nearly one-eighth of the world's population, most of it located in developing countries, live under the direct threat of volcanic eruptions. In the context of risk management with limited resources, volcano observatories should prioritize monitoring activities that could be sustained and that would provide more information about the state of the volcano. The magnitude and composition of volcanic gas emissions provide key information about the geochemical and geophysical conditions of volcanoes, but permanent monitoring of volcanic gas emissions with modern techniques require knowledge that tends to be lacking in volcano observatories.

Over the past 20 years, the global Network for the Observation of Volcanic and Atmospheric Change (NOVAC) has enabled volcano observatories around the world to adopt automated techniques for gas monitoring at nearly 60 active volcanoes. Data analysis from these instruments requires knowledge of spectroscopy, radiative transfer, and meteorology. Within the International Geosciences Program (IGCP) sponsored by UNESCO and the International Union of Geological Sciences (IGCP), we have supported capacity building activities for staff of volcanic observatories in the Global South. These activities mainly take the form of field workshops and online training. The objective is to contribute to the training of personnel in the operation, analysis and interpretation of volcanic gas monitoring data produced by NOVAC remote sensing instruments.

One particular form of training is what we call “side-by-side” data analysis, in which, after an introduction, the instructor and students process the same data independently and then compare their results. This practice can be seen as an example of situated learning (Lave and Wenger 1991); and is characterized by being participatory and legitimate, in the sense that students work on solving problems that are relevant to themselves. In this contribution we present some results of this pedagogical practice that is highly relevant in the context of capacity development, but that could also be extended to formal education in various fields of Earth Sciences.

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Explorational field teaching: how students and teachers learn together in a field course in geomorphology

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Perceptions of 'authentic learning' in geomorphological field teaching

As with all teaching, field-based teaching aims to guide the students towards some pre-determined goals such as knowledge, new skills or development of a problem-solving mindset. However, there are multiple paths for teachers and students to reach these end goal together, some which may be more inspiring and informative than others. The prevailing approach to field teaching largely mimics traditional classroom teaching - the teacher as the educator, and the students as passive learners. However, there are alternatives that may boost students' motivation and learning. In this study, we introduce the concept of *explorational field teaching* - a concept grounded in Barnett's (2007) 'authentic learning', defined as *'a kind of shared journey of discovery through high-risk situations'* (here, high-risk is defined as situations where there is no known 'correct' approach). In late summer 2023, we carried out a field course in geomorphology for 12 master and PhD students in the mountains of southern Norway. In the spirit of 'authentic learning', the field course had a strong explorational emphasis, meaning that the end-point goals and study region were pre-defined, but the specifics of study sites and known knowledge to be conveyed by the teachers were yet to be discovered. Initial responses from students were positive, and hence we dig deeper into several concepts: (i) Student experiences and motivation in relation to the field course, (ii) Student self-perception with the flat hierarchy and joint-research nature of the field teaching, and (iii) How the perceptions of students coincide with, or differ from, the perceptions of the teachers. We use these concepts to uncover and discuss potential benefits and drawbacks of explorational, joint-research focused 'authentic' field teaching in geoscience. We make use of several simple methods to garner student ideas, including a web-based anonymous questionnaire, open group discussions with students, and the end-of-course evaluation results. Through this approach, we provide new insights on how 'authentic learning' fieldwork teaching can improve the knowledge, independence and motivation of students of geoscience at large.

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Hydrogeology education in Sweden: are our curricula designed to meet society's demands?

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Society is facing many groundwater related challenges, some specific for Sweden and Nordic countries, some concerning many countries around the globe. The latter are foremost related to groundwater overuse and contamination, but increasingly more frequently also to hydrological extremes such as flood and drought. Hydrological extremes are predicted to increase even more because of climate change and even the water-rich Nordic countries have recently been affected by water scarcity and low groundwater levels (Nygren et al., 2021).

The more specific hydrogeological challenges in Sweden are often related to the construction of roads, railways, tunnels, big buildings, etc. Land-subsidence, as a result of groundwater abstraction, is a common problem that has created huge damage in the past and must be avoided in the future. Sweden is also facing problems of groundwater pollution, PFAS being just one popular example (Banzhaf et al., 2017). Another new and hot topic is the restoration of wetlands to reduce greenhouse gas emissions and to secure water supply. All these are challenging questions that require an integrated hydrological and geological perspective.

Against this background, we as university teachers and responsible for curricula, need to ask the question if we are educating enough groundwater professionals and if those future groundwater professionals have the required skills and knowledge to tackle the challenges.

To investigate this, three surveys were carried out: One, among group, team and section leaders in hydrogeology at all major Swedish consultants and agencies, to determine how easy it is for them to recruit new staff, how new staff meets the requirements and expectations, and how they see the future of the job market. A second survey was sent to professionals working in hydrogeology. They were asked about the contents of their education and how well they felt prepared for their work as professionals. A third survey was sent to teachers teaching hydrogeology or related subjects at Swedish universities.

The surveys were complemented with a compilation of all groundwater related courses taught at Swedish Universities using the University webpages as a data source. LinkedIn profiles containing groundwater or hydrogeology in keywords of 300 Swedish groundwater professionals were used to determine where groundwater professionals work and what kind of education they had.

Altogether a very detailed and complete picture of hydrogeology education in Sweden could be compiled. Results show positive and negative developments. On the negative side, it is not possible to obtain a complete education in hydrogeology at any University in Sweden. Each university offers only relative few specialized courses. At the same time, employers have difficulties to recruit staff which is worrying against the background of an increasing demand. On the positive side, many groundwater professionals feel that their education prepared them well for the demands of the job market. There is a common agreement though, that there is a growing demand for both broader and deeper education in hydrogeology. There is also a need for standardization and certification of hydrogeological education.

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Thirst for knowledge: Think H_2O!

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Water is at the core of sustainable development and touches every aspect of our lives from drinking to food production; it is essential for energy, healthy ecosystems and for human survival. However, freshwater is under threat from climate change, hydropower, industrial allocation, land use changes, and pollution. Despite growing awareness, there is still a great need for an multi layered approach coupled with extensive educational efforts approach and extensive educational efforts. Education plays a key role in shaping how individuals and communities understand the importance of water, its availability, management, consumption and what challenges our future water resource faces. These education efforts need to spread more widely in society, as the world sees a greater need for skilled professionals in water management.

Sydvatten AB provides drinking water to one million inhabitants in Skåne, Sweden. At the same time the company is committed to promoting the value of water and encouraging quality education. From this context, the educational event Think H2O! started in 2014 as a collaboration between Sydvatten and Lund University, with a dual purpose of increasing young people's awareness of the value of water and encouraging them to careers in the water industry (Brogaard et al. 2016). “Think H2O!” is designed as an annual scholarship program offered by Sydvatten with an attempt to ignite young minds on the significance of safe and reliable water supply to society. Our mission is to raise awareness, inspire and secure future sustainable water users.

Think H2O! offers a unique opportunity for high school teachers and their students to explore and learn about water from a multifaceted perspective at Lake Bolmen, southwest Sweden's primary source of drinking water. Based on place-based learning, this two-day adventure weaves theory, practice, and situational experiences into a solid foundation of lasting knowledge. Through workshops, lectures, role plays, experiments, and outdoor activities all with a focus on the hydrological cycle, students learn about water consumption, water access and demand, water ecosystem and drinking water production and more. Participating schools are encouraged to integrate this interdisciplinary knowledge both before and after the course.

In recent years, "Think H2O!" has experienced a steady increase in the number of school applicants. This growing interest underscores the relevance and importance of water-related education among high school students. Furthermore, the program's impact on students' future career choices has been evaluated as part of a doctoral project, initiated in collaboration with Sweden Water Research and Lund University's Department of Psychology. The project examined if and how students are influenced in their career decisions after completing the "Think H2O!" course. The results highlight the program's long-term impact and demonstrate its role in shaping the future of participants as they consider water-related careers and other related fields. Participants’ confidence in their ability to succeed in an engineering education increased. Their feeling that they would fit in socially, and the perception that their career goals would be fulfilled by working as an engineer was also strengthened. However, the longevity of effects were short termed, and more persistent for men than for women (Björklund et al, 2023).

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Students as partners – obstacles, possibilities and solutions in Norwegian Earth science education

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The first Centre for Excellence in Education (SFU) was started in 2011 with the goal of stimulating innovation and excellence in higher education in Norway. It has been followed by another 5 generations of centers. Each center is funded by the Norwegian Directorate for Higher Education and Skills for 5 to 10 years. The Centre for integrated Earth science education, iEarth, is a national consortium consisting of four universities in Norway and achieved SFU status in 2020 with the goal of transforming Earth science education. Including students as partners in their education is an integral part of the iEarth mission. So how do students at the iEarth institutions view their role in their own education?

We report from a workshop gathering 30 students from four Norwegian geoscience departments exploring the need for, and road towards student involvement. The workshop is arranged by students for students and focus on students as partners in their education. The students explore questions such as: What are the benefits of student involvement in higher education? What teaching methods are most effective from the students' perspective? What are challenges, possibilities and solutions for today's Earth science education and in what direction should the education evolve? We will present the workshop, the discussions and the student perspective on these questions.

Are textbooks making Isostasy unnecessarily hard for students to get to grips with?

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In an analysis of introductory geosciences textbooks, we have found that isostasy is introduced almost identically to its original 1855 presentation (Airy, 1855). This presentation neglects the importance of lithospheric flexure and introductions therefore do not reflect the modern understanding of the Earth's behaviour (Watts, 2001). We find that the presentation of the underlying physics of buoyancy is often unclear, and that the analogies used are usually poorly explained in the textbooks. Interviews with students indicate a tendency to focus on the surface features of analogical presentations, rather than the structural relations that reflect causal processes. They easily identify some of the limitations of the analogies, but without explanation struggle to integrate this into their understanding of the Earth's tectonic behaviour. Drawing on the idea of Image Schemata from Embodied Cognition (Johnson, 1987), we consider some everyday experiences that may be relevant to support students when developing a conceptualisation of isostasy and lithospheric flexure.

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Ytterby – a mine under redevelopment

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Ytterby mine, where several rare earth elements were first isolated during the 18th and 19th centuries by Swedish chemists is under redevelopment. A scoping study has started, but not to open the mine again, but to turn the site into a place where chemistry, geology and other life sciences can be in focus. A place where the interest and curiosity of students of all ages can be stimulated and also where research can thrive. Social scientists will also find a place to study history of science and a mine that so far has had two lives first as a supplier of raw materials to the steel and ceramics industries later as a storage vault for military purposes and today is undergoing a third metamorphosis.

The history of the mine will serve as a background to a discussion of the present plans led by the Ytterby Mine Foundation.

Geology in science teacher education in Norway: introducing a textbook integrating geological knowledge and geology education

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Geology has become a stronger component in the latest national science curriculum for primary and lower secondary school in Norway, particularly in secondary school where students should be able to 'use the theory of plate tectonics to explain the evolution of the Earth over time and provide examples of observations that support the theory' (NDET, 2019). Despite its presence in the national science curriculum, geology is a minor part of science teacher education. To our knowledge, geology is nearly neglected in science teacher education and is often taught by professors from other scientific disciplines, such as Physics or Biology. Hence, more support for student teachers is needed to ensure that they have the necessary content knowledge in geology and how to teach geology. Therefore, we embarked on a project to write a textbook for science teacher education, with the working title 'Å undervise om ei jord i endring: Geologididaktikk i og utenfor klasserommet' (translated to: Teaching about a changing Earth: geology education in the classroom and outdoors'.

Each chapter integrates geology and geology education. This means that the book not only provides a description of geological knowledge, but also how to teach it. We have chosen to focus on the topics and concepts that are included in the curriculum goals in the national science curriculum, which include plate tectonics, observations that support the theory of plate tectonics, how the theory of plate tectonics developed in the scientific community, as well as more specific concepts such as the geological cycle and landscapes formed by plate tectonics, ice, and water. Finally, we reflect on the role of geology in education for sustainability, as sustainable development is one of three interdisciplinary topics in the Norwegian curriculum. For each topic and concept, we also provide research-based suggestions for how it can be taught in the science classroom, for instance by using analogies, digital maps, and practices such as argumentation based on evidence. In this presentation, we describe our work in progress with this textbook and provide examples of classroom activities that integrates geological content knowledge and research on geology education.

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A new marine geoscience education at Stockholm University

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In-depth knowledge about the seas and oceans is essential for sustainable use of marine resources, and the demand for such expertise is increasing on all scales from local to global. The marine industry sector is growing worldwide, and the need for sea floor mapping and environmental assessments is increasing, especially in connection with marine installations such as offshore wind farms. To meet these demands, we have designed a new candidate program in Marine Geoscience, which started in the autumn 2023 at the Department of Geological Sciences at Stockholm University (Gyllencreutz et al., 2023). The program is intended to meet the increasing knowledge needs in society about our seas and oceans, which in many ways are related to climate change and sustainability.

The first year of the program includes a comprehensive basic course in earth systems science, followed by courses in mathematics, chemistry and physics to give a broad scientific understanding and a solid foundation for later, more specialized courses. The continued program gives a broad theoretical understanding of marine waters, sea floors, and sediments, together with practical skills in geophysical mapping methods, sea floor sampling, laboratory techniques and report writing. Many courses include fieldwork onshore as well as offshore, and we utilise the state-of-the-art vessels and geophysical equipment at the Askö laboratory, Stockholm University Baltic Sea Centre's field station, for marine fieldwork and excursions. In addition, Stockholm University holds a large repository of sediment cores and other sea floor samples from the Baltic Sea as well as from remote areas such as the Arctic Ocean, which give the students unique possibilities for hands-on studying of various marine geological sedimentary environments. The competences in equipment proficiency and analytical thinking acquired through this program are well suited for a career in the industry as well as in academia.

Although we offer a well-profiled education that meets a high demand on the job market, the number of applicants to the program is low. One reason to this is that geoscience in general is quite unknown to most students in Sweden, and marine geoscience even more so. This is partly explained by the fact that geoscience is excluded from the curriculum in the Swedish upper secondary school programs in natural sciences and engineering.

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Teaching environmental geology – challenges in academical and societal viewpoints of practical application in the learning process

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Introduction

One explanation of *environment* is: "the sum of all features and conditions surroundning and influencing an organism". *Geology* is basically the study of the earth and the physical environment we all live in. As Montgomery (2014) express it, "all of geology might in one sence be regarded as environmental geology. But usually the term environmental geology primarily describe geology and how it directly relates to human activities, that also could be described as geology applied to living". It could also be decribed as applied geology, natural hazards, pollution and waste-disposal etc. Important is that geology is central to many types of problems and challenges we face today and for sustainable development. Geoscience knowledge is crusial for environmental work.

"From Wheat to Bread"

There are several challenges when teaching environmental geology. On one hand there is the *theoretical* part with basic knowledge of geology, geochemistry, geoscience etc. and the progress in research on almost every field today dealing with environmental geology issues. On the other hand there is a very *practical and applied part*, with ways to work and routines to follow when performing environmental geology practically. Neither of these two parts are more or less important when teaching environmental geology. In different part of the working process, these two parts play different roles, depending on questions at hand, and sometimes they both interfear in the planning, performing, evaluation, interpretation etc. of environmental geology work. There is also several other disciplines and subjects that claims to be the central part of environmental issues and viewpoints. No other viewpoints is basically wrong, but it is obvious that geology is very central for environmental work. For example in areas like sulphide bedrock, contaminated soil, emissions to air, soil, surface- and groundwater, deposition of pollutants and toxics in soil, water and sediments etc.. These are all examples of environmental issues directly addressing geology and earth science.

I present a solution from teaching environmental geology in master course (half semester course) at Gothenburg University, with two main tracks of learning following the whole course. On track is the theoretical and scientific research part, picking up both basic knowledge on subjects like sulphide bedrock and brining upp current questions of in society as PFAS in soil and water. The other track is what I call "from wheat to bread". This is the practical part of the course, built up as an environmental geology investigation of a site. In groups the students have to perform an investigation project from background and geology check, planning – with sampling strategy according to routines – to actual sampling, analysing (students and/or professional lab), finally evaluating results. The investigation project ends with writing report with oral presentation, poster with oral presentation and explaining in "popular" and easy access text. The investigation must follow up the theoretical part, like in sampling strategy or choise of type of analysis, and also relate to handbooks and recommendations for performance and qualitative work in these situations from organisations and state authorithies.

High quality results

The outcome of the course is high quality work and presentations, in line with professional managed work. It is also very common that students from the course ends with practice and/or first professional work after studies, and sometimes already during the course. A great acknowledgement of how the course is managed.

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Denmark uncovers fossils – geological citizen science at the Natural History Museum of Denmark

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Many people have fossils hidden in drawers at home or have come across them walking in the countryside. However, few know of the valuable knowledge these fossils hold to better understand the past, present and future or where to go to find out more.

This new Citizen Science project at the Natural History Museum of Denmark aims to involve and engage more people in the study of geology and paleontology. In collaboration with avocational collectors, other Danish natural history museums and fossil themed societies we are developing an online portal as a go-to resource for Danish fossil collecting: mitfossil.dk. This website allows both new and experienced collectors to upload their fossil finds, curate their own digital collection, and interact with experts and view finds of others, whilst also providing information on how to fossil hunt safely and responsibly. Through a gamified voting system, users of the website can help identify each other's fossils. Users are also rewarded for applying as much scientific information to the fossils as possible, encouraging them to work more scientifically with their fossil finds.

The online portal will also be used as a springboard for inviting people to participate in the research of the paleontological collections at the museum, giving people firsthand experience working with paleontology and museum collections. By building a dataset of the fossils found across Denmark, we hope to harness the power of these hidden fossils, and the enthusiasm of the public to bring new insights to palaeobiodiversity and distribution studies.

The project and its many aspects will help improve people's general perception of the relevance of geology and encourage engagement in the geosciences.

TIMREX: An EIT-labelled Master's program transforming mineral exploration education for innovation, entrepreneurship and sustainability

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The European mineral exploration landscape is evolving rapidly, with Nordic and West Balkan countries becoming key investment areas for mineral projects. However, a shortage of skilled personnel, especially in the West Balkans, presents a significant challenge. To address this, a consortium consisting of the University of Miskolc (Hungary), University of Zagreb (Croatia), Wroclaw University of Science and Technology (Poland), and Luleå University of Technology (Sweden), has created an EIT-labelled, innovative joint master's program: TIMREX. These universities are implementing the programme through a curriculum focusing on future mineral exploration professionals.

The TIMREX curriculum centers on state-of-the-art raw materials exploration techniques, emphasizing innovation, entrepreneurship, and social responsibility. It incorporates cutting-edge exploration methodologies, sensitive equipment, robotized tools, and advanced data processing for large datasets. This curriculum aligns with industry stakeholders' vision of mineral exploration, covering field geology, exploration methods, data processing, sustainability, and societal and regulatory considerations.

The program integrates EIT Overarching Learning Outcomes (OLOs) as core components, emphasizing innovation, entrepreneurship, sustainability, creativity, leadership, and intercultural competences. Notably, cross-organizational components, including an Exploration entrepreneurship course, Summer field camp, Internship, and Social and civic internship, foster these essential skills. The whole joint programme and especially the OLOs are achieved by a strong collaboration of the participating universities with eight non-academic partners of the consortium. Addressing the mineral demands of the European Green Deal and COP26 necessitates increased resource production, including for critical raw materials. TIMREX focuses on innovative field techniques and advanced data processing, alongside nurturing an entrepreneurial mindset and promoting sustainability and societal awareness as crucial soft skills for future mineral exploration professionals.

This publication outlines TIMREX's curriculum development and its alignment with EU Education strategies, with emphasis on field education. The fieldwork modules aim to cultivate robust practical skills encompassing cutting-edge exploration technologies and traditional geological mapping techniques. These field activities are complemented by lectures that establish a strong theoretical foundation. Field exercises are conducted in the classic Skellefte mining district of Northern Sweden, and aim to simulate the discovery of a volcanogenic massive sulphide (VMS) deposit through a hands-on mapping campaign and the successful application of a VMS exploration model.

Practical activities include the examination of historic exploration drill cores, drill core logging practice, and discussions regarding mapping implications. Industry experts active in the exploration sector deliver presentations on various topics, including exploration business models, social license to operate, research and development, exploration success stories, and career development. The course employs a flipped classroom approach, providing extensive study materials such as theoretical backgrounds, instructional videos, and photogrammetric outcrop models via an online platform before the field mapping week in Sweden. This approach not only enriches the learning experience but also prepares students for the collaborative and interdisciplinary nature of real-world mineral exploration teams.

Reflections on a hybrid continuing education course for school teachers: Student perspectives and lessons for the future

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To support school teachers in updating their skills, knowledge, and teaching methods, universities and colleges offer Continuing Education (CE) courses. Traditional CE typically requires physical attendance at teaching sessions held at a university or college. These sessions are often spread over a semester and involve several instances of a few days of intense teaching. However, this can pose challenges such as lengthy traveling, high costs, and interference with regular teaching duties, along with the negative environmental impact of commuting. Such obstacles may be prohibitive for some school teachers. A potential solution lies in digital teaching, such as Massive Open Online Courses (MOOCs). By substituting in-person instruction with digital meetings, traveling can be eliminated, and asynchronous teaching permits participants to choose when and where they engage with the course. Nonetheless, this approach also presents challenges. Limiting face-to-face and synchronous interaction between course teachers and students, as well as among students themselves, can make it more difficult to elicit the social, affective, and (meta-)cognitive benefits associated with collaboration.

This contribution presents the results of interviews conducted with students enrolled in a hybrid CE course at the University of Bergen, Norway. The interviews aimed to understand the students' perceptions of in-person and digital teaching experiences, the strengths and challenges they encounter, and gather suggestions for future CE course development.

Learning and working in the field: on belonging, identity and educational spaces

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Fieldwork is celebrated for promising high quality learning, creating potentials for students to connect theory and practice, and inherently create belonging and identity. Fieldwork is also a space where scientific cultures, history, safety measures, interests, practical and financial issues meet and collide. Researching fieldwork within the framing of 'culture of power' (Barton & Yang 2000) makes possible to critically assess the use of fieldwork as a pedagogical tool as well as evaluate taken-for-granted values and practices. Learning in the field further includes a series of embodied and tacit knowledge (Polanyi 1966) that is learned through conducting observations, handling instruments and interpreting data. Here, instruments and students' bodies become entangled with the meaning-making and knowledge production (Barad 2007) and this adds to the complexity of the learning environment. Thus, learning spaces and the materials shape what is learned. In addition, the spatial dimension allows for understanding complex processes of inclusion and exclusion in education (Buchner & Köpfer 2022). Spatial patterns are always relational and socially produced, and consist of numerous social and fluid micro-spaces that are interlinked with broader social, societal and cultural dynamics. In this presentation, I discuss the spatial dimensions of mechanisms of in- and exclusion in fieldwork while drawing on my research of the intersections of disciplinary and cultural norms of fieldwork, learning in the field and students' negotiations of belonging (Malm et al. 2020) and identity work (Madsen & Malm 2022).

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Facilitating student engagement in geological fieldwork using Activity Bingo

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Gamified activity prompts in the form of Activity Bingos have been proposed by Glessmer et al. (2023) as a way to engage students in field learning, and was tried out by them on a research cruise. The game builds on the classical “Bingo” game, where each square on the bingo card is a task for the students to complete. By including different kinds of activities, the Activity Bingo can be adapted for different purposes and contexts. Some potential goals for the Activity Bingo are the social aspect, the “hidden” curriculum (i.e., aspects of fieldwork useful to learn but not present on exams), fieldwork quality, and lessening of the novelty space.

We try out and present two Activity Bingos in traditional field teaching contexts at both the bachelor and master level. The two Activity Bingos have different focus areas. The first was adapted for a 1st semester bachelor course (35 students) and presented to them two weeks into the semester whilst on a field trip in an arctic environment (Finse Alpine Research Station). The Activity Bingo was designed by two teaching assistants (Lisa and Kjersti) and one teacher, where the focus was mainly on these three aspects: 1. social (as they were new students), 2. novelty space (they had never been to the station or in the alpine area before), and fieldwork quality (hands-on experience and learning how to perform fieldwork).

The second Activity Bingo was co-created by the students taking a 1st semester masters course. The majority of students were from different countries and backgrounds (3 Norwegian students and 14 foreign nationals). The co-creation was initiated by one of the teaching assistants above (Lisa) who was taking the course for her masters. The focus of this Activity Bingo was primarily social, but also included activities to reduce novelty space, and curriculum related activities (e.g., identify glacial landforms). The Finse Alpine Research Station was again part of the novelty space, but also Norwegian culture.

The participation rate was distinctly higher in the co-created Activity Bingo. In this poster we present how well the goals of the two different Activity Bingos were met according to the students who participated in the Activity Bingo, and according to some of the makers of the Bingos. We also reflect on the challenges and advantages of using the Activity Bingo. The data are collected through a digital questionnaire and through direct feedback from the participants.

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The multifaceted benefits of teaching for consultant geo professionals – the Åseberget case study

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Integrating teaching into the daily consultant work environment offers a multitude of advantages across various dimensions. These advantages can be categorized into personal benefits (encompassing both students and consultant supervisors), project-related benefits (resulting in enhanced work quality aligned with project and academic requirements), societal benefits (contributing to competence enhancement), and advantages for consulting companies (including financial gains, competence development, and technical progress).

This presentation will draw its inspiration from the Åseberget Geo Cooperation Project, a collaborative effort involving the Municipal Housing Company (BOKAB), Chalmers University of Technology, Norconsult, and the University of Gothenburg. The Åseberget Land Development and Building Project, situated just north of Gothenburg in central Kungälv, aims to result in approximately 1,500-2,000 new apartments and new infrastructure. This project has been meticulously examined from geological, hydrogeological, geophysical, geotechnical, and environmental perspectives by both MSc and BSc scholars (Sundström & Waerme, 2022; Welander, 2022; Kongerslev, 2022). Additionally, insights from other projects addressing quick clays, novel ground investigation tools and geohazards will be leveraged to further expose the manifold benefits (Ekström & Möhl, 2019; Berghel & Hagrydh, 2023; Jörgensen, 2023).

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Interactive understanding of groundwater hydrology and hydrogeology – the iNUX project

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Groundwater accounts for more than 97% of the world's available freshwater resources. Located within geological structures beneath the surface, groundwater is not immediately visible, making it challenging to characterize and manage. As a result, it often gets overlooked by authorities, the general public, and within educational frameworks. Nonetheless, imparting knowledge about Hydrogeology and Groundwater Management at universities, as well as offering continued education for professionals, is crucial to address future challenges. Thus, it's imperative to utilize appropriate teaching materials to enhance the comprehension of this intricate subject among these audiences.

The recent challenge posed by the COVID-19 pandemic has accentuated the need for digital and remote instruction. The ongoing Erasmus+ cooperation project, iNUX – Interactive Understanding of Groundwater Hydrogeology, is designed to fulfill the growing demand for digital educational resources. The iNUX project is funded by the European Union, with project partners from Spain (UPC Barcelona), Sweden (University of Gothenburg), Austria (University of Graz), and Germany (TU Dresden), and engages with various other European entities.

The iNUX project aims to create a digital learning platform in hydrogeology and groundwater management, targeting educators and students not just in Europe, but globally. By using the teaching expertise from renowned European universities, we are developing interactive digital materials that cover both foundational and practical aspects of hydrogeology. This content presents basic theories and couples them with field and laboratory applications observed in diverse European settings (Northern Europe, Central Europe, and the Mediterranean). The educational toolkit includes: (1) diverse video formats (e.g., field and lab experiments, screencast tutorials on calculations and software applications), (2) interactive Jupyter notebooks amalgamating narrative with live code (predominantly Python-based), and (3) a variety of questions and assignments that enable diverse assessment methods, fostering self-directed student learning. All these resources are intended for open-source public accessibility.

The iNUX activities also comprise initiatives to establish interest groups to combine efforts towards larger pools of commonly developed digital teaching material (e.g., question pools) and to link with other activities like the 'Groundwater project' (https://gw-project.org/). The presentation will include existing examples of the digital teaching materials and initial evaluation results to investigate the effect on student learning. More information about iNUX is available at https://gw-inux.org/.

Sustainable development as an interdisciplinary topic in education: A video study from geoscience in upper secondary school in Norway

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Sustainable development is an interdisciplinary topic in the latest Norwegian national curriculum implemented from 2020. Geoscience – an optional science specialization subject in upper secondary education in Norway is no exception. Here, sustainable development is described as follows (Directorate of Education, 2021; our translation):

In geoscience, the interdisciplinary topic sustainable development is about understanding earth systems as foundations for natural resources that humans depend on. It is also about how human-induced and natural changes in earth systems can cause climate change, natural hazards and alter geological diversity, as well as how society can prevent and adapt to these changes. Further, it is also about finding solutions for a more sustainable use of resources today and in the future.

However, little is known how sustainable development is taught in geoscience in upper secondary school. Therefore, the present study explores how sustainable development was enacted in a teaching period in geoscience, in order to discuss the challenges and opportunities for teaching sustainable development in geoscience for upper secondary school.

The teaching period was carried out by an experienced geoscience teacher and the class of grade 13 students aged 18. In this context, we collected data by interviewing the teacher before and after the teaching period, as well as videotaping the teaching practices, what learning activities that were provided to the students and how the students engaged in these learning activities.

The teaching was situated in the last part of a longer period in which the students had worked with natural and human-induced climate change. The teaching about sustainability consisted of the following: the teacher introduced sustainable development by referring to the UN's definition of sustainable development as three-dimensional – environment, social and economic, and then the UN's 17 sustainability goals. Then, the students were asked to discuss solutions to sustainability in all the three dimensions. Finally, the students were asked to prepare a role play regarding the different interest groups involved in mining. The role play itself involved roles as local politicians and representatives of the mining company, and representatives from nature conservation organizations.

Our analyses of the interview and video data focus on the possible tensions that occur during the teaching period, both tensions between the teaching and the learning, and tensions in sustainable development as a global, human idea. Preliminary findings indicate that the first tension come to the surface when students are introduced to sustainable development, as they are tired of learning about sustainable development in school. Then, during the learning activities, tensions arise between 'we' and 'them' who have different opportunities for contributing to a more sustainable development, between the anthropocentric and ecocentric perspectives, and between local initiatives and global responsibility. On the level of the individual student, there seems to be a tension between the feelings of hope and hopelessness as they engage in the various learning activities. Based on these preliminary findings, we suggest that the role of geoscience knowledge and skills appear to be a challenge in the teaching of sustainability in geoscience.

The main implication from this study is that teachers in geoscience for upper secondary school need to be aware that their students are not entering geoscience as empty boxes when it comes to sustainable development. In fact, they have learned sustainable development in many subjects during their previous 11-12 year education. Therefore, we argue that geoscience in schools may emphasize more the contribution of geoscience knowledge to sustainable development, rather than exploring the concept and dilemmas itself.

Direcorate of Education, 2020: National curriculum for geoscience specialization. Tverrfaglige temaer - Læreplan i geofag (GFG01-02) (udir.no)

*Pictionary** as a muti-purpose tool in teaching sequence stratigraphy

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Playing is an instinctive practice with plenty of acknowledged benefits: well-being, active participation, social interaction, learning new skills, etc. (e.g., Smith & Pellegrini 2008). Playing *Pictionary* in educational settings has been a common practice for incorporating vocabulary when learning a new language (e.g., Hamer & Lely 2019) or reviewing concepts in sciences (e.g., Peterson 2017). This work presents an educational experience in teaching the practicals of sequence stratigraphy for master students at the University of Oslo. The experience was applied to a course of 8 students during 6 sessions covering different exercises of sedimentology and sequence stratigraphy. The aims were 1) to encourage students to draw key sequence-stratigraphic concepts, architectural elements, processes, and time/space variations, as a way of communicating their interpretations, and 2) to facilitate interaction between students, and between students and teachers, in a generally shy group. The experience consisted in playing *Pictionary* at the beginning of each practical session, as an introduction to the day's exercises. Like in the traditional game, one person drew, in this case at the board, no talking/writing was allowed, and the whole class guessed. Cards had either key concepts related to the day's topic, or occasional concepts from previous classes to observe different versions of the same concept, and even one or two things totally unrelated to geology just for a funny disruption. The experience allowed me to observe their degree of understanding on the day's topic and reinforce concepts when needed (e.g., by modifying a drawing, establishing relations between the drawing and other concepts, discussing examples, asking how changing a forcing mechanism would affect the drawing, etc.). In addition, although *Pictionary* sessions were few, I could observe a significant change in the group dynamics, e.g., students expressing their opinions, asking questions and volunteering answers during the exercises, and talking to each other during the breaks. There were also changes in the way students owned the classroom space, e.g., talking to each other before class started, walking to the board and draw more confidently, choosing drawing to answer a question. These observations were confirmed by the student's answers to a brief questionary asking them to describe in three words their group interactions both before and after applying *Pictionary*. The most common answers were "shy, quiet & unsure" (before), while "easy discussion, comfortable & confident" (after). When asked how they felt while playing *Pictionary*, the most common words were "fun, interesting & thought provoking". The results of this experience indicate that playing *Pictionary* can be a useful tool not only for improving skills in conveying geological interpretations, but also for fostering social interaction and enhancing students' self-confidence in open discussions, which in turn will impact positively on their learning.

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Ukrainian knowledge exchange and scientific resilience

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The development of new knowledge is a main goal of science, but only part of scientific resilience, which also includes the adaptability, relevance and acceptance of science within a changing society. Maintaining both aspects of science will partly depend on the balance of activities and conditions in science education and research projects, such as conceptual modeling, case studies, financing, education and communication, societal relevance and project time. The focus and character of project activities, in both education and research, are also influenced by the urgency of the issues involved and the resulting time frame for these activities. Using our group's collective experience from 7 Ukrainian case studies with different time perspectives, we model the variations in project characteristics when dealing with war-related and reconstruction-related issues and with long-term environmental and societal change. The diverse case studies from 2022 and 2023 (https://kermitcooperation.wixsite.com/platform) demonstrate the interdependency between science education and research, as well as "tools" for project initiation that are suitable for initial analysis of complex issues by students and researchers and for communication with multi-disciplinary, multi-sectoral and multi-national partners and stakeholders.

Our analytical modeling methodology includes system characterization and system structural analysis, both of which aim to help understand the variable dynamics. Multi-criteria analysis is then used as one type of constructive and predictive modeling in the initial, conceptual model. The project characteristics most specifically favorable for new knowledge development and those most favorable for scientific resilience are evaluated. Activities such as "system modeling" and "case-study investigations" are clearly important when new knowledge is in focus. In contrast, "communication" and "societal relevance" become more predominant when scientific resilience is the major goal. Financing has a major role for both objectives. The consequences of war and other societal crises underscore the need for societally relevant scientific education and research and international cooperation.

From research to outreach – an example from the Smøla island, Mid-Norway

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The BASE project, short for Basement Fracturing and Weathering on- and offshore Norway, is a research project funded by the Norwegian Research Council. While the project`s primary focus has been on disseminating its findings through scientific channels, there is growing interest emerging from local communities and schools. After several seasons of extensive fieldwork and a comprehensive core drilling campaign, we have observed an increased local curiosity and interest, particularly regarding the "why" and "what" behind our efforts.

In our quest to synthesize the wealth of collected data, our goal is to contribute to a local geological exhibition showcasing updated bedrock information and delivering a compelling geological narrative of the Smøla island. This exhibition will illuminate the age of the rocks, the processes that formed them, and unravel the intricate story they convey.

Our fieldwork has uncovered remarkable geological outcrops, which we believe should be shared with the broader community. In collaboration with the local “Friluftsliv” (outdoor life) community, we plan to create stops along their popular “Stikk UT!” routes. These routes and paths are clearly marked on maps and equipped with informative signs. We plan to incorporate geological insights about selected outcrops to enrich the experience for those who visit this remarkable area.

Furthermore, in addition to our outreach efforts, we are dedicated to making our research relevant for primary and secondary school, with specific focus on 5th and 8th -grade pupils studying geology as part of their curriculum. To achieve this, we will employ a comprehensive approach that includes interactive storytelling on the Geological Surveys website, Geologisk arv (ngu.no) (Geoheritage), and we will provide ample information to teachers.

By combining these strategies, our aim is not only to make geology accessible, but also to make it attractive and fascinating for the 5th and 8th -grade pupils. We hope to inspire the next generation of geologists and curious minds based on the captivating geological history of Smøla.

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Geologisk arv (ngu.no)

Stikk UT!

What do students learn about stratigraphy?

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Stratigraphy is a fundamental concept in Earth Sciences and presents a variety of challenges to the learner. Stratigraphy encompasses layers of rock that vary spatially and temporally. Our aim was to investigate what students learn and understand about stratigraphy. We studied students learning before and after a one day field excursion in an introductory course in Earth Science at Uppsala University in the autumn 2020. The students were in the first year of their BSc and had just entered university with a school science background, there were 23 students enrolled in the course. We gave them a questionnaire to fill out before they went on the field excursion and a second one for after the excursion, to examine the influence of the fieldwork. We used content analysis to inductively identify critical factors in the responses of both before and after questionnaires. Resource graphs are used to analyse the responses from individuals both before and after fieldwork and look for connections between ideas. Content analysis revealed ten themes within the answers, the content provides a wide range of conceptual understanding from very basic to well developed. There were very few alternative conceptions found within the responses. Resource graphs show a wide range of patterns from a few connected ideas to highly complex interconnected patterns between themes. We found three levels of complexity within the responses. Students who showed little insight, have simple resource graphs with a few connected ideas, they notice minerals, fossils, lithology and layering. They consider the rock record as an archive of time very generally. Moderate insight considers stratigraphy to show order of events, time and depositional environments. Good insight is associated with resources graphs that are complex and feature time, depositional environment and spatial scale. These students make connections between fossils and depositional environment, as well as demonstrating conceptal understanding of sedimentation rate and climate. The analysis thereby show a diversity in the complexity of students conceptual understanding and provide us with insights into the challenges of teaching and learning stratigraphy.

Session 23
Geoheritage and geoparks

Session Chairs:
Anna Bergengren,
Platåbergens UNESCO Global Geopark
Kristin Rangnes,
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Celebrating 20 years of Global Geoparks: areas of international geological significance developing local societies

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In 2004, the Global Geoparks Network was founded. It was preceded by the Digne Declaration, the international declaration of the Earth's memory, in 1991, and later by the European Geoparks Network, which was formed in 2000. In 2015, the Member States of UNESCO ratified the creation of a new label, UNESCO Global Geoparks, as part of a new program called IGGP.

UNESCO Global Geoparks are areas where sites of international geological significance are managed holistically, with a focus on local communities. Geoparks work to develop geotourism, disseminate knowledge, and preserve geological natural values. Knowledge about geology is contextualized within the area's cultural, industrial, and intangible cultural heritage. Through a strong bottom-up approach, a sense of pride is cultivated among the local population, fostering a desire to stay, invest in, and preserve their landscape and its globally unique values.

As of 2023, 195 territories from 48 countries form the Global Geoparks Network. These UNESCO Geoparks are organized regionally into four Regional Networks.

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https://www.unesco.org/en/iggp/geoparks

https://globalgeoparksnetwork.org/

Mountains as a livelihood: a project within Platåbergens UNESCO Global Geopark, West Sweden

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Platåbergens Geopark in West Sweden was designated as Sweden's first UNESCO Global Geopark in 2022. The geopark covers an area of 3690 km^2 and spans nine municipalities. Within the geopark, you can find geological phenomena and sites that are unique to this region or found only in a few places in the world. Examples include the peneplain (parental bedrock surface) with its smooth rock outcrops, the table mountains with their unique bedrock layers rising from the flat landscape, and glacial deposits that create a breathtaking landscape. This geology has also created conditions for diverse flora, rich fauna, intriguing cultural and industrial history, and active outdoor activities.

Platåbergens Geopark has initiated a three-year project with EU-funding from Leader Nordvästra Skaraborg and Leader Östra Skaraborg, focusing on collecting stories under the theme "Mountains as a Livelihood." Additionally, the initiative is supported by four savings bank foundations. These stories revolve around how mountains served as a livelihood in the past, delving into our industrial history, and how they can provide a sustainable livelihood today through tourism. The stories are published online on an editorial section of our website and some of them in a printed magazine.

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https://www.platabergensgeopark.se/berattelser/

Geopark comparisons, functional system modeling, and landscape-scale sustainability

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Geoparks are recognized by UNESCO with respect to important geo-heritage features, but the range of characteristics and the varied connections to the local ecology and culture are significant for their individual management. The long-term goal is to develop a basis for comparison between Geoparks and a generic model that can be adapted and used to understand the crucial, functional relationships between system variables and how these variables can be optimized for stainable management. The model is related to management variables and the Geopark comparisons. Multi-criteria evaluation can be used to combine these in predicted scenarios, for instance, to evaluate the advantages and risks of creating geoparks in densely populated areas. Where geological sites of global importance and valuable landscapes are located in close proximity to historical settlements, the Geoparks have influenced the regional identity. Conservation customs, culture development, economy, and scientific research can be affected positively or negatively. The previously established Geoparks of Western Europe and possible Geoparks in Sweden and elsewhere in Europe were selected for comparison. Best management practices are considered for the selected sites. Geoinformation technologies can be used to improve the visualization of spatial features and as a basis for scenario predictions. Overall, the comparison indicated the important role of sustainable resource management in the design of effective Geoparks, including their possible contributions toward comprehensive, low-carbon economies and biodiversity. Conceptual modeling of “system” components and processes can potentially help include qualitative and quantitative information for a wider and more in-depth investigation. For instance, the modeling methodology can address the likely consequences in 10, 50, and 100 years if a Geopark is, or is not, established. Further, these models can facilitate the establishment of new Geoparks in areas of special geo-heritage.

Keywords: Geopark, landscape, multi-criteria evaluation, geo-heritage

Geopark Indalsälven – geological heritage presented thematically through geological history, human interference and scientific history

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Introduction

The UNESCO definition of a geopark is *a single, unified geographical area with sites and landscapes of international geological significance managed in a holistic concept of protection, education and sustainable development*. A growing interest in geopark context is the bottom-up approach and involving local communities (UNESCO, 2023). The first steps to develop the Geopark Indalsälven (Geopark Indalsälven, 2023), Ragunda municipality, started in 2020 and it was recogniced as Swedish Geopark 2022 by Swedish geological survey (SGU), according to SGU applications for Swedish geoparks following the UNESCO definition (SGU, 2023). Important part in the work of Geopark Indalsälven has been efforts to involve the local society in engagement in managing and developing the geopark. People have been engaged locally in project work and practical outdoor work ("naturnära jobb") in developing the geopark, visiting sites, and making the geology available and visible.

Describing the Geopark thematically

The geopark presents a long geological story withing the geographical frames of the park, from around 2000 million years ago until today. To manage this, the geopark is working with five thematics: landscape, ice ages and glaciations, continental drift, the "dead falls" and scientific breakthrough.

The story is starting from the development of the supercontinent Columbia 2000 to 1700 million years ago, going through the development of magma chamber around 1500 millon years back in time, clearly visible at several sites. This thematic part of the geopark describes continental drift and bedrock formation of the landscape. The story continues through times of landscape weathering and erosion, moving on to Quaternary times with glaciations and collapsing ice-dammed lakes. Finally, the story gets to human interference on the geology and landscape, ending with thematic on the "catastrophic" experiment with river Indalsälven, resulting in the total drain of lake Ragundasjön and the creation of the famous "Dead falls". From the last glaciation, there is active physical processes visible at sites. River Indalsälven and its tributaries are central nerve and guidance through the whole geopark. All the thematics are pedagogically visualized in the geopark. There is also a geological scientific story in the geopark. This is the area where Gerard De Geer (*e.g.* De Geer, 1940) developed his clay varve chronology. At one visiting site this is visualized with exposed varves in the sediments to help visitors understand the central ideas of varve chronology, as well as geological stratigraphy. The clay varves in Ragunda, described by De Geer and clay varve chronology, was 2022 designated and included in the list "*The first 100 IUGS Geological Heritage Sites*". The history of science is incorporated in the geopark thematics as "scientific breakthrough".

"Living document"

The geopark is a "living document" with discussions for progress: pedagogical, the geopark, scientific and education development etc. The ambition is to stretch out the geopark to east and the west in county Jämtland, with river Indalsälven as the central nerve. In first place to the east to reach town Sundsvall and the Baltic Sea. Geology is always developing, therefor the geopark is developing.

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Geopark Riddarhyttan – a locally-driven initiative

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Geopark Riddarhyttan is a local initiative in the Skinnskatteberg municipality in the province of Västmanland, Sweden. Riddarhyttan is an example of a former place with extensive iron ore mining and iron working industries. The place has had a very long tradition in mining and the region was very important in the industrialization process in Sweden. After the last mine was closed in 1979, Riddarhyttan is nowadays mainly a residential and service place with about 300 inhabitants.

Riddarhyttan has several sites with examples of industrial historical heritage as well as localities where geological processes and remains can be exemplified and studied in nature. The geological remains concern mineralogy, petrology, and Quaternary deposits. In addition, there are interesting in-situ objects with hydrogeological content. A few examples are:

- Nature reserves: Forsån, Passboberget and Råmyran – examples of active meanders, biodiversity above former highest shoreline (Yoldia) and perennial contact spring (cupola) in a mire.
- Bastnäs mine field – technology historical remains with mines, galleries, draught engine, water-driven reciprocating-action shaft, windlass; one of the richest mineral sites in Europe.
- Lienshyttan – a preserved and disused former blast-furnace with impressing slag heap.
- Skilå, Korphyttan – Ruins of old blast-furnaces.
- Kopparverket – Copper works with old storehouse for copper and the remains of roasting furnaces.
- The Ice Age Trail - A journey through time and space. An approx. 20 km long trail adjacent to a glacifluvial delta highlights 30 specific sites to understand the Weichsel deglaciation.
- Röda jorden – the Red soil area (approx. 5 km^2) with remains of bloomery-furnaces and extensive deposits of limonite. One of the oldest evidences of iron production in Sweden, more than 2 700 years old.
- Stor-Kari sten – A mythological glacial erratic boulder

Geopark Riddarhyttan's general aim is to increase the interest in natural science and geoscience in combination with cultural, technical, and scientific history and based on a local perspective within the so called “Bergslagen” area in Sweden. The geopark highlights the in-situ destinations for residents as well as for external visitors through events and information sites in nature.

The activities are run by an association with an administrative board. The association has its own meeting localities and exhibition areas. Information is disseminated through a website that is continuously updated (see https://geoparkriddarhyttan.se/). Funding is obtained through membership fees and certain targeted grants from the municipality and county administration.

Geopark Riddarhyttan has developed into a local “knowledge pool”. The association organizes seminars, recurring evening excursions during the summer, conducts guided tours for, e.g., school classes and tourist groups. Furthermore, the association, as an NGO, may give second opinions about relevant municipal environmental matters and is a collaborative partner in certain relevant research projects. Geopark Riddarhyttan frequently participates in the annual “Geology Day” in Sweden.

The activities within Geopark Riddarhyttan have gradually developed over about 10 years. A long-term goal is that the activities in Riddarhyttan can be considered a Swedish geopark, i.e., become a national geopark according to criteria of the Geological Survey of Sweden.

Mineralriket – a new Swedish geopark!

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What is a Geopark?

A geopark is a model and cooperation action to perform geotourism. A geopark contains sites of geological interest in a confined geographic area, and local actors linked to the different sites. Here they work together to develop and mediate geology for visitors (geotourism) and to create pedagogic programs aimed for school. Creating cooperation in research and support sustainable development of the sites is also of importance. Geoparks are a global concept with UNESCA status, like world heritage and biosphere areas. In Sweden the status of a Swedish geopark may be applied to at the Swedish Geological Survey (SGU), as a step towards an application for UNESCO status.

Background and motivation

The ore-fields of Filipstad ore district (Filipstads bergslag) is internationally reknown as one of the most mineral rich areas in the world. Here a unique number of minerals have been discovered. Långban, Persberg and Nordmark are internationally famous for a number of mineral localities, but there are more areas with mineralogical and geological high values. The narratives of this mineral richness is fascinating and important. It's a story from how the earth was created to how human societies developed and grew over time. A story of innovations, how society works and how much it is dependent on metals. In this area there are unique geological values, and also groups of local actors with different incidences who wish to focus on the geology of the area. To show this, get more people interested and by that create development, innovation and form the basis for the preservations of valuable nature and cultural environments that benefits the region.

The declaration of intent of Mineralriket Geopark

Filipstads kommun, Värmlands Museum, Bergsskolan, Naturhistoriska Riksmuseet and Nordmarks hembygdsförening intend to start the work of creating a geopark in the Filipstad ore district, were the mineralogical richness of the area will be displayed and explained.

Visions and long-term goals of the geopark

- Show the worlds most mineral rich area
- Apply for a Swedish geopark at SGU, and later apply for a UNESCO Global Park (UGG)
- Create a long-term and durable organization with high concern and responsibility
- Work with destination development of the area
- Find new and develop existing destinations
- Offer visits to geosites and other interesting destinations of e.g. cultural interest
- Offer qualified staff for guiding and communicating high geological values to visitors
- Stimulate new business formation for the local development and product innovation
- Develop cooperation with school to make pupils take part of geological knowledge and show them the importance of minerals in the development of society historically and in the future
- Stimulate more young people, especially girls, to apply for studies in geosciences
- Work together with landowners and property owners regarding sustainable development of nature and cultural sites in the area
- Make the geopark an effective stage for cooperation from which projects of international importance are initiated and operated
- Take active part in national and international networks

From porcelain to ytterbium: on Rörstrand castle and Ytterby mine

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On June 13, 1726, an agreement was signed which allowed production of porcelain in Sweden "as it was made in Delft". This agreement, which refers to a Dutch imitation of porcelain called faience allowed a German alchemist, Johann Wolff, to establish a porcelain factory in the cellar and wings of Stora Rörstrand, a castle built by the nobleman Mårten Wewitzer using bricks from Lilla Rörstrand, his own brickyard which dated back to the 11th century, when it was run by the eminently capable Clara nuns. Sixty-two years after the agreement was signed, Reinhold Geijer, a chemist and mineralogist and then owner of what had become Rörstrand porcelain factory, published a letter (Geijer, 1788) describing a heavy black non-magnetic mineral which had been found in the Ytterby mine by an amateur geologist, Carl Axel Arrhenius. The mineral, a sample of which had also been sent to Johan Gadolin, professor at Åbo Academy, was later called gadolinite.

Gadolinite was found to contain oxides of aluminium, iron and a hitherto unknown element. In a paper published in 1794 (Gadolin, 1794)), Gadolin hinted that this unknown element was in reality a mixture of several elements, none of which were known. Three years later, Anders Gustaf Ekeberg, a chemist from Uppsala, called the oxide "ytterjord" meaning "yttria" (Ekeberg, 1797), from which Friedrich Wöhler in Berlin isolated yttrium in 1828. Gadolin's suspicions that "yttria" was actually a mixture several oxides was verified by Carl Gustaf Mosander in 1847. Based on wet chemistry, he showed that "yttria" was a mixture of 3 oxides, the others of which were oxides of terbium and erbium.

With the advent of spectroscopic techniques, Jean de Marignac in Geneva, found thatwhat had been called erbium was actually a mixture of 2 elements, the other being ytterbium. In the early 1900s, Carl Auer von Welsbach in Vienna and Georges Urbain in Paris found, within weeks of one another, that ytterbium too was a mixture of 2 elements. Both Auer von Welsbach (1907) and Urbain (1907) attempted to claim not only one, but both new elements by proposing new names for both of them. Welsbach's proposal was aldebaranium and cassiopeium, and Urbain's was neo-ytterbium and lutecium. Urbain's attempt to re-name ytterbium was unsuccessful. However, the name, lutecium, which he proposed gained favour of the International Committee on Atomic Weights over the names put forward by Welsbach (Clarke, 1909). If this had anything to do with the fact that Urbain ended up chairing the committee remains a mystery (Skelton & Thornton, 2017).

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Reassembling and refurbishing the content of The Norwegian geoheritage database

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The Norwegian geoheritage database is currently undergoing a large content update, the content in this context meaning the database´ geosites, the geosite's metadata and georeferencing. Here, we give a summary of the present-day status of this work, including the governmental regulatory framework. Today, the database is comprised of approximately 1800 non-value assessed geosites and 1200 geosites mainly gathered from older geological protection proposals. The on-going update started with a quality assessment, accompanied by on-going language correction, adding new information and updating old information (metadata) of the geosites. In addition, new geosites are continuously added from in-house fieldwork, from proposals from the public (crowd-sourcing) and from impact assessment and spatial planning. The latter includes both data from official administrative bodies and private companies. The geological survey of Norway also holds webinars on this theme. Value assessments of the different geosites are an important part of both in-house and external work and will be implemented in the database.

Session 24

Deglaciation: dynamics, processes and products

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Pre-LGM sea levels in northern Svalbard

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Past sea level changes reflect changes in climate, ice sheet volume and crustal movements and by reconstructing past sea level variations, inferences about all these factors can be made. The post-glacial sea level history is well known on Svalbard but relative sea levels prior to the Last Glacial Maximum (LGM) are less constrained, both in time and elevation.

Raised littoral and marine deposits older than the Last Glacial Maximum have been documented in many places on Svalbard and reliably dated at some sites. Six or seven high relative sea-level events during the last 200 000 years have thereby been identified, but some of them are not well constrained in time. Of particular interest are deposits from Marine Isotope Stage 3 (ca 57-29 ka), an interstadial with small ice sheets and relatively high sea level. Deposits from this time are being studied both on land and in the sea to investigate how climate and sea-level change affected both terrestrial and marine environments, including glaciation, methane release and submarine slumping.

Here we present luminescence and radiocarbon ages and descriptions of mainly raised littoral deposits from several sites on NW and NE Spitsbergen as well as on Sjuøyane. The samples were taken from coastal cliffs, river sections, ridges, deltas and terraces and the results add to the existing chronology of high relative sea-level events in northern Svalbard.

Ribbed moraines formed during deglaciation of the Iceland Ice Sheet

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Understanding the geomorphological fingerprints of palaeo-ice streams is essential for our perception of the ice-stream behaviour, as the formation of bedforms provides a window into processes at the ice/bed interface. Cross-cutting flow-sets of palaeo-ice streams, during and following the Last Glacial Maximum (LGM), have been suggested in northeast Iceland based on mapping of streamlined subglacial bedforms (SSBs; drumlins and MSGLs) and crevasse-squeezed ridges. Here we map transverse ridges, together with glaciofluvial and ice-marginal bedforms, within the Vopnafjörður-Jökuldalsheiði flow-set. The main emphasis is on the transverse ridges, that are primarily interpreted as ribbed moraines - the first to be described in Iceland. Morphological data is combined with sedimentological analyses of the ribbed moraines to increase our understanding of their formation and dynamics of the IIS in northeast Iceland during deglaciation. The ribbed moraines are composed of pre-existing material, a base of glaciofluvial sediments draped with subglacial till. Deformation within both units suggests compressional flow during the formation of the ridges. Ribbed moraines are often considered to form at the transition zone between fast and slow ice flow and their distribution upstream from drumlin fields agrees with that. Furthermore, they have been linked to ice stream onset zones and their shutdown. Based on ridges superimposed on drumlins and „ribbed" drumlins, the ribbed moraines are considered to post-date the SSBs and signify the waning stage of ice streaming. Correlating the formation of the ribbed moraines with the known glacial history in this region we suppose that the ridges formed during the Younger Dryas deglaciation. Eskers superimposed on ribbed moraines indicate channelized water drainage during the deglaciation. The eskers frequently terminate at ice-marginal positions on Jökuldalsheiði, implying stillstands or small readvances during the deglaciation. This study has implications for the deglaciation behavior of ice streaming in the northeastern part of the IIS and sheds light on the formation of ribbed moraines under palaeo- and modern ice sheets.

Early Holocene deglaciation of eastern Iceland constrained by cosmogenic ^{36}Cl exposure ages and tephrochronology

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The Iceland Ice Sheet (IIS) is thought to have extended to the shelf break around Iceland at the Last Glacial Maximum and then collapsed and retreated to a position inside the present-day coast during the Bølling-Allerød. Following the Younger Dryas (YD) and Preboreal readvances to coastal areas, the IIS retreated inland and deposited a number of end moraines of unknown age. Several records suggest that remnants of the IIS were smaller than present glaciers by ~9 ka BP. However, the rate of retreat from the Preboreal position (just inside the YD position) to the interior highlands remains unresolved. Recent studies in NE-Iceland revealed the tracks of palaeo-ice streams, one of which extended from the highland interior north of the present Vatnajökull to the coast in Vopnafjörður. Several end moraines are preserved along the center flow line of this former ice stream, indicating periodic stillstands or readvances that punctuated its overall retreat. In this project, roughly 30 samples were collected for cosmogenic 36Cl surface exposure dating of glacially scoured bedrock and end moraines along a ~120 km long transect from the coast in Vopnafjörður to near the northern margin of Vatnajökull. We expect exposure ages to decrease from the coast towards the highlands and reveal a rapid deglaciation of the IIS during the early Holocene.

Preliminary 36Cl ages from the Skessugarður bouldery end moraine, approximately mid-way along the transect between the coast and present Vatnajökull, suggest that it was formed between 10.8 and 9.5 ka BP. A continuous Holocene tephra sequence at the upglacier end of the transect reveals a potential G10 ka tephra series resting directly on till, possibly indicating completely deglaciated highlands by 10.3-9.8 ka BP.

More ^{36}Cl dates and tephra analyses from the transect are expected in 2024, providing a unique dataset in Iceland. The outcome of these dating efforts has important implications for our understanding of the rates and pattern of IIS decay and serves as a critical constraint for palaeoglaciological modelling of the IIS.

A landform-driven simulation of deglaciation of the Scandinavian Ice Sheet and the PalGlac project's progress on data-modelling integration

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The field of palaeo-glaciology has evolved from inquisitiveness about glaciated landscapes - how they came into being - into the wider role of improving glaciological understanding and more recently, into testing or improving the fidelity of ice sheet modelling approaches. Such endeavors are crucial for improving forecasts of today's diminishing polar ice sheets and for predicting sea-level rise. The PalGlac project (2018 to 2024) is using glacial landform mapping and analysis to advance our understanding of ice sheets, and in this talk, we will focus on the demise of the Scandinavian Ice Sheet and how landform data is used to either test or calibrate (nudge) ice sheet modelling simulations.

Glacial landforms such as drumlins, moraines, meltwater channels and eskers record spatially extensive components of ice sheet activity, namely 1) ice flow geometry and thermal regime, 2) the pattern of ice-marginal recession, and 3) the subglacial flow of meltwater that likely modulated the first two. High-resolution (metres) digital elevation models (DEMs) are revolutionising the mapping and understanding of glacial landforms (Johnson et al. 2015). They permit detailed investigation across areas so large as to have been unimaginable decades ago. We here report on a multi-person mapping investigation of glacial landforms across the land areas of Fennoscandia, northern Europe, and parts of Russia, and which have yielded over 350,000 individual features recording ice flow (250,000), ice margins (70,000), and meltwater routing (30,000). All data, held in a GIS, are used to build a first-order reconstruction of the pattern of ice flow changes and ice margin retreat. Much of these data reveal a useful confirmation and replication of prior studies, which we now know with improved robustness, and with many new aspects being revealed, notably in ice divide positions.

Our ultimate aim is to build a simulation of whole ice sheet growth and decay incorporating changes in ice thickness and flow geometry and tracking successive ice-marginal positions. This is being achieved using the mapped landform data along with chronological data (Hughes et al. 2016), glacio-isostatic constraints and other constraints from the literature and comparing them with ice sheet modelling simulations using PISM (Winkelmann et al. 2011). We focus on using identified empirical changes in ice flow geometry (from the landforms) to choose between dozens of alternate ensemble ice sheet model simulations. The challenge is to build a three-dimensional simulation of ice sheet evolution that is physically well-founded that satisfies most of the flow geometry changes, and fits within empirically defined ice marginal positions.

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Reconstructing post-glacial landscape evolution around Inari, Finland using novel survey and dating instruments

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The landscape between Inari in Finnish Lapland and Younger Dryas age moraines in Finnmark, NE Norway holds a rich succession of landforms reflecting the dynamic final retreat of the Fennoscandian Ice sheet. However, despite the unusually well-preserved landforms this remote area is understudied, and large uncertainties remain about the pattern of retreat.

In this project a combination of DEM studies, field mapping, portable and laboratory-based optically stimulated luminescence and 14C-dating has been used to unpick the history of the retreat and the subsequent development of the landscape. Use of unmanned aerial vehicles, handheld photogrammetry and LiDAR scanning and a portable luminescence instrument has allowed the collection of a large data set from limited field time. These data allow more efficient analysis of the landscape and make it easier to share the research process and results.

Preliminary results show a pattern of ice-dammed lake formation and rapid drainage events giving way to the breakup of active ice and fast decay. Aeolian processes formed large dune fields stabilised by vegetation growth but containing preserved charcoal layers suggesting forest fire events.

Footprint of the Baltic Ice Stream: geomorphic evidence for shifting ice stream pathways

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Den baltiska isströmmen – the Baltic Ice Stream – was first conceptualised by the earliest workers in Scandinavian Quaternary geology. Over ~150 years of research, the Baltic Sea basin has been variably considered to have hosted floating or grounded ice of the Fennoscandian Ice Sheet, single or multiple ice flow events that breached the basin's terrestrial flanks, an independent ice dome or a funnelled flow path. Today, there is a widely held view that the Baltic carried a fast-flowing ice stream, in the modern glaciological sense. However, evidence for the Baltic Ice Stream has been largely restricted to its terrestrial periphery, and its true form, scale, function and role in driving deglaciation of the southern sector of the Fennoscandian Ice Sheet remain enigmatic.

Here we present geomorphological evidence directly from the Baltic seabed that confirms the existence of the Baltic Ice Stream and informs us of its behaviour (Greenwood et al., in press). From an extensive collection of high-, moderate- and low-resolution bathymetric terrain data, complemented by LiDAR-data over the Baltic islands, we have mapped >20,000 subglacial bedforms, meltwater landforms and grounding line landforms throughout the Baltic Sea basin. We present here a six-stage landform-based reconstruction of ice flow and retreat in the Baltic. We find that ice streaming was persistent, but stream pathways were variable in extent, timing and duration: different sectors of the Baltic exhibit asynchronous streaming and out-of-phase grounding line changes. Grounding line readvances occurred in both the south-western and northern Baltic. Abundant iceberg ploughmarks indicate that calving was a significant mechanism for ice loss, yet lobate, extended margin shapes suggest that upstream ice supply to the Baltic was consistently high. The reconstruction we present here is a first hypothesis, based on direct seabed evidence, for how the Baltic Ice Stream evolved, yet the seabed record remains fragmentary and incomplete. We look forward to discussing how the known landform record can be extended and how it, along with stratigraphic, core and chronological data, can provide insights into subglacial and grounding line processes governing the behaviour and the timing of Baltic Ice Stream flow and retreat.

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Holocene deglaciation and environmental history of Washington Land and Warming Land, north-western Greenland

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Sediment sequences from two small lakes on ice-free peninsulas in north-western Greenland, adjacent to the Nares Strait, separating Greenland from Ellesmere Island, form the basis for studies of immigration and persistence patterns of terrestrial plants and animals following the last deglaciation. The sediment records, collected as part of the icebreaker-based Ryder19 expedition in 2019, have been rigorously dated and analysed, combining biostratigraphic and geochemical methods.

A 203-cm long sequence from Ringed Plover Lake, Warming Land (269 m a.s.l., 81°48’N, 53°19’W), spanning the last c. 2300 years, consists of banded to laminated silt and clay (TOC content 1−5%) with bryophyte layers (Wangritthikraikul 2023). Although not reaching back to the local deglaciation, this record provides evidence of distinct fluctuations in the deposition of terrestrial macroscopic plant remains, such as *Salix arctica* and *Dryas integrifolia* as well as *Cenococcum geophilum* fungal spores, which reflect centennial-scale fluctuations in catchment runoff and erosion, mediated by precipitation and snowmelt intensity. Additional insight into these climate-related processes is provided by accompanying changes in the sediment concentrations of aquatic bryophytes, mineral grains coarser than 250 µm, chironomid head capsules, as well as by C/N ratios and key element contents and ratios obtained by X-ray fluorescence (XRF) core scanning. An extended period of generally mild and humid conditions after about 1500 cal. BP was succeeded by a shift to colder and drier climate around 400 cal. BP, likely associated with the Little Ice Age. Subsequently, an anomalous warming and wetting trend across recent decades is captured by some of these parameters.

A 186-cm long sequence from Red-Throated Loon Lake, Washington Land (186 m a.s.l., 80°35’N, 61°59’W), spanning the last c. 7300 years, consists of about 50 cm of clay overlain by silty gyttja (TOC content 8−15%) with organic detritus (Frisendahl 2023). Representing continuous sediment deposition since the local deglaciation, this record shows clear imprints of ice-proximal conditions with high suspension load in the water column until about 5500 cal. BP. Thereafter, aquatic productivity and catchment mineral weathering increased substantially, reaching maximum levels under relatively mild and humid climatic conditions, followed by declining trends after 3000 cal. BP. Together with XRF, TOC and C/N ratio variations, a sparse pollen record demonstrates early dominance and subsequent continuity of *Salix arctica* since the deglaciation, as well as millennial-scale changes in catchment soil and vegetation development. Ostracod remains in the sediments contribute to the environmental reconstruction, and the presence of coprophilous fungal spores (*Sporormiella* sp.) indicates the local presence of muskox at least during the last 3300 years.

These unique sediment records, deposited near the likely postglacial entry point of terrestrial biota to ice-free areas of northern Greenland are now subjected to palaeogenetic analyses, targeting key plant and animal species for a more holistic view of Holocene ecosystem dynamics in Arctic Greenland.

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Circular hummocky moraines in High Asia similar to Veiki moraines / ice-walled lake plains

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Hummocky moraine regions with irregular semi-circular rims surrounding a central depression are regionally widespread in the footprints of the Fennoscandian as well as the Laurentide ice sheets. In Fennoscandia, circular hummocky moraines known as Veiki moraines in northern Sweden are interpreted as formed during an earlier ice advance of the last glacial cycle and preserved under non-erosive ice during the last glacial maximum. In North America, circular hummocky moraine regions known as ice-walled lake plains formed during the deglaciation of the last ice sheet along the south central region of the ice sheet in USA and Canada. Apart from a handful of present-day glaciers in Alaska and Svalbard that may be producing analogues to the circular hummocky moraines, these landforms have only been described from paleo-ice sheet regions.

We present the first record of circular hummocky moraine regions in High Asia, identified by remote sensing of satellite images and high resolution elevation models. We have identified circular hummocky moraine regions in multiple locations across the Tibetan Plateau and the Altai Mountains. The hummocky moraines are generally found on widespread and often massive latero-frontal end moraines which spread out in relatively flat locations. The hummocks vary in morphology but they are commonly strikingly similar to Veiki moraines in northern Sweden and ice-walled lake plains in North America. The circular hummocks in High Asia have similar dimensions and morphology to their analogues in Fennoscandia and North America and they are located close inside a former glacier terminus similar to the ice sheet hummocks. The High Asia circular hummocky moraines are formed by alpine glaciers considerably smaller than the ice sheets that former the Veiki moraines and the ice-walled lake plains, and our findings indicate that these landforms are not exclusively formed by ice sheets.

A last spasm of the Scandinavian Ice Sheet: Traces of an Early Holocene glacial surge in south central Norway

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The final demise of the Scandinavian Ice Sheet in Norway occurred by rapid frontal retreat and vertical thinning and involved the formation of numerous meltwater features and ice-dammed lakes. The nature of ice sheet retreat is largely unknown, however, although the presence of De Geer moraines signals dynamic glaciers that retreated actively through some of the palaeolakes. Here we present a suite of landforms close to the former ice-divide in south central Norway, that we suggest are indicative of a glacial surge in the Early Holocene. The landform record comprises end moraines, extensively fluted terrain and a myriad of delicate ridges. The delicate ridges often superimpose flutes and drumlins and are generally oriented transverse to the moraine ridges, but also appear as a more chaotic and intricate network of rhombohedral-like ridges of various orientations proximal to the moraines. The ridges, which have amplitudes of 0.3-2 m and are typically spaced 30-100 apart, are interpreted as crevasse-squeeze ridges. The triggering cause for the purported surge event is unknown. The area is located just south of the southernmost palaeoshorelines related to the Early Holocene glacial lake Nedre Glomsjø, however, and we accordingly speculate that the glacial surge occurred as a result of a reconfiguration of the remnant ice sheet induced by a catastrophic drainage of the glacial lake.

New multibeam mapping data from Ammassalik Basin, SE Greenland: A tale of glacial landforms influenced by variable basement lithologies

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The Ammassalik Basin, offshore SE Greenland near Tasiilaq, is a Mesozoic rift basin bounded to the west by Precambian basement rocks. The basin was heavily influenced by Paleogene volcanism associated with the Iceland mantle plume and eventual opening of the North Atlantic (Gerlings et al., 2017). Eastward of where basin sedimentary rocks sub-crop below the seabed, subaerially extruded flood basalts cover the basin and give way seawards to a thick pile of seaward dipping reflectors characteristic of volcanic rifted margins (Peréz-Gussinyé et al., 2023). In addition, it has been suggested that parts of the margin may be underlain by older, Proterozoic–early Paleozoic meta-sedimentary rocks (e.g. Fyhn et al., 2012; Guarnieri et al. 2022).

In 2022 as part of the SEAMS project (SurvEy of AMmassalik basin Sediments), a collaborative effort between GEUS and Aarhus University with support from the Danish Center for Marine Research and Danish Arctic Command, we collected ~3000 km^2 of multibeam data supplemented by Innomar sub-bottom profiler data on the Danish patrol vessel *HDMS Lauge Koch*.

The data illuminate a number of glacially influenced landforms that appear to be in part controlled by the underlying substrate. Areas interpreted by Gerlings et al. (2017) as older meta-sedimentary rocks appear strongly eroded by ice tongues that must have covered the shelf, with several broad U-shaped valleys. Over the main part of the Mesozoic basin, only limited erosion is observed, but crag-and-tail features associated with sub-cropping basaltic sills are apparent, not unlike similar features that have been found in the Vaigat in West Greenland, where a sill intruded Cretaceous basin sub-crops below seabed. The hard Precambrian basement to the west, and the flood basalts to the east, do not appear to be greatly affected by glaciation, with no evidence for flow parallel striations, though these areas appear to have scour marks that could have resulted from icebergs.

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DATED-2: An updated ice-extent chronology for the Eurasian ice sheet complex, 40–10 ka

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DATED-1 comprised a fully-documented empirical reconstruction of the changing extent of the Eurasian ice sheets through the last glacial cycle, 40-10 ka (at 1000-year resolution after 25 ka) based on a glaciological-geological assessment of all relevant chronological data (n = 5477 dates) (Hughes et al. 2016). All uncertainties within the underlying data were synthesised and expressed in terms of distance; deviation between maximum and minimum limits, and their relative proximity to the extent considered 'most-credible', indicates the degree of chronological uncertainty along the ice margin for each 1000-year time-slice. Explicitly representing all uncertainties in this way provides a straightforward means to compare geological data with results from numerical modelling of past ice extent; an approach that has been replicated by recent synthesis reconstructions of other ice sheets (e.g. Dalton et al. In press; Clark et al. 2022). Our process created an archive of published dates (and associated data necessary for their interpretation, quality, and recalculation) relating to the build-up and retreat of the British-Irish, Scandinavian, and Svalbard-Barents Kara seas ice sheets. Both the time-slice reconstructions and underlying chronological dataset are available for further use via the online data repository PANGAEA (Hughes et al. 2015). However, new empirical geological data and interpretations are generated almost continually and valuable syntheses such as this run the risk of being frozen-in-time and losing relevance if not maintained and updated to reflect the latest observations. A decade on from the DATED-1 census of 1 January 2013 the volume of data has grown significantly (~5100 additional dates, >1000 additional sites), and in-tandem with methodological developments in dating procedures and calibrations. Here, we present the second-generation chronological synthesis, DATED-2, which brings the chronological dataset and time-slice reconstructions for the Eurasian ice sheets up-to-date; including all new chronological information published up to 1 January 2023. We highlight the main changes required to satisfy the new dates, present a new calculation of the evolution in ice sheet volume and timing of sea level contributions from the Eurasian ice sheets, and discuss implications for, and obstacles to, constraining the timing of ice sheet build-up and demise using empirical geological data.

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Does Late Glacial GIA aid Holocene ice cap persistence?

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Yes.

Given the terrain and glacial history (ice cover thickness and duration), glacio-isostatic emergence helps sustain Svalbard´s Holocene ice caps.

Fluctuations of the western flank of the Scandinavian Ice Sheet during Marine Isostope Stage (MIS) 3

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We describe glaci-lacustrine sediments buried under thick tills in Folldalen, south-east Norway, a site located close to the former center of the Scandinavian Ice Sheet. Thus, the location implies that the entire ice sheet had melted away when the sediments were deposited. The best age estimate from 20 quartz luminescence dates is 55.6 ± 4.6 ka for this Folldalen interstadial (Mangerud et al., 2023).

We consider that the Ålesund Interstadial, dated with more than 30 AMS ^{14}C dates to 38-34 cal ka BP (Mangerud et al., 2010), is the best dated interstadial during MIS 3. At that time much of western Norway, and possibly areas well inland, were ice free.

A glacial advance across the west coast of Norway during the time interval between the Folldalen and Ålesund interstadials is dated by a paleomagnetic excursion correlated with the Laschamp, well dated to about 41 ka BP (Valen et al., 1995).

Using our new data we will present an updated glaciation curve and compare it with the development of vegetation and climate in western Europe south of the ice sheet.

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Deglaciation history and subsequent lake dynamics in the Siljan region, south-central Sweden – LiDAR evidence and sediment records

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The Siljan region hosts Europe´s largest impact structure. The high-relief landscape, with a central granite dome bordered by lake basins, contains an array of glacial and shore-level landforms. We investigated its deglaciation history by mapping and analysing landforms on high resolution LiDAR-based Digital Surface Models coupled with well-dated sediment successions from peat and lake sediment cores. The granite dome and bordering areas are characterized by streamlined terrain and ribbed moraine with a streamlined overprint. These suggest an ice-flow direction from NNW with wet-based thermal conditions prior to deglaciation. During its retreat, the ice sheet was split into thinner plateau ice and thicker basin ice. Sets of low-gradient glaciofluvial erosion channels suggest intense ice-lateral meltwater drainage across gradually ice-freed slopes, while 'down-the-slope' erosion channels and eskers show meltwater drainage from stagnated plateau ice. Thick basin ice receded with a subaqueous margin across the deep Siljan–Orsasjön Basin c. 10,700–10,500 cal. BP. During ice recession the ingression of the Baltic Ancylus Lake led to diachronous formation of highest shoreline marks, from ~207 m in the south to ~220 m a.s.l. in the north. Differential uplift resulted in shallowing of the water body, which led to the isolation of the Siljan–Orsasjön Basin from the Baltic Basin at c. 9800 cal. BP. The post-isolation water body – the ‘Ancient Lake Siljan' – was drained through the ancient Åkerö Channel with a water level at 168–169 m a.s.l. during c. 1000 years. A later rerouting of the outlet to the present course was initiated at c. 8800 cal. BP, which led to a lake-level lowering of 6–7 m to today’s level of Lake Siljan (~162 m a.s.l.). This study shows the strength of an integrated methodological approach for deciphering the evolution of a complex landscape, combining highly resolved geomorphological analysis with well-dated sediment successions.

Lateglacial to Early Holocene deglaciation of central North Iceland

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Following rapid wasting and subsequent early Bølling collapse of the Icelandic Ice Sheet (IIS) coastal North Iceland and outer Eyjafjörður fjord became ice-free. At this time, the earliest ice-lakes were formed in northern part of the Fnjóskadalur valley collecting considerable amount of sediments. Later, and due to a significant but yet unknown extent of deglaciation, outlet glaciers from the IIS advanced into the outer parts of Eyjafjörður and Skjáfandi bay. This resulted in the formation of the about 38 km long Austari-Krókar ice-lake in Fnjóskadalur. Deltas, formed at the shoreline of this ice-lake and containing large quantities of the Skógar/Vedde tephra, produced in an explosive eruption of the Katla Volcano (^{14}C dated to 12.1 cal. ka BP). Stratigraphical studies of glacio-lacustrine sediments have revealed that the Austari-Krókar Ice-lake was drained before the formation of the Fnjóskadalur ice-lake, that subsequently also drained following the retreat of the Eyjafjörður outlet glacier.

Succeeding this extensive deglaciation, glaciers in central North Iceland readvanced and the Eyjafjörður outlet glacier terminated at Espihóll and Melgerði some 56 and 63 km, respectively, south of the island of Hrísey. There, ice-contact deltas and sandar were formed when relative sea level was at about 40 and 30 m a.s.l., respectively. On the west side of Eyjafjörður, outlet glaciers in Hörgárdalur and Svarfaðardalur valleys terminated at two separate occasions with relative sea level at successively lower positions. Associated relative sea level was at about 20 and 10 m a.s.l. at the mouth of Hörgárdalur and at about 10 and 5 m a.s.l. at the mouth of Svarfaðardalur. Furthermore, raised shoreline features are found along the west side of Eyjafjörður at altitudes increasing towards the south.

Changes in shoreline gradient over time, due to non-uniform glacio-isostatic uplift is best expressed with an exponential equation. Applying such a glacio-isostatic age-model for tilted ice-lake shorelines in Fnjóskadalur and marine shorelines along Eyjafjörður has returned Younger Dryas ages for ice margin located in the outer parts of Eyjafjörður. Additionally, the glacio-isostatic age-model suggests Preboreal ages for glaciers terminating in the outer parts of Svarfaðardalur and Hörgárdalur as well as in the inner parts of Eyjafjörður. Interestingly an even younger position of the Eyjafjörður outlet glacier is found about 14 km south of its Melgerði position.

A ‘virtual ice surface’ for representing the vertical down-wasting of ice in the Upper Etne valley, southcentral Norway

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It is acknowledged that meltwater landform domain hold valuable information on the dynamics and deglaciation of past ice sheets. Yet, analyzing the retreat patterns from spatial and temporal relations of meltwater landforms are difficult and inherit large uncertainties.

By using a GIS tools that have the roots in flood modelling and using the upper Etne valley in southcentral Norway (an inner area of the former Fennoscandian Ice Sheet) as a case study we aim to use meltwater landforms to reconstruct the deglaciation in detail. In ArcGIS software a simple reference surface gradient was implemented as a ‘virtual ice surface’ and used for representation of the vertical down-wasting of ice (in ArcSCENE) within the area previously described by Garnes & Bergersen (1980).

As a result, delineations are traced along the positions where reference surfaces intersect the terrain (DEM). Comparing the delineations with the distribution pattern of meltwater landforms have revealed several important ice marginal positions and significant events of the meltwater drainage. Further, a reasonable sequence of events at the final stages of the deglaciation illustrating changes in ice dynamics, disintegration of ice, existence and drainage of local ice-dammed lakes were reconstructed in greater detail than described before.

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The "Lund Moraine" – the geomorphic limit of the last ice advance in the Öresund region

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Here we present geomorphological evidence of a ~50 km long, ice-marginal moraine complex in southwestern Skåne, southernmost Sweden, which we name the "Lund Moraine". The moraine can be traced from Bonderup in the southeast and continuing northward through Dalby, Lund, Eslöv and Svalöv up to the Öresund coastline and onto the island of Ven. The morphology of the moraine changes along its length from being confined to a single, although locally hummocky, ridge only a few 100s m wide to broader zones of hummocky and/or multi-crested moraine zones up to 4 km broad. Regionally, the moraine has a lobate form with local extensions of sub-lobes following lower parts of the terrain. It marks a sharp boundary between a heavily streamlined landscape distal to the moraine and a gently undulating landscape within the moraine, and closely outlines the extent of the "Lund till/diamicton". Based on the extent of the Lund Moraine, and it overriding an older esker, we interpret that the moraine was formed by a readvance, corresponding to a late Young Baltic readvance of the Scandinavian Ice Sheet sometime after *c.* 16 cal. ka BP. Our observations will hopefully settle the ~50 years long controversy concerning the extent or even existence of such a readvance into Öresund. We expect that our findings will guide further work towards disentangling the complex deglacial history of Skåne and the wider Öresund region.

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Ice sheet thinning and final decay in central south Norway

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In a new paper we describe the development of the Scandinavian Ice Sheet during the last deglaciation in the Gudbrandsdalen area, central south Norway (Romundset et al., 2023). The study combines three independent datasets; (1) radiocarbon-dated lake records, (2) cosmogenic ^{10}Be-dated, glacially transported boulders, and (3) shoreline gradients of former ice-dammes lakes. We conclude that the ice sheet lowered below the ~2000 m high mountains surrounding northern Gudbrandsdalen in the Early Holocene and disappeared by ca. 10.0 ka BP. The ice-sheet thinning rate through this period is estimated at ca. 2 – 6 m yr^{-1}. The final phase of deglaciation involved formation of large proglacial lakes which were dammed between the ice sheet remnants and topographic saddle points. We mapped several such lakes, most notably the Store Dølasjø (480 km^2 and 80 km^3) which was formed after 10.4 ka BP and finally drained around 10.0 ka BP. The ice-marginal landforms that characterize the mountain region of northern Gudbrandsdalen, i.e., moraine ridges, lateral meltwater channels, as well as deposits and shorelines from ice-dammed lakes, thus collectively originate from a period of rapid ice sheet downwasting over ca. 1600 years.

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Configuration of the Scandinavian Ice Sheet in SW Norway during the Younger Dryas

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Based on ^{10}Be dating we reconstruct the 3d configuration of the Scandinavian Ice Sheet along a transect extending from the Younger Dryas margin just west of Bergen city and over to the Ra Moraine on the opposite side of the mountain range in southern Norway (Briner *et al*. 2023). We sampled many bedrock surfaces and perched boulders on or near the highest summits in the Bergen area, which lies slightly within the Younger Dryas ice extent. In addition, we have dated some ice-transported erratics located up to 1600 m a.s.l. in a mountain area (Tarven) 120 km further inland. All exposure ages were calculated by using the ^{10}Be production rate of Goering et al. (2011, 2012) and using version 3 of the online exposure age calculator (https://hess.ess.washington.edu/; Balco et al. 2008). The results indicate that all mountain summits around Bergen, ranging from 400-680 m a.s.l, were covered by the ice sheet during the final phase of the Younger Dryas cold spell. Furthermore, in the light of the dating results from the mountain Tarven further inland it seems clear that the ice surface had risen to well above 1600 m a.s.l. in this area. The inferred ice sheet configuration resembles today's profiles over the Greenland ice sheet. By making a comparison with Greenland we find it likely that the surface of the ice dome in the area just north of the Hardangervidda mountain plateau reached a height of about 2100 m a.s.l. during the Younger Dryas maximum ice sheet extent. With the support of a large number of existing ^{14}C dates and sea-level data, it seems clear that the subsequent collapse of the entire ice sheet happened in response to the Early-Holocene warming.

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Dynamics of the last ice sheet along the Gardno moraines (northern Poland): reconstruction inferred from landforms analysis and ^{10}Be dating

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Geomorphological record of the past ice margin positions is a robust proxy for reconstructing palaeo-ice sheets dynamics and their reaction to climate warming at the Last Glacial Termination. Coupling geomorphological traces of the palaeo-ice sheets to a time-scale enables our better understanding of timing and dynamics of deglaciation. It usually shows complex behavior of the palaeo-ice sheet's fringes with episodes of ice margin stillstands, local re-advances and/or extensive retreat. After the Last Glacial Maximum the southern margin of the last Fennoscandian Ice Sheet (FIS) receded gradually, leaving glacial landforms clearly visible in the landscape. However, this general ice sheet retreat was discontinuous and asynchronous, often punctuated by the ice margin stillstand or local re-advances (Marks 2012, Lüthgens et al. 2020, Tylmann et al. 2022). Here we present a new results of glacial landforms mapping based on high-resolution LiDAR Digital Elevation Model and ^{10}Be surface exposure dating of erratic boulders at the northern fringe of Poland.

The study area covers a part of the Polish middle-coast region with conspicuous ice-marginal moraines. The Gardno moraines are the end moraine ridges recording the ice margin position after a local ice sheet re-advance, which is recently correlated with the phase of deglaciation dated at 16.8–16.6 cal ka BP or 16.5 ± 0.5 ka (Marks et al. 2016, Tylmann & Uścinowicz 2022). However, our new results show that the geomorphological record of palaeo-ice margin positions in this area suggests highly dynamic oscillations of the ice front which may be chronologically constrained with a new ^{10}Be surface exposure dating.

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New geological maps from the continental slope and shelf north off Svalbard

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The MAREANO-program (www.mareano.no) is an interdisciplinary mapping program focusing on increasing the knowledge of the seabed and producing thematic geological and biological maps, contributing towards a more sustainable and knowledge-based management and commercial development of the Norwegian seafloor. The MAREANO-program is a collaboration between the Geological Survey of Norway (NGU), the Institute of Marine Research and the Norwegian Mapping Authority.

Geological seabed maps created by NGU include maps of sediment grain size and genesis, sedimentary environments and landforms. The maps are created based on terrain and stratigraphical analyses of geophysical data (e.g. detailed bathymetry, backscatter, and high-resolution seabed sediment profiles), sediment samples (grabs, boxcores and multicores) and video footage.

In this study we present a few selected highlights from the seven newly mapped areas, and while the seabed is mainly dominated by glacial landforms on the continental shelf (such as moraines, troughs, mega-scale glacial lineations and ploughmarks), which moves towards more gravity driven/influenced processes on the slope (e.g. glacigenic debris flows, slides and canyons) there are interesting and significant differences in morphology between the sites that illuminates more of the geological history and glacial influence on the Svalbard margin.

Session 25
Glacial processes: Under ice and under pressure

Session Chairs:
Adrian Hall,
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Mark Johnson,
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The Skessugarður bouldery end moraine, east Iceland: preliminary results on clast shape and moraine formation

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The Skessugarður end moraine is located in the highlands of eastern Iceland in the middle of a palaeo-ice stream flow-set extending from the interior highlands north of the present Vatnajökull ice cap in the southwest towards the coast in Vopnafjörður in the northeast. The moraine is situated on a streamlined bedrock hill and is around 7-m high and 10-m wide with a slightly steeper up-ice slope. The moraine is unique in that it consists almost entirely of boulders. Boulders are abundant on the bedrock hill, though seemingly less inside the moraine. The aim of this study was to examine clast morphology within the moraine in order to shed light on its formation and glacial processes operating during the deglaciation of the Iceland Ice Sheet. The clast morphological analysis involved measuring the a-, b-, and c-axis of boulders within as well as inside and outside Skessugarður both in the field and, for comparison, on a high-resolution DEM built from drone images. The purpose of the comparison was to explore the usability of high-resolution DEMs for clast morphological analyses. The comparison indicated that the high-resolution DEM can be used for analysing the morphology of stacked boulders that are well exposed within the moraine. In contrast, this method shall be used with caution where boulders are partly buried inside and outside the moraine.

A preliminary hypothesis involves initial creation of boulders through hydraulic jacking from the bedrock, subsequent glacial ripping of the loose clasts and downglacier transport, and finally deposition at the ice margin. More data on clast morphology, regional boulder distribution, and bedrock characteristics is needed to test this hypothesis.

Transient overpressure in subglacial meltwater corridors during rapid deglaciation of the Fennoscandian Ice Sheet

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Abrupt warming at the Younger Dryas-early Holocene transition triggered rapid melt of the Fennoscandian Ice Sheet. In low relief terrain in Uppland, east-central Sweden, meltwater arriving at the bed was distributed through an arborescent network of subglacial conduits. Evidence for hydrofracture, hydraulic jacking, and the brecciation of rock surfaces on conduit floors indicates transient development of overpressure (Pw > Pi). Small rock hills were distended by fluid flowing into and dilating fractures and burst open. In rapidly opening esker tunnels, boulders up to mega-block size were released and transported at minimum estimated flow velocities of 1-8 m s^{-1}. Inversely graded, poorly sorted, rubble and gravel beds in which the boulders are seated indicate flow of hyper-concentrated, dilatant slurries. Similar damage markers are present in rock-cut meltwater channels, demonstrating that extreme pressure and flow conditions developed transiently in both Röthlisberger- and Nye-channels. Hydraulic damage markers also occur across the floors of 0.4-4.0 km wide meltwater corridors, with disruption of many small roches moutonnées and formation of spreads of angular boulders. Sharp lateral and vertical limits indicate that damage occurred within 1-4 m thick sheets of pressurized meltwater that developed during ice-bed separation. Till layers were eroded or became dilatant and fluid, moving as debris flows. Glacial transport of boulders over short distances (1-100 m) is consistent with glacial ripping of brecciated bedrock in response to brief (days to weeks) accelerations in ice flow.

Hydraulic damage to rock surfaces, release and transport of boulders, and hyper-concentrated flows are typical of ancient and Pleistocene subglacial floods and have been recorded from historic Icelandic jökulhaups. Along segments of Swedish eskers, forming mainly within 10 km of the ice margin, subglacial floods briefly exceeded conduit capacity, forcing overpressure and bursting seals at esker tunnel margins to release sheets and jets of sediment-laden meltwater. Along meltwater corridors, overpressured sheet flow advanced rapidly, before coalescing into conduits and draining. Most hydraulic damage likely occurred rapidly during peak pressure at subglacial flood wave fronts. The former Fennoscandian Ice Sheet provides an accessible testbed for understanding the impacts of transient overpressure during rapid ice sheet melt and analogue for future rapid melting of the Greenland Ice Sheet under anthropogenic warming.

Murtoos and related landforms cross-cutting ribbed moraine in Western Finland: Implications for rapidly increasing subglacial drainage

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Murtoos and related depositional landforms have recently been associated with subglacial meltwater routes (SMR), representing transition from distributed to channelized drainage systems within the Fennoscandian Ice Sheet (e.g. Peterson Becher & Johnson 2021; Ojala et al. 2022). SMRs are often found cross-cutting ribbed moraine fields and later occupied by eskers or exhibit downflow transition to eskers. Vérité et al. (2022) propose that repeated subglacial flooding of ribbed moraine features can form murtoos. According to Mäkinen et al. (2023a) Finnish murtoos, influenced by ice-stream dynamics, were deposited with effective pressure close to zero. Due to high meltwater pressure, deformation by ice-flow remained low.

We describe the Lestijärvi-Kinnula ribbed moraine field that has been intensively modified by subglacial meltwater flow, including murtoo formation, which indicates that the field was formed about 40–60 km from the coeval ice margin (Hepburn et al. 2022). The aim of this ongoing study is to interpret the development of the depositional environment and subglacial hydrology responsible for the evolution of the SMR and the associated ribbed moraine field. The study area is located in Western Finland within the trunk of the Finnish Lake District Ice Lobe (FLDIL) and represents a probable shear-zone margin of an ice-flow corridor delineated by streamlined terrain and a major marginal esker (cf. Vérité et al. 2021). Our study is based on geomorphological mapping conducted using high-resolution LiDAR DEM along with sedimentological data from excavated pits, ground-penetrating radar surveys, geomorphological field control, and drone images of selected boulder fields.

The murtoo related ridges characteristic for the SMR were interpreted to evolve on erosional remnants of till, forming a locus for the deposition of sorted sediments and murtoos in subglacial conduits. Various escarpments indicate meltwater erosion after murtoo formation. Large channels are present along the up-ice margins of the ribbed moraine field and seem to have spilled over, forming extensive boulder fields. Boulder fields typically fringe ribbed moraine ridges and hummocks or mark channels between them, indicating widely distributed meltwater erosion. Many of the ridges also exhibit reworking by meltwater flows. Overall, the results indicate rapid increase in subglacial drainage but it remains to be discussed whether this flooding was due to an outburst from a subglacial lake or from a supraglacial water source possibly related to intense crevassing along the shear-zone margin of the ice-flow corridor. Supraglacial water input is suggested by geomorphological features and boulder fields possibly related to moulins or larger water blister marks (Mäkinen et al. 2023b).

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Sediment exposed in murtoos at Växjö, southern Sweden, shows evidence of over-pressurized subglacial water during formation

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V-shaped or triangular-shaped hummocks that are referred to as murtoos were discovered in Finland and Sweden in 2017 (Mäkinen et al. 2017; Peterson, Johnson & Smith 2017). The initial publications and subsequent literature interpret these forms to have formed subglacially around 50 km or so from the ice margin during times of rapid ice retreat. Eskers are found on top of murtoos, and murtoos occur in places in corridors parallel to regional ice flow. Rapid retreat would have delivered large amount of supraglacial meltwater to the bed, and the diamictons and sorted sediment found in murtoos have been interpreted as having been affected by this increased meltwater causing remobilization of existing sediment, fluvial deposition, and fluvial erosion (Peterson Becher & Johnson 2021).

An exposure at Växjö in a murtoo field reveals sediment that generally supports this model. The exposure contains interbedded diamicton and sorted sediment of varying character. The sorted sediments range from silt and fine sand to gravelly, and the diamictons vary as to clast content and friability. In thin section, the sorted sediments reveal deformation structures including deformed bedding, faults, and sandy sediment that we interpret to be fluidized sediment. Isolated intact sediment 'rafts' occur within this sandy sediment. None of the thin sections reveal sorted sediment that appears to be in original position. Cross-cutting relationships indicate several generations of deformation and/or injection events. Brittle deformation (micro faults) post-date fluidized features. Long axes of elongate grains cluster in up-ice dipping patterns. Finally, silt caps are present on some clasts seen in thin section, and we think these are associated with permafrost following deglaciation.

The murtoo field at Växjö was deglaciated during the Bölling-Alleröd, which was a time a rapid ice retreat in southern Sweden. The observations in the outcrop and in thin sections of the Växjö murtoo support the idea that murtoos were created during times of rapid ice retreat and that increased water pressure at the bed created the features we describe. Eskers overtopping murtoos indicate a later time when efficient bed drainage had been achieved.

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Water at the ice-bed interface and below: processes, sediments and landforms

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Subglacial water is a critical element of the glacial system modulating the nature of interactions between ice sheets and their beds. Its impact can be deciphered using the sedimentary and geomorphological record of past glaciations coupled with numerical simulations. Water pressurized by the overlying ice reduces the strength of coupling between the glacier and the lithosphere below, which accelerates the flow of ice and reduces its stability. Modulated by the ice surface slope, the water will be driven to the ice margin either through distributed or channelized drainage systems at the ice-bed interface, or it will recharge the subglacial aquifers and drain to the ice margin as groundwater flow. Heavily pressurized porewater reduces the strength of the underlying sediment, which may lead to sediment advection in a mobile traction carpet and generate subglacial diamictons found in such landforms as drumlins, mega-scale glacial lineations and flutings. Here we present examples from the geological record indicative of specific meltwater-related processes including deeply incised tunnel valleys, glacial curvilineations, infilled meltwater channels (Fig. 1), subglacial sheet-flow deposits, mega-scale glacial lineations, and subglacial traction tills. Taking into consideration also numerical experiments on groundwater flow under past ice sheets, we highlight possible genetic relationships between these elements and suggest the mechanisms driving them. Growing evidence points to ubiquity of pressurized meltwater under large continental ice sheets of the Pleistocene and importance of the resultant palaeoglaciological consequences.

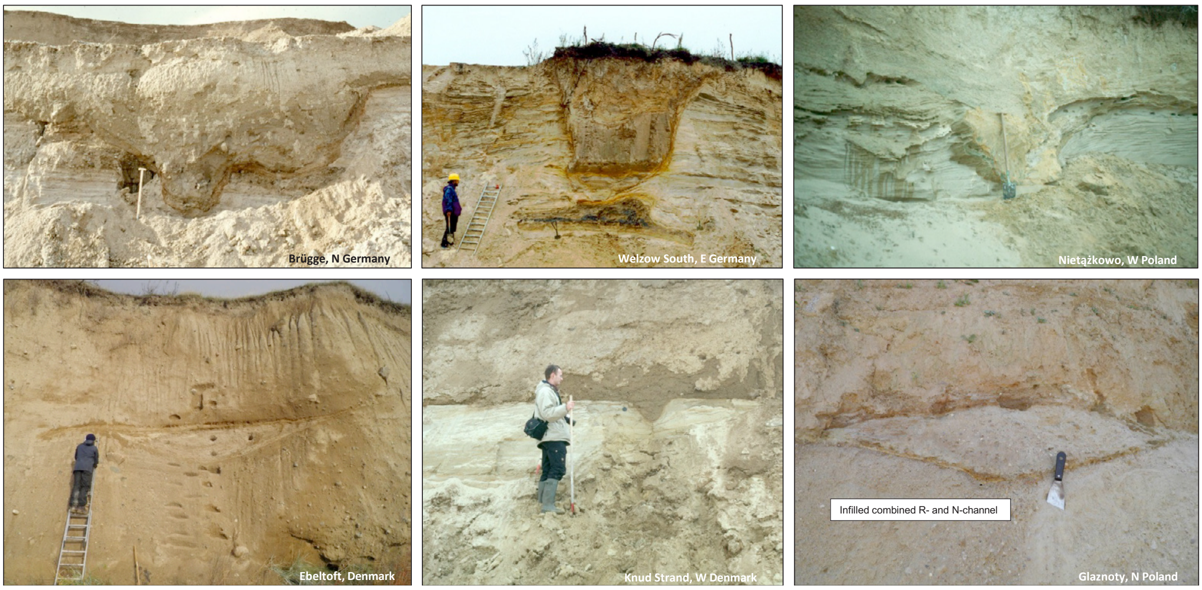

Fig. 1. Examples of small infilled subglacial meltwater channels from the southern outskirt of the Scandinavian Ice Sheet.

The Boulder Story: Kvarken archipelago

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Kvarken archipelago in Gulf of Bothnia lay in the southern part of Fennoscandian Ice Sheet frozen-bed region during the Late Weichselian glaciation (cf. Kleman et al., 1999, Lundqvist 2007). A complex glaciated terrain development is indicated by highly variable geomorphology. The region is characterized by fields of hummocky and ribbed moraines, glacial lineations, and the De Geer moraine field in Raippaluoto island (Breilin et al. 2011). The final shaping of the terrain suggests rapid retreat of the ice margin in relatively deep water. This presence of angular boulder fields in the region remains mysterious, because the traditional formation story connected to iceberg calving or ribbed moraine formation is not fully agreed.

In recent studies, special attention has been paid to the erosion by pressurized meltwater in the subglacial environments (cf. Hall et al. 2020). The latest LiDAR mapping and field studies at Kvarken has provided new evidence for pressurized subglacial waters providing both channelized and sheet flow of the melt waters. According to the broken rocks in many locations they may became disrupted by over pressured water pulses or hyper-concentrated slurries during subglacial floods resulting rock damage and / or rubble diamicton surfaces. Excluding the surfaces of the ribbed moraines, these terrains are so widely exposed that it is possible to represent wide areas that have undergone these conditions leaving behind rough boulder dominated glaciated terrain. These observations show a previously unknown role of the subglacial waters in glaciated terrain formation in the region.

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The Fennoscandian ice sheet as driver of groundwater aquifer flushing offshore northern Norway

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Ice sheet loading plays a crucial role in flushing groundwater aquifers and altering large-scale groundwater systems (Boulton et al. 1993, Person et al. 2007). These processes can result in offshore groundwater freshening and submarine groundwater discharge (SGD) due to overpressurized aquifers (DeFoor et al. 2011, Hong et al. 2019). In the vicinity of the maximum extent of the Fennoscandian Ice Sheet (FIS), offshore the Lofoten Islands, northern Norway (approximately 800 meters water depth), we observed downcore porewater freshening and a linear relation between $\delta^{18}O$ and $\delta^{2}H$ of the porewater, evidential of a meteoric water-sourced component. Radiocarbon content profiles of the Dissolved Inorganic Carbon (DIC) suggest the advection of old groundwater into the marine sediment porous media. Based on the chloride content of this upward-advected groundwater, brackish conditions seem to predominate. The freshwater component has been attributed to past aquifer freshening during the Last Glacial Maximum (Hong et al. 2019). However, the origin of the saline component remains ambiguous. By employing radiocarbon dating of the DIC carried by the groundwater and a two end-member mixing model, we demonstrate that groundwater residence times of the saline component coincide with the retreat of the FIS. This implies that the collapse of the FIS facilitated seawater infiltration into offshore aquifers, catalyzing a profound shift in subsurface hydrology. The $\delta^{18}O$ values (> 2.5 ‰ VPDB) of methane-derived authigenic carbonates indicate that carbonate precipitation occurred in the presence of ^{18}O-enriched water. This suggests that methane seepage and subsequent carbonate precipitation coincided with saltwater intrusion, as supported by previously reported U-Th ages of authigenic carbonate crusts (Hong et al. 2019). Our study underscores the profound impacts of the collapse of the Fennoscandian ice sheet on offshore groundwater systems, with potential consequences for the local carbon cycling.

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Distribution of hydraulic damage from overpressure beneath the rapidly retreating margin of the last Fennoscandian ice sheet in Uppland, Sweden

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Understanding processes that operate beneath rapidly melting ice margins is critical for predicting the responses of the ice sheets to anthropogenic global warming. Where large or rapid meltwater inputs arrive at the ice sheet bed, ice flow may temporarily accelerate, and meltwater flow mobilises and erodes sediment. Where the capacity of subglacial conduits is reached, water pressures may briefly exceed ice-overburden pressure (Pw>Pi) and water can laterally burst out of the conduit. Yet the timing and distribution of overpressure beneath former Northern Hemisphere ice sheets remains largely unknown. Here we examine patterns of overpressure development during final retreat of the Fennoscandian ice sheet across low relief, Precambrian basement terrain in Uppland, Sweden. We first integrate evidence from digital elevation models, aerial photos and field survey observations with existing map data on landforms and sediment from the Swedish Geological Survey to identify and delimit subglacial drainage pathways. We then add markers for hydraulic damage at the ice sheet bed that include rock hydrofractures, brecciated rock surfaces, and associated boulder spreads, and disrupted and partially disintegrated roches moutonnées to reveal where large volumes of subglacial meltwater reached overpressure.

Elevated areas of Uppland generally lack meltwater flow traces, retain till cover, and carry undamaged precursor rock surfaces. These are interpreted as zones of low volume, distributed subglacial drainage. In contrast, crossing meltwater corridors, 0.4-4 km wide, with up-down centerline profiles indicate high-volume and high-pressure meltwater flow. Meltwater corridors include fracture-controlled rock trenches that acted as Nye-channels, esker tunnels that functioned as Röthlisberger-channels and elongate hummock tracts that drained sheets and jets of meltwater beneath the retreating ice margin.

Hydraulic damage is scarce in zones of low volume distributed subglacial drainage. Hydraulic damage from overpressure is also absent from 1-20 km long rock trenches along the edge of the Åland Deep rock basin and from 0.5-10 km long segments of N- and R- channels. Despite availability of large volumes of meltwater in these former conduits, overpressured conditions did not develop. Here, subglacial meltwater was efficiently drained along hydraulically well-connected rock channels and crossing rock trenches. In contrast, other 4-40 km long segments of meltwater corridors carry hydraulic damage consistent with transient development of overpressure at full pipe flow. Sharp lateral and vertical boundaries to hydraulic damage are observed that are interpreted to represent the maximum local extent of sheetflow caused by overpressured sediment-laden water. Abrupt terminations and onset zones for hydraulic damage are consistent with the development of transient subglacial water pressures by sudden transfer of large volumes of supraglacial meltwater to the glacier bed as the ice margin retreats. We find that the role of overpressured meltwater is critical for understanding erosion of rock, mobilisation, transport and deposition of subglacial sediment, and formation of subglacial landforms beneath rapidly thawing ice margins.

Session 26

Sedimentary ancient DNA applications to Quaternary geology

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Ernst Jonsson,
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Flore Wijnands,
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Culture, climate or both? 6000 years of human activity from Ireland using sedaDNA, stable isotopes, lipid biomarkers and pollen

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In the humid-temperate western seaboard of the North Atlantic the roles of climate and culture in settlement and lake history are hard to disentangle due to multiple forcing factors. In this study a 6000 year record from a lake in Ireland (Lough Catherine) is analysed using geochemistry (stable isotopes, biogenic silica, XRF), molecular methods (sedaDNA metabarcoding and lipid biomarkers), and biological proxies (pollen and spores). We also present a collation of the archaeological data, which provides a comprehensive sequence for the major site in the catchment (Island MacHugh). Our analysis reveals close tracking of the archaeology by the molecular data from later prehistory to the modern period. The development of agriculture from the Late Bronze Age into the Iron Age is revealed by sedaDNA of the common agricultural plants and animals as well as direct evidence of site occupation in the form of fecal stanols. A second major peak of activity occurs in the early Medieval period when the island-site is converted into a defended settlement. The authenticity of the sedaDNA data is confirmed by the sedaDNA-estimated date for the introduction of exotic species (trees) into the catchment. GAM modelling reveals that the lake variables (BSi and stable isotopes) are principally driven by vegetation, which reflects human influences on land use rather than climate. The sedaDNA, biomarker and isotope data also reveal only weak correlation with climatic factors. In contrast to a deterministic view of climate being determinant the controlling factor here is human activity and subsistence culture.

Using sedimentary ancient DNA to reveal postglacial recolonization patterns in Sweden

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The area around the lakes Siljan and Orsasjön in Dalarna, Sweden, is interesting from an archaeological point of view given the amount of pre-historic activity. The earliest evidence of human presence, derived from radiocarbon dated burnt faunal bones found at Orsandsbaden, dates back to c. 10,2 cal. ka BP. The early Holocene environment which the pioneers encountered had seen the Fennoscandian ice sheet disappear a few centuries before. As the ice sheet retracted from Fennoscandia, the recolonization of flora and fauna was initiated when the land became accessible. Plants and trees are represented in pollen and sedimentary ancient DNA (sedaDNA) records from lake cores in Sweden. However, there is no direct genetic evidence from the first early Holocene humans in the region, mainly due to an absence of osteological findings. This has left the answer to who the first colonisers were and where they came from clouded with uncertainties. It has been established that two main routes into Sweden were taken by the pioneers, one from southwest through Denmark and Norway, and one from east via Finland, but more detailed genetic information is yet to be undisclosed. Modern technology has provided the field with an updated toolbox which allows for novel approaches in order to reveal the origin and genetic profiles of the first Scandinavians, and the attention is turned towards sedaDNA. Lakes have the potential to record environmental changes and species present in the catchment area within the sediment layers. Here, we analyse newly generated sedaDNA found in lake sediments from Orsasjön, which allows us to investigate postglacial recolonisation patterns of plants and animals, including humans.

The SciLifeLab Ancient DNA unit, a national resource for sediment DNA analysis

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Analysis of ancient sediment DNA provides a wealth of information on biodiversity, ecology, development of agriculture and land use, and the impact of *e.g.* human activity and climate changes on local environment over time. Generating high-quality ancient sediment DNA requires specialized laboratories, methods and expertise. The SciLifeLab Ancient DNA unit, also part of the ArchLab and Swedigarch national research infrastructures, is a core facility that provide support with analysis of ancient sediment DNA. The unit is based at the Center for Palaeogenetics, part of Swedish Museum of Natural History and Stockholm University, and at Uppsala University. The facility has state-of-the art clean-room laboratories for ancient DNA processing, and staff with expertise in both laboratory and computational analysis. Our unit can analyze a range of different type of samples and also perform analysis of *e.g.* DNA from human and animal material, in addition to sediment samples. You are welcome to contact us for further information and project discussions.

Multiproxy reconstruction of the variability of the East Greenland Current during the last 150 000 years

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Due to climate change the Arctic region is warming at a rate two to three times higher than the global rate. Most strikingly this becomes evident by the expansion of the warm Atlantic Water (so-called Atlantification) into the Arctic Ocean. The process further causes severe reductions in sea-ice coverage and a decrease in winter sea-ice thickness. These processes lead to increased open water areas and further the oceanic uptake of atmospheric heat which can lead to ice-free Arctic conditions by the end of this century. In recent years, Atlantification was observed also near the coast of Greenland where warm Atlantic water mixes with the East Greenland Current. Despite the fact that the heat fluxes, caused by the inflow of Atlantic Water threaten to destabilize the Greenland Ice Sheet there is a lack of long-term information regarding ocean variability at the Greenland shelf. Therefore, the main ambition of this project is to reconstruct the changes in the strength of the East Greenland Current and the behavior of the Eastern Greenland ice sheet throughout the last 150 000 years. The project emphasizes the Eemian period (~130 000–115 000 BP). Due to the higher than today temperature, Eemian is considered a past analogue for future climatic warming. To overcome the limitations due to the lack of fossils e.g. shells, material creating several gaps in marine records, a traditional palaeoceanographic approach such as analyses of foraminiferal species and measuring oxygen and carbon stable isotopes recorded in their shells, will be combined with biomarker data (IP25) for sea-ice reconstructions, and state-of-the-art analysis of sedimentary DNA (*seda*DNA). Analyses of *seda*DNA is based on the reconstruction and analysis of genomic information of species preserved in marine sediment and indicate the presence of marine organism also foraminifera, even in the absence of visible residues e.g., calcareous shells. This will allow to create so far missing, a coherent baseline of information on the variability of the East Greenland Current, and the Eastern Greenland ice sheet in response to climate warming. This information can further provide an evaluation basis for ocean and ice sheet models, and information regarding ocean ecosystem shifts to come.

Sedimentary ancient DNA for sea ice reconstructions: a case study from the Yermak Plateau (Svalbard)

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Sea ice is a critical component of the Arctic ecosystem, but it is probably one of the least well-documented and understood components, especially on historical and geological timescales. In the past, large climate-induced reorganizations of environmental conditions were associated with significant changes in sea ice cover. Despite its importance for the Arctic ecosystem, the variability of sea ice cover is relatively poorly documented over geological timescales. The tools to document the evolution of sea ice conditions are few and have limitations.

There were few attempts to test the utility of sedimentary ancient DNA (sedaDNA) in sea ice reconstructions; however, they were based on the comparison between eDNA and other proxy records. Herein, we present the sedaDNA record from the Yermak Plateau spanning the last ca. 180,000 years. We focus on planktonic organisms: foraminifera and radiolaria, two well studied groups, commonly used as paleoceanographic proxies; and MAST (Marine STramenopiles), a poorly studied group, which was not used systematically in paleoreconstructions. We strengthened our study by establishing a statistical correlation between the presence of selected planktonic ASVs and specific sea-ice conditions. We propose potential indicators of marginal and extended ice cover and ice - free conditions.

Our study is a further step towards the application of sedaDNA in the reconstructing past climatic and environmental changes.The sedaDNA approach has the potential to become a useful tool in sea-ice reconstructions in the Arctic regions, especially in environments where other approaches are limited.

The research leading to these results has been funded by the Norwegian Financial Mechanism for 2014-2021, project no. 2019/34/H/ST10/00682 in the framework of project ‘Sedimentary ancient DNA - a new proxy to investigate the impact of environmental change on past and present biodiversity in Nordic Seas’.

The LEAD project: Atlantification of the European Arctic across geological times: new insights from sedimentary ancient DNA

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In the last decades, the Arctic experienced a significant increase in the transport of warm Atlantic water from lower latitudes, a phenomenon called "atlantification", which leads to fundamental changes in critical components of the Arctic ecosystem, including primary productivity, food web complexity, and biodiversity. The aim of the project is to explore how atlantification of the Arctic has impacted Arctic marine biodiversity and how such changes impact Arctic marine ecosystems. We will determine the spatial and temporal variability of marine organisms, especially microbial communities, to fill a knowledge gap on the impact of ocean warming on marine biodiversity using a paleogenomic approach. In the project, we will study atlantification-driven spatial and temporal variability of the European Arctic biodiversity at multiple levels: from the community, through taxonomic/ecological groups, to intragenomic variability. We will focus on a wide range of organisms, from macrofauna to microorganisms; however, we will pay special attention to microbial eukaryotes communities, which are often overlooked in biodiversity studies.

The key research questions of the project are as follows.

How large is the part of boreal diversity in the European Arctic marine ecosystems? Are the boreal species "new" to the Arctic, or do they return to the habitats they have occupied before (i.e., in the geological past)?

Does atlantification affect the planktonic and benthic biota? Are their responses consistent in time and space?

What are the origins of most boreal species colonizing the European Arctic? Which parts of the European Arctic may be considered modern analogs for the future of the Arctic?

During the project, we will test the following hypotheses.

Boreal taxa constitute a considerable part of marine biodiversity in the European Arctic, but most of those taxa recolonize areas they have already inhabited in the geological past.

Atlantification affects both the planktonic and benthic communities, with a major impact on microorganisms characterized by short life cycles and fast evolution rates.

The primary source of boreal taxa in the European Arctic is the Faroe-Shetland region. Therefore, this area is a potential modern analog for the future of European Arctic ecosystems.

From a scientific perspective, the project is at the cutting edge of paleogenomics, paleoceanography, and environmental microbiology. The project has the potential to fill many gaps in our very limited understanding of biodiversity changes in the Arctic since the Last Glacial Maximum and the role of these changes in ecosystem functioning.

The project is funded by the National Science Center in Poland, grant no. 2022/47/B/ST10/03050

Sedimentary ancient DNA provide new data to be added to the late-glacial fauna history of southernmost Sweden

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The fauna history of Sweden is mainly based on two kinds of materials: Bone material found during the late 19th and early 20th centuries when people were exploiting small wetlands for peat and marl, and bone material found at archaeological excavations. Neither of these materials have been found because of scientific questions raised or sites selected to primarily investigate fauna history. This is in great contrast to research on vegetation history based on pollen analysis for example, where site selection based on research questions is much more easily done as pollen will be found in great numbers in all kinds of peat and sediment.

However, the rapidly developing methods of analyzing ancient sedimentary DNA, will change this unbalance in between the two kinds of palaeodata, and animal data will become collected and investigated on more equal terms with floral data. As a result, the faunal history will be significantly complemented and revised.

Our recently started project aims at being an early part of this revision by increasing the knowledge of marine, limnic and terrestrial fauna history within the earliest deglaciated area of Sweden, Kullaberg in the province of Scania. Questions raised include:

- How many more animal species from the Late Weichselian can be added to the south Scandinavian species list?
- How does the immigration order of the different species relate to the well-documented vegetation and climate history of the area? Previous research claim for example that the cold stadial Younger Dryas caused the extinction of almost all larger mammals in southern Sweden (Liljegren & Ekström 1996). Can this be verified by sedimentary ancient DNA?

To answer these questions, we have selected a site with a well-documented lithostratigraphy of 5,5 m marine and limnic sediments spanning the time period 12-17,5 ka cal BP (Hammarlund 1999). We intend to analyze 100 samples for sedimentary ancient DNA and thereby hopefully reveal a fauna history of high time resolution well suited to compare to the vegetation and climate history of the region.

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Sedimentary ancient DNA retraces plant postglacial immigration along the Atlantic edge of the Fennoscandian Ice Sheet

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During the Lateglacial, the Fennoscandian Ice Sheet began retreating from its maximal extent along the Atlantic coast. This allowed for vegetation to expand northwards and colonise newly deglaciated areas. However, traditional palaeolimnological proxies that are pollen and macrofossil represent a regional signal and lack sufficient taxonomic resolution (Parducci et al. 2019), thus can only provide a limited insight into the timing and diversity of plant postglacial dispersal (Birks 2000). Sedimentary DNA records can help addressing these questions and even provide an accurate picture of past local conditions (Alsos et al. 2022). Here we present the case of Dybingen Lake in southwestern Norway, dating back to 16,5 ka BP. We used a metabarcoding approach targeting the *trn*L P6 loop chloroplast locus on lacustrine sediment cores from coastal sites of Western and southwestern Norway. We put these results in perspective with similar data from northern Fennoscandia (Rijal et al. 2021), in order to infer recolonisation routes of arctic and boreal vegetation into Scandinavia and its timing. We show that stadials and interstadials correlate with heavy shifts in vegetation diversity, with tree establishment during the Early Holocene, and how past plant communities composition can indicate local environmental conditions such as thermal range, soil pH and disturbance, and even lake trophic status (Revéret et al. 2023). We also discuss the putative drivers of plant immigration along the Atlantic coast of Scandinavia, such as reconstructed abiotic factors and the role of propagule dispersion by birds.

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A geochemical perspective on eDNA taphonomy: implications for ecological inference

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Introduction

Retrieval of modern and ancient environmental DNA (eDNA) from sediments has revolutionized our ability to reconstruct past and monitor present ecosystems. Little emphasis has been placed, however, on the fundamentals of the DNA-sediment association. Currently, our understanding of interfacial reactions and the controls geochemical processes and DNA-mineral association can have on eDNA taphonomy remains extremely limited. If we are to accurately infer community dynamics across time and space from eDNA, we need to understand how depositional processes and the stability of DNA-sediment associations in different environments influence our interpretation of retrieved eDNA.

Approach and scope

In this talk, I'll give an overview of our work on DNA-mineral interactions at the nano to bulk level. We show how mineral surface characteristics help drive DNA adsorption and stabilization and how we conceptually can use this data to address eDNA taphonomy.

Specifically, we:

- Apply interfacial geochemistry to address DNA preservation in sediments. We use atomic force microscopy and monitored the mobility of adsorbed DNA to a range of mineral surfaces and investigate how the mobility and forces of the interactions changes as a function of solution composition (ions, pH). Molecular dynamic simulations provide insight into the chemistry of the bonds involved in the binding and highlight that a strong DNA-mineral bond can lead to fragmentation.
- Combine mineralogic composition with experimental adsorption data and outline a way to increase the DNA extraction yield as well as scope and resolution of ecological interpretations from eDNA,
- Use distribution coefficients to address the fate of DNA in aqueous environments and showcase how it is influenced by the mineralogy of sediment particles and by the particle loading in the water column.

We outline how mineralogic and geochemical principles can be integrated with eDNA taphonomy analysis to improve the reconstruction of modern and past ecosystems. Furthermore, we evaluate the challenges associated with inferring ecological information when using eDNA from sediments of different provenance subjected to various sedimentary processes.

Session 27
Aeolian sediments, landforms and processes and their paleoenvironmental record

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Martin Lund,
Department of Geosciences, University of Oslo,
Department of Geology and Geophysics, Texas A&M University,
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Late glacial to Early Holocene deflation events and aeolian deposition on a raised ice-contact delta at Veinge, SW Sweden

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Wind-abraded cobbles (ventifacts) and aeolian sand are known from the sandy-gravelly coastal areas of south-western Sweden, especially in association with raised deltas. Ventifacts are recorded on at least two different stratigraphic levels, on top of glaciofluvial sediment and/or on top of littoral deposits, while aeolian sand usually forms a surficial cover. The formation of ventifacts has usually been coupled to abrasion due to katabatic winds from the retreating ice sheet or with periglacial climate during the Younger Dryas stadial (12.8-11.6 ka). However, there are very few absolute ages, and the timing of wind deflation has recently been challenged and proposed to be much older (110-70 ka).

To determine the timing of these deflation events, we have applied a combination of dating methods to ventifacts and associated sediments on top of an ice-contact delta at Veinge, south-western Sweden. Quartz and feldspar luminescence dating as well as portable luminescence profiling has been used for the over- and underlying sediments, while rock surface luminescence burial dating and paired ^{14}C-^{10}Be cosmogenic nuclide dating were done on ventifacts. The results show that a first deflation event occurred c. 16.5 ka, just after deglaciation and prior to a regional transgression that peaked around 15.7 ka. At 12.4-11.4 ka, during and just after the Younger Dryas stadial, a new set of ventifacts formed on the surface of the exposed littoral sands and gravels. Some wind abrasion also occurred in the early Holocene, but at c. 8.5 ka the surface was covered by aeolian sand, up to 2.5 m thick.

The combination of dating methods allowed us to extract more information about the timing and duration of these wind abrasion/transport events than we would have if only a single method had been used, and it is also possible to infer some environmental conditions. For example, both glaciofluvial and littoral deposits show evidence of incomplete bleaching of the luminescence signal. This suggests short subaerial transport and brief reworking by waves, respectively, though bleaching conditions improved during shore regression. Rock surface burial luminescence profiles reveal that some ventifacts were repeatedly exposed, but that later event(s) were shorter in duration as indicated by quartz-feldspar age comparisons.

Coupled abrupt climate-dust events driven by ice sheet dynamics: Combined source and age analysis of last glacial loess in NW Europe

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Abrupt climate change events during the last glacial represent some of the most dramatic environmental transitions in the recent geological past. These $10^{1\text{-}3}$ yr shifts in climate are closely linked to ice sheet fluctuations, meltwater pulses and their influence on North Atlantic ocean circulation. Significantly, dust archives around the globe show that these events are also coupled to abrupt changes in atmospheric dust activity. Yet, the mechanism behind this climate-dust coupling and the role of dust in rapid climate change remains unclear. Wind-blown mineral dust deposits (loess) in Europe serve as source-proximal archive of past dust activity and a potential means to address this gap. However, uncertainties over the depositional age and sources of this material essentially limit constraint of the drivers of last glacial dust deposition variability in Europe, and prevent any analysis of their role in abrupt climate events. Here, we address this question through combined multi-technique provenance analysis and high sampling resolution luminescence dating of last glacial loess along a W-E transect across the English Channel region in NW Europe. During the last glacial, the English Channel basin was exposed due to global sea level lowering and acted as drainage route for sediment-rich meltwater derived from the Eurasian Ice Sheet (EIS) into the North Atlantic. Zircon U-Pb age spectra, heavy mineral assemblages, and quartz grain morphology of loess from areas adjoining the English Channel demonstrate that these ice sheet derived sediments acted as source for atmospheric dust deposited along the meltwater drainage route. Moreover, new published and unpublished detailed chronologies of last glacial dust deposition across this region (e.g., Stevens et al., 2020) indicate phases of greatly enhanced dust activity that match the timing of EIS decay phases and associated meltwater pulses. Based on these findings, we propose that EIS dynamics not only affected North Atlantic ocean circulation via meltwater pulses but also caused abrupt and substantial changes in atmospheric dust loading over NW Europe. The combined ocean-atmospheric effects of these meltwater and dust pulses drove and reinforced abrupt climate events of the last glacial. This mechanism would provide the first coherent explanation for the close coupling of dust and climate on millennial timescales during the Quaternary.

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Modern-type Central-East Asian aeolian regime and global cooling-modulated dust provenance during the late Paleogene

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Atmospheric mineral dust is an extremely important component of the climate system, but its long-term effect and response to climate changes are poorly understood. The thick, nearly continuous aeolian dust deposits on the Chinese Loess Plateau (CLP) and adjacent areas provide invaluable archives to study the past Central-East Asian aeolian regime and dust-climate interactions during varying global climate states. Here we investigate the provenance of a rare late Paleogene (35–27 Ma) Ulantatal dust sequence in Inner Mongolia, China, ~400 km northwest of the central CLP. Provenance research on aeolian dust is one of the few ways to reconstruct past wind trajectories and to understand the whole dust cycle from emission to transport to deposition. We use joint single-grain provenance analysis with detrital zircon U-Pb ages and detrital rutile trace element geochemistry, combined with anisotropy of magnetic susceptibility and source contribution modelling of modern dust transport.

The results demonstrate the northwesterly and westerly late Paleogene dust transport pathways to Ulantatal, which are equivalent to those observed from the late Neogene-Quaternary CLP deposits and modern circulation. Further comparison of the late Paleogene Ulantatal provenance signals with those of the late Neogene northern CLP dust deposits and modern dust source contribution modelling suggest that modern analogues, such as the phase of the Arctic Oscillation (AO) and the Siberian High pressure system, may be used to explain the past dust cycle.

We argue that the warmhouse Eocene favored a long-term negative phase of AO -like conditions, allowing planetary mid-latitude circulation to dominate both the northwesterly and westerly dust transport pathways to Ulantatal. After the Eocene-Oligocene transition from warmhouse to coolhouse, the Siberian High and long-term positive AO -like conditions dominated the northwesterly and planetary westerly dust transport pathways, respectively. We further argue that the Ulantatal dust provenance, and possibly, the formation of the northern CLP region dust deposits since the latest Eocene were linked to Northern Hemisphere glaciations via the Siberian High and northwesterly winds.

Magnetic fabric of last deglaciation-Holocene loess in southern and central Sweden

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Loess deposits are scarce and poorly documented in Sweden, relative to the extensive deposits found in Central and Eastern Asia, Eastern Europe and North America, with only a handful of known loess locations having been investigated and mapped during the last century. Recently though, detailed investigation of the best-known loess areas in Sweden suggests that, at least at these locations, loess deposits are more extensive than previously known (Stevens et al. 2022). However, these investigations do not allow wider inferences about loess coverage in Sweden to be made, and furthermore, raise questions about the wind-regimes responsible for the transport of silt particles that formed the loess. As such, here we conduct detailed mapping and analysis of possible newly identified loess sites in Småland, Bohuslän and Dalarna. Furthermore, we apply anisotropy of magnetic susceptibility (AMS) methods in order to determine the degree of reworking and possible palaeo-dust transporting wind directions during loess deposition at these sites (Bradák et al. 2020). Overall, we find loess to be more widely distributed throughout Sweden than previously thought and suggest that these deposits have a similar depositional history and geomorphic associations to those found elsewhere in Sweden. These loess deposits comprise sediments that, typical to Swedish loess, are relatively reworked and mixed with underlying sediments, as well as being thin and patchily distributed over the land surface. Furthermore, they are generally coarser and less extensive than at other Swedish loess sites, with the notable exception of deposits in Bohuslän centred on Svartedalen. Despite this, our AMS analyses yield promising results with many samples showing preserved primary depositional fabrics, from which palaeowind directions can be inferred. Our findings suggest promise in this method for application to loess sediments from more sites in Sweden (and wider Fennoscandia) with the aim of painting a clearer picture of the post-glacial Nordic landscape and atmospheric conditions.

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Holocene relative sealevel and storminess variations recorded at Kolga strandplain, northern Estonia

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The Kolga strandplain of coastal ridge-swale system in the uplifting southern Gulf of Finland, demonstrates a potential for understanding past storminess and high-sea-level events in Estonia. The ridgeplain is spanning 5x3 km and stretches on the altitudes between 0 and 28 m, with younger ridges situated at gradually lower altitudes and is formed during the Ancylus Lake and the Littorina Sea between 11.1 and 0.3 ka. This study aims to: 1) identify the genetic type and sequential formation of the uplifting Kolga strandplain, 2) establish a relationship between terrain altitude and relative sealevel change, and 3) identify periods of elevated sealevel and increased storminess in the Baltic Sea area over the past 12 ka based on the occurrence of higher beach ridge sets. Airborne LiDAR-based relief analysis, ground-penetrating radar surveys, sedimentological and magnetic susceptibility analyses, and luminescence and AMS radiocarbon dating were used to reconstruct Holocene shoreline displacement and architecture of the ridge swale system. We report near-cyclic occurrence of more prominent (0.5-2 m) ridges among the majority of 0.2-0.4 m high ridges. Internal structure of these swash-aligned ridges displays seaward-dipping (off-lapping) of sandy-gravelly coastal deposits and are interpreted to reveal the intervals of enhanced storminess. Attributed ages to the prominent ridges, based on the rate of uplift and optically stimulated luminescence dates, align with the periods of enhanced storminess I to V described by Sorrel et al. (2012) as well as with stormier period around 5.4 ka described in Narva-Jõesuu in southeast Gulf of Finland (Rosentau et al. 2013). We see the method to serve as a new independent proxy for past storminess and high-sea-level events. This study contributes to the broader understanding of Holocene climate variability and complements existing research on storminess in Estonia, thereby enriching the scientific discourse on climate change impacts in the Baltic Sea region.

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Thin loess in southwest Sweden

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A thin (20-80 cm), patchy layer of silt-rich sediment occurs at the surface throughout Svartedalen, a nature reserve in southwest Sweden 30 km north of Gothenburg. This surface silt, known locally and colloquially as *rödfemma*, mantles a bedrock-dominated, fracture-valley landscape. Through grain-size analysis, OSL dating and detrital-zircon U-Pb dating we argue that the silt is loess and that it was deposited following deglaciation from glacial sediment that was derived from local bedrock sources. The silt has a grain-size distribution typical of loess, especially similar to thin deposits of loess overlying coarser material. The Svartedalen silt contains more fine and medium sand than far-traveled loess in other regions of the world, and we interpret this is due to local sources and post-depositional mixing by bioturbation and slope processes. OSL ages on five samples range from 1 to 8 ka, although analysis of equivalent dose distributions of one may suggest an age as old as 11 ka. We argue two explanations for these dates. The dates can represent true depositional ages and indicate several periods of deposition and or reworking during the Holocene. However, we also consider that the loess was deposited during or slightly after deglaciation, and quartz-grain signals have been partially reset during bioturbation; we consider this latter explanation more likely. U-Pb ages on 273 zircon grains from the loess show prominent peaks at 1.6 and 1.8 Ga, as well as smaller numbers of grains from 1.0 to 1.6 Ga. These ages strongly match dates from the Idefjord Terrane, formed during the Gothian and Sveconorwegian orogenies, and which comprises the bedrock of the study area. As such, we argue that during ice-margin retreat, the glacier sediment load was dominated by locally derived debris. This glacial sediment was left in thin patches on the Svartedalen uplands during retreat and particularly in larger accumulations in ice-marginal deltas. These deposits provided the proximal source for the loess. The extensive presence of thin loess in Svartedalen suggests loess to be a common component of surface soils of southwest Sweden, particularly above the marine limit. The loess deposits can provide more information on past eolian activity, as well as understanding the character of regional surface soils.

Back to the lab again: How well do proximal aeolian storm records agree?

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Projections of future *storminess* (a term that encompasses both storm intensity and frequency) in the Euro-Atlantic region are conflicting. This uncertainty stems in large part from a lack of data, particularly on pre-instrumental timescales, limiting our understanding of the mechanisms driving natural storm activity. To fill this temporal gap, we turn to aeolian archives like coastal dunes and ombrotrophic peat bogs. Periods with sustained, strong and persistent winds that drive the movement of coastal dunes can be dated using Optically Stimulated Luminescence (OSL). The identified time intervals are however, only snapshots of activity and, due to analytical limitations, often quite broad. A more continuous picture is revealed by looking at changes in the inorganic fraction of peat bogs, where more material and larger grain sizes are deposited during stormier periods.

The nature of storms presents significant methodological challenges – being rare, short-lived and local – and site-specific factors may impact the storm signals at proximal sites and across different archives, even at small spatial scales. The island of Islay in southwestern Scotland provides a natural laboratory to test the reproducibility of storm signals between peat-based reconstructions as well as against dune chronologies. The RSPB1 peat record (~8 ka) has been analyzed for basic peat properties, geochemistry (elemental concentrations and infrared spectral-inferred mineralogy of the inorganic fraction) and grain size. Principal Component Analysis (PCA) of the elemental data suggests that the second principal component (PC2) is representative of elements hosted in coarser size fractions (Si, Ti and Zr). PC2 also shows a high correlation with the inferred quartz content (r=0.7). This coarser endmember is more important 8.0-7.1, 6.2, 3.4-2.7, 2.3, 2.0-1.8, 1.5, 1.2, 0.9-0.8 and 0.7-0.5 ka. These periods all show some increase in grain size which suggests stormier conditions. Interestingly, the opposite is not true: there are periods of increased grain size (e.g., 5.8-4.8 ka) not captured by PC2. There are potential mineral (sand) sources located at nearly all cardinal directions to RSPB1. Given the glacial transport pathways in the area, we expect a quasi NW-SE divide in source signatures. Early characterization of our “NW site” Machir Bay shows coastal dunes there have greater Si and Ti concentrations and grain sizes than our “SW site” the Big Strand (average medians of 275 vs 206 µm, respectively). Thus, the changing relationship between PC2 and grain size may actually reveal changes in wind direction.

We then compare RSPB1 with the Laphroaig storm record located 16 km away just north of the Big Strand (Kylander et al., 2020). The grain size records from these two sites shows remarkably good agreement in terms of the timing, but not the magnitude, of coarser input. This likely stems from sea level and its influence on source supply (i.e., distance to shoreline, accommodation space) early in the records. RSPB1 has more muted signals in more recent times which may be a result of its relatively higher position in the landscape (25 vs 13 m a.s.l.). In comparing these results with our OSL data from Machir Bay and the Big Strand, which date significant dune events to 2.1, 1.5–0.9 and 0.76 – 0.31 ka, we find patchy agreement. We hypothesize that the dune records may show a bias towards more recent and cooler storm periods.

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Sedimentary archives of storminess and storm induced coastal flooding – do they tell the same story?

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The Baltic Sea basin is located between the North Atlantic water masses and Eurasian land masses, in the transitional zone between oceanic and continental air masses. This area is highly sensitive to changing climatic conditions, in particular, to the position and strength of the North Atlantic Oscillation (NAO) and the westerly storm tracks (Rutgersson et al. 2021). The storminess, defined as frequency and intensity of storms within the Baltics Sea is intrinsically related to position of westerly storm tracks.

It is not fully understood, what is the influence of enhanced storminess periods on frequency and intensity of storm induced coastal flooding. The aim of this review is to compare the sedimentary archives of storminess and storm induced coastal flooding. The state of the art of the knowledge on storminess intensity fluctuations as well as the frequency and intensity of storm induced coastal flooding, is presented.

The sedimentary archives of storminess, coming from inland peatlands, span continuous periods of few thousand years and indicate processes operating on extra regional scale. Majority of the published record comes from south-eastern, southern and south-western part of the Baltic Sea basin, ie. Estonia, Denmark, Sweden. The preservation potential of sedimentary archives of storm induced coastal flooding is less well understood, with extensive research spanning only the southern and south-western coast of the Baltic Sea basin. Sedimentary archives of storm induced coastal flooding represent local record of only extreme events of marine inundations.

Due to fragmentary character of depositional evidence for storminess and coastal flooding caused by storms it is important to base the inference on past patterns of these weather phenomena on combined evidence from various settings. The periods of enhanced storminess within the Baltic Sea deciphered from the sedimentary archives span periods between 9700-9100, 8800-8600, 8300-7100, 6900-6700, 6400-5500, 5100-4700, 4400-3800, 3300-2800 B.P. (Goslin et al. 2018).

The analysis of sedimentary archives of extreme sea levels and storm induced coastal flooding shows geographical variability of susceptibility to marine inundations. Along the Swedish coasts of the Baltic Proper and Gulf of Bothnia, exposed to the east, the threat of storm induced coastal flooding is the lowest within the Baltic sea basin. This is associated with the exposure of these coasts to the lee side in relation to westerly winds as well as pressure centers and air masses travelling within the region from the west to the east. The southern part of the Bothnia Bay, central part of Baltic, i.e. Baltic Proper and the Danish Straits are areas of medium threat of coastal flooding associated with storms due to strong deviations of the weather and hydrological conditions at the "ends" of elongated Baltic Sea basin (Wolski & Wiśniewski 2020). The most extreme storm induced coastal flooding events with highest frequency took place along the eastern and north-eastern coast within the Gulf of Riga, Gulf of Finland and Bothnia Bay due to exposure of these shorelines to westerly wind. The Mecklenburg Bay and Kiel Bay represent a special case being particularly sensitive to subtle changes of the sea level due to seiche effect and following from that storm induced coastal flooding due to shallow depth and exposure to the east.

The comparison of geological evidence for both, storminess as well as storm induce coastal flooding shows that these two types of evidence tell complementary stories. The sedimentary archives of marine inundations give an insight into local consequences of extreme events, while the depositional signature of storminess draws a context for these events.

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An Icelandic aeolian system as an analogue for Mars

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Aeolian systems are among the most prevalent systems encountered on planetary bodies in the solar system (e.g., Lorenz et al. 2006, Rubanenko et al. 2022), despite significant differences in physical parameters. The presence of these systems over such different settings suggests commonalities in processes forming ripples and dunes on these planetary bodies. Planetary missions have been vital for our understanding of processes forming the surface of planetary bodies (e.g., Ewing et al. 2017, Squyres et al. 2004). However, these missions are costly endeavours, and take many years from initiation to conclusion. Terrestrial analogue studies offer a resource and time efficient compliment to planetary missions, where sites on Earth can help us understand landscape evolution on other planets, such as Mars. One popular terrestrial analogue for Mars is Iceland, where many recent analogue studies have been conducted (e.g., Ehlmann et al. 2012, Sánchez-García et al. 2020).

In 2022 we conducted fieldwork at a mafic cold climate aeolian system in Iceland. The field site is situated next to the headland Ingólfshöfði, and is part of the easternmost extent of the Skeiðarársandur glacial outwash plain. Aeolian processes are active in the area, forming bedforms and also causing dust storms. Surface samples were collected along a 2 km transect, including cover sand, ripples, and protodunes, as well as nearby sand sources (i.e. beaches and creeks). The composition of the samples was measured using a µXRF, and no major variations in major and minor elements were found along the transect, or between different grain sizes. This indicate that there is minimal heterogeneity between source rocks, or that any potential heterogeneity is lost on this glacial outwash plain. This might be due to mixing during the glacial abrasion and transport, during stream migration, longshore drift, flooding events and a bimodal wind regime. This is contrasted by other studies finding a noticeable sorting by density and grain size in systems with less variable transport (cf. Pye and Tsoar, 1990). The degree of sorting is strongly dependent on the directionality and interactions between sedimentary systems. This study shows how sedimentary transport processes, on chemically similar rocks, leads to homogenisation, which has implications for understanding the provenance of deposits on Earth and Mars.

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Ventifacts and wind deflation surfaces in context with glaciofluvial sediment successions in southern Sweden

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Recent suggestions propose that the glacial landscape of southern Sweden is a relict landscape from the Saalian glaciation (>130 ka) (Lagerbäck, 2018). The primary argument supporting this viewpoint is the claimed observation that the majority of glaciofluvial deposits in this region exhibits a covering till bed, often accompanied by wind-abraded clasts (ventifacts) at the contact between glaciofluvial sediment and till. It has been further posited that this wind abrasion event dates back to the Early Weichselian, preceding the last glaciation, and occurred during periglacial conditions of that period. If this were indeed the case, it would imply that generations of Quaternary geologists had overlooked or disregarded this relationship, necessitating a paradigm shift in our comprehension of the Quaternary geological history of the area.

To assess the validity of these claims, we conducted a comprehensive evaluation of purported stratigraphic conditions within 54 gravel quarries south of the Middle Swedish End Moraine Zone (MSEMZ). The presence of a covering bed of what can be sedimentologically interpreted as a glacially deposited diamict – a till – above glaciofluvial sediments was confirmed in only 22% of the gravel pits. These occurrences were primarily linked to locations in close proximity to well-known positions associated with ice-margin standstills or oscillations during the Late Weichselian. In all other quarries, where the presence of covering till could not be confirmed, ventifacts were found in various stratigraphic positions. These positions were contingent upon deglacial and post-deglacial environmental conditions and included ventifacts at the contact between glaciofluvial and overlying littoral sediment, ventifacts redeposited within littoral sediment, and ventifacts at the contact between glaciofluvial or littoral sediment and overlying aeolian sediment.

To ascertain the age of the ventifaction event(s), we conducted an extensive luminescence (OSL) dating program (n = 74) in 22 of the gravel pits that were more meticulously studied from a sedimentological perspective. Out findings indicate that wind abrasion in southern Sweden was not a single, simultaneous event but a process that occurred at varying times. It sometimes coincided closely with the local deglaciation and at other times or locations extended into the Early Holocene. Importantly, none of the identified ventifact surfaces predate the Last Glacial Maximum (LGM).

For west-coast sites, the evidence suggests wind abrasion occurring as early as between 17 and 16 ka ago during periglacial conditions. This is indicated by the presence of ice-wedge casts in delta topset surfaces. In upland sites, ventifact formation age presents two possibilities – either it occurred immediately after deglaciation or during the Younger Dryas period. All upland sites were deglaciated during the Bølling–Allerød interstadial complex (14.7–12.8 ka). Despite protective vegetation further away from the ice margin, areas close to the ice margin may have experienced a sufficiently harsh wind climate conducive to ventifact formation. Moreover, several sites suggest a period of intensive ventifact formation also took place during Younger Dryas, even extending to regions far south of the ice margin at the time. The formation of patterned ground, as evidenced by recorded ice wedge casts, implies a severe periglacial climate with reduced vegetation cover, resulting in sand drift and ventifact formation, with the former also leading to aeolian sediment deposition as the Early Holocene commenced.

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Triassic aeolian mudstones of Southern Britain: orbital forcing of hothouse climates

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The late Permian to Triassic (~ 260-201 Ma) is one of the hottest periods in the last 500 Ma, and covers two mass extinctions, including the largest ever recorded. The Triassic witnessed dramatic changes in environment on the Pangea supercontinent, with extensive dusty desert formation and the development of a strong monsoonal regime (Ruffell & Hounslow 2006). Extensive deposits of at least partly aeolian terrestrial late Permian and Triassic desert mudstones crop out along the southwest coast of England (Mercia Mudstone Group; Hounslow and Gallois, 2023) and potentially provide insight into the forcing of climate change in over this interval. However, to date, no systematic analysis of possible past climate proxies has been undertaken from these deposits and the forcing of Triassic arid hothouse climates and dust activity remains uncertain. Given atmospheric mineral dust's role in climate change and the potential interactions of climate variability with extinction events, resolving this uncertainty is of the utmost importance.

To address this, here we undertook detailed, regularly-spaced sampling of Ladinian (242-237 Ma) mudstones of the Mercia Mudstone Group (Sidmouth Mudstone Formation) and applied mineral magnetic susceptibility, grain size, and colour analysis to constrain the environmental controls on these parameters, as well as test for early Middle Triassic environmental changes with age. Measurements of bulk magnetic susceptibility at low frequency (976 Hz) show considerable variation in magnetic properties, which also correspond to stratigraphic alternations between green-grey silty mudstones and red mudstones, potentially reflecting wider scale changes in water table level and humidity. Detailed multi-spectral colour analyses show close correspondence of colour variation (CIE L*a*b*) and magnetic susceptibility parameters, supporting an environmental driver for these variations. Particle size analyses show complex relationships to mineral magnetic and colour parameters, although clay content shows close correspondence to magnetic susceptibility, while brief episodes of enhanced sand deposition likely reflect periodic flooding of the desert basin. Overall, we propose that the combined proxies allow analysis of likely monsoon-driven humidity changes, and analysis periodicities in the climate proxies suggests strong orbital control on these climate changes.

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Paleoenvironmental record of loess in southern England – decoding sediment sources and transport pathways by magnetic anisotropy

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Considerable research efforts have been attempted to use loess deposits in southern England to unravel late Quaternary past climate fluctuations and wind patterns (e.g., Eden 1980, Stevens et al. 2020). However, this extensive investigation has not included the analysis of the magnetic mineral composition and the alignment of minerals i.e. the magnetic fabric of the sediments, which if successful would significantly improve the understanding of outstanding questions over late Quaternary climate and dust transporting wind-directions. Samples from two distinct sites in southern England were collected: Lowland Point (LP) in eastern Kent and Pegwell Bay (PB) on the Lizard Peninsula of Cornwall. Rock magnetic analyses, such as temperature dependence of the magnetization and susceptibility were conducted to gain insight into the mineral magnetism of the studied units. Alongside the magnetic mineral composition, the analysis of the primary origin of the magnetic fabrics and the potential influence of various post-depositional processes as detected through anisotropy of magnetic susceptibility (AMS) measurements is assessed.

Our findings reveal a comparable magnetic mineral composition at both LP and PB sites, arising from both sedimentary (aeolian) and post-sedimentary sources. Magnetite, with sedimentary and pedogenic origins, was identified as the primary ferrimagnetic contributor. Additionally, maghemite, a product of weathering and/or pedogenic processes, is prevalent. The presence of goethite and superparamagnetic (SP) particles suggests a higher degree of weathering in the source area and/or alternatively pedogenesis in cooler and drier conditions.

The bulk AMS results indicate variations in magnetic foliation between the two sites, generally aligned with the bedding plane. In the PB section, magnetic foliation is more pronounced, implying slightly stronger compaction of dust fall deposits and suggesting a sedimentation environment characterized by lower wind transport energy. Conversely, the LP site's results suggest stronger wind transport energy and a consistent record of stable winds. Furthermore, the presence of a prolate fabric in the frequency-dependent AMS results within the LP and PB section suggests the potential influence of secondary processes, probably caused by vertical alignment of the secondary SP fraction, such as seasonal thawing, cryogenic processes, and the infiltration of precipitation. While the magnetic lineation of bulk AMS is relatively weak, there is a noticeable tendency toward alignment, with flow directions from the SE direction in the PB section (weak winds) and similarly (if a stronger wind) in the lower LP site (or SW direction for a weaker wind assumed). These observations may imply the preservation of paleowind directions during dust transport, with a substantial southerly component, in contrast to earlier studies. The inferred dominant southeasterly wind direction suggests a limited influence of katabatic, westerly or polar northeasterly winds during dust transport, and rather may imply the effect of low-pressure systems passing through the English Channel, to the south of the field area, during that period. This further implies a pronounced local source of material originating from the exposed North Sea and the English Channel shelf and interconnected braided river systems.

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Unraveling Late Holocene dust dynamics and climatic in the high arctic: Insights from loess in Adventdalen, Svalbard

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Holocene dust activity in the Arctic and its connection to climatic changes remain subjects of significant uncertainty. One approach to address this uncertainty is to investigate loess deposits, terrestrial records of atmospheric mineral dust in the past. Loess in Svalbard forms source-proximal archives of dust deposition and dust dynamics spanning the late Holocene. A loess-permafrost core extracted from Adventdalen provides a unique opportunity to investigate dust-climate relationships in the high Arctic in unprecedented detail.

Here we present a fully independent age model for this loess core, employing 136 quartz luminescence ages at a 2-cm-resolution together with Bayesian age modeling (Rasmussen et al., 2023). This approach makes it the most detailed luminescence chronology of a sedimentary archive to date. By complementing the high-resolution dating by grain size analyses, cryostratigraphic investigations, mineral magnetic analyses, anisotropy of magnetic susceptibilitly (AMS), and stratigraphic examination of an adjacent exposed profile, we gain insights into changes in loess accumulation rates, dust transport dynamics and reworking, and permafrost development over the past 3000 years.

Our findings reveal a noteworthy variability in loess mass accumulation rates during the late Holocene of Svalbard. Strikingly, exceptionally high rates of loess deposition, reaching up to 0.35 cm per year, coincide with coarse silt deposition and potential warm phases. This suggests a crucial link between the availability of sediments, driven by temperature-related processes in glaciofluvial source areas, and the dust levels in Adventdalen. Source-proximal transport of dust along Adventdalen is further supported by our results from AMS measurements, which indicate a dominantly aeolian mode of transport along the main axis of the valley, with episodical reworking by other surface processes.

If the observed deposition rates mirror broader trends across the valleys of Svalbard, it implies that the archipelago may be a more significant high-latitude dust source than previously recognized, and highly sensitive to temperature fluctuations. To further investigate the relationship between dust dynamics and warm phases, we test the reconstruction of paleo-temperatures utilizing glycerol dialkyl glycerol tetraether lipids (GDGTs). By combining advanced dating techniques, sediment analysis, and temperature reconstructions based on GDGTs, we aim to unravel the significance of temperature-driven processes in influencing dust activity in the High Arctic.

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Beyond traditional proxies: Exploring multi-frequency magnetic susceptibility in loess deposits

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Loess deposits, terrestrial accumulations of wind-blown mineral dust, forms long, continuous climate records in many parts of the world. Some of their properties reflect variations in regional and local climate and in places loess deposition extends for hundreds of thousands or millions of years and therefore provides long and quasi-continuous climate records over the Neogene-Quaternary. Some such deposits are preserved in Tajikistan, Central Asia – a place where the loess even hosts numerous stone artefacts from multiple phases of ancient hominin occupation. As such, detailed past climate reconstructions from these deposits are of wide-ranging importance. However, precise, semi-quantitative past climate records for many of these sequences remain scarce, and are at times based on assumptions regarding climate signal acquisition that remain untested. Here we address this through detailed multi-frequency magnetic susceptibility analyses on a range of loess deposits.

Many loess deposits contain ultra-fine ferromagnetic particles that measure up to several tens of nanometres in diameter. These nanoparticles exhibit strong magnetism and superparamagnetic behaviour under an applied alternating magnetic field, which is reflected in their magnetic susceptibility (χ) at varying frequencies. One important mechanism for the in-situ neoformation of such particles is pedogenesis, which is influenced by the seasonality of moisture availability and by temperature variations. In fact, in a semi-arid climate such as in Tajikistan, moisture availability is a limiting factor for the formation of pedogenic ferromagnetic particles. Therefore, their abundance can be used as an indicator of palaeo-precipitation intensity.

The concentration of magnetic nanoparticles can be estimated by calculating the frequency dependence (χ_{FD}) of magnetic susceptibility, i.e. the difference in χ measured at two different frequencies. However, a critical limitation emerges from the fact that nearly all loess studies have traditionally employed just two or three frequencies in the analysis of magnetic nanoparticle contributions to magnetic susceptibility. This restriction prevents a full quantification of nanoparticle assemblages in loess and potentially limits the sensitivity of the proxy to subtle variations in rainfall.

Here we present an innovative approach that extends the range of frequencies at which magnetic susceptibility is measured, from a conventional dual-frequency setup to a multiple-frequency spectrum spanning several orders of magnitude (44 Hz to 85 kHz at 15 different frequencies). To exemplify the usefulness of this new proxy, we calculate an extended total frequency dependence parameter (χ_{TFD}), the difference between the highest and lowest frequency along the multi-frequency spectrum. The approach is tested on the Khonako II loess-palaeosol sequence in Tajikistan, a site at which the formation of ferromagnetic nanoparticles is limited by moisture availability. Our results reinforce that χ_{TFD} has great potential as a more sensitive palaeo-precipitation proxy compared to conventional dual-frequency χ_{FD}. We also demonstrate how multi-frequency magnetic susceptibility data from modern loess profiles can be used to build a calibration for quantifying palaeo-precipitation, and reveal far more complexity in how magnetic susceptibility varies with frequency in certain loess deposits that previously realised. This has wide ranging implications for the use of this technique in certain loess deposits.

Mid-Holocene paleostorminess in north-western Ireland inferred from grain size, mineral and molecular content

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Substantial uncertainties exist regarding how future climate change will affect storminess (a term that includes both storm frequency and intensity) in Ireland and the British Isles. Knowledge about spatiotemporal variations of past storminess can contribute to a better understanding of the mechanisms that govern storminess on centennial to millennial time-scales, and shed light on the potential impact of external forcing on future storminess in climate models. Here, we present a storm record, covering the last 8000 years, reconstructed from a coastal bog, located in north-western Ireland. The sequence was analyzed for grain size by laser diffraction (Mastersizer 3000), chemical (EMMA-XRF), mineral (pXRD) and molecular composition (FTIR-ATR). The chronology of the peat sequence was built on 11 AMS radiocarbon dates. The deposit characteristics, location and low inorganic content suggests that minerals were aeolian transported to the bog throughout the studied period. The grain size results allowed identification of periods of increased wind strengths and storminess, and also estimation of minimum wind velocities (Bagnold, 1941, adapated by Mckenna Neuman, 2003) required to entrain particles above >100 µm. Cluster analysis of the grain size frequency curves, together with a ratio between coarse and fine sand, allowed identification of eleven periods of increased storminess (cal BP): 6150–5500 (1); 4970–4130 (2); 4000 (3); 3490–3290 (4); 3230 (5); 2850–2590 (6); 2170–1920 (7); 1440 (8); 1225–890 (9); 620–470 (10); 290–230 (11). The minimum velocities required to entrain the coarsest particles during these periods varied from 6–9 $m\ s^{-1}$ (22 to 32 $km\ h^{-1}$). The results show that during mid-Holocene (8.2–4.2 ka) an initial period of deposition of fine grain sizes, was followed by two longer cycles, of *c.* 1000 years each, where progressively coarse particles were deposited, implying a progressive increase in wind strengths. During this period the sea level was lower and the local beach sources located further away, implying that sand particles were transported a longer distance compared to when the sea level stabilized *c.* 5 ka. From 4.2 ka, shifts in storm frequency and duration were noted, with a higher number of shorter events occurring. Taken together, the results suggests that stronger winds were more common during the mid-Holocene compared to late Holocene, possibly related to a eastward shift of the Iceland low during the warmer mid-Holocene (Curran et al. 2019). Comparison between our results and regional peat paleostorm records from Islay (Kylander et al., 2020) and Hebrides (Orme et al., 2016) show an anti-correlation with the Islay record while little to no similarities with the Hebrides records was observed. This may be related to latitudinal shifts of the storm track in the past, that different methodological approaches were applied, or a combination. By extending the number of peat paleostorm records in the region, with similar analytical approaches, could help identify spatiotemporal shifts of the North Atlantic storm track during Holocene, and increase the understanding of the processes governing the storm track on longer time-scales.

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Constraining the timing of Holocene aeolian dune activity in Arctic Sweden

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Aeolian parabolic sand dune fields are widespread over northern Sweden and reveal extensive aeolian activity (Stammler et al. 2023). The initial formation of these dunes presumably immediately followed local deglaciation, but their stabilization and reactivation history remains less clear. Stratified sand deposits forming dune cores likely represent initial dune formation and movement, while multiple overlying homogenous sand units separated by podzols indicate a long history of repeated phases of dune reactivation and stability. In some locations, this activity continues to the present, as witnessed by extensive active blow outs and hollows on dune surfaces. As well as their timing, the environmental or human controls on these activity and stability phases are also unclear, although the presence of charcoal layers underlying some of the reworked sand units suggests that fire activity may be a key factor. Whether this local burning is linked to wider climate or land-use forcing, however, remains uncertain.

Critical in resolving this uncertainty is detailed, independent dating of multiple individual dunes and dune complexes. To date, no such chronological framework exists for Arctic dunes in Sweden. As such, here we test and apply protocols for both quartz optically stimulated luminescence (OSL) and potassium feldspar post-IR infrared stimulated luminescence (pIR-IRSL) dating in detail at multiple dune sites located in the pine (*Pinus sylvestris*) forest, mountain birch (*Betula pubescens*) forest, and tundra zones of Arctic Sweden. Furthermore, we apply detailed AMS ^{14}C dating to charcoal fragments recovered from dune profiles to constrain fire history and cross check luminescence ages. A double single aliquot regeneration (SAR) protocol is required for OSL dating, due to likely feldspar microinclusions within quartz, but most aliquots pass internal tests and resultant pIR-IRSL and OSL ages are generally consistent with ^{14}C ages and are in stratigraphic agreement. Low quartz luminescence sensitivity and feldspar contamination limits precise OSL age assignment in samples from stratified sands that likely represent early dune movement prior to initial stabilization post-ice retreat, as well as some of the youngest reworked sand layers, and necessitates the use of pIR-IRSL. Our dating results suggest repeated and long lasting aeolian activity in Arctic Sweden throughout the Holocene. They also hint at periods of wide-scale dune activation, perhaps linked to broader climate forcing, although there are also numerous differences in detail between dune chronologies across Arctic Fennoscandia.

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Combined radiocarbon and luminescence dating of Holocene Arctic loess deposits around Kangerlussuaq, Greenland

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The current pace of Arctic climate change is unprecedented in instrumental records. This change is of wide significance because many Arctic-specific climate feedbacks have global impacts. It is therefore crucial to examine geological archives of past Arctic environments in order to understand abrupt Arctic change. Loess deposits are preserved around the ice-free area of Kangerlussuaq, western Greenland (Willemse et al., 2003), and potentially provide a means for understanding climate change on Greenland during the Holocene. However, to date there are no detailed depositional chronologies or climate proxy records for these sediments, limiting their use in understanding past Arctic change. Here we sample loess and combined peat-loess sections around Kangerlussuaq for detailed luminescence and radiocarbon dating, as well as testing of possible climate proxies. Preliminary sampling yielded few organic macrofossils, meaning that initial radiocarbon dates were obtained on bulk organic matter. While the results are stratigraphically consistent, this approach is susceptible to carbon contamination during soil formation. Luminescence dating via standard quartz optically stimulated luminescence methods was not possible due to weak quartz signals, but the post IR infrared stimulated luminescence (IR50; pIR IRSL180) signal yielded reproducible and stratigraphically consistent ages. However, Holocene pIR IRSL ages are susceptible to overestimates due to ‘partial bleaching’, where solar exposure is insufficient to completely zero the signal. Comparison of bulk organic matter 14C and pIR IRSL ages from one test site close to Russell Glacier shows that these two independent methods are offset from each other by c. 2 thousand years. We present further results of tests for the causes of these offsets between different age-dating techniques. We also present results from initial climate proxy analyses, including mineral magnetic, particle size, geochemistry, and bacterial brGDGT approaches, revealing fluctuations in environment since initial loess formation, at c. 4-6 ka.

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Continental dust accumulation in Central Asia: using high resolution luminescence dating to identify gross discontinuities in deposition

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The loess-palaeosol series of Central Asia records the history of subaerial sedimentation over the last 2 million years. These thick loess-palaeosol deposits are usually regarded as complete, an important prerequisite for a detailed study of the paleoclimatic changes that occurred during the accumulation of these deposits. The significant thickness, large number of palaeosols, and the resulting impressive chronological framework make it possible to carry out detailed paleogeographic reconstructions over a long period of time. These sediments also record the presence and absence of human activity throughout the deposition period, and so record some of the earliest human migrations and occupations of Central Asia. As part of a major NordForsk funded project 'Timing and Ecology of the Human Occupation in Central Asia' (THOCA; www.thoca.org), we have studied several important sections on the Khovaling loess plateau (Kuldara and Khonako-III sections) in Tajikistan; this will allow us to develop a chronostratigraphic scheme for the entire Central Asian region.

In order to provide an independent timescale for palaeoclimatic studies and to check the completeness of the sedimentary record, 70 luminescence samples for Kuldara site and 130 samples for Khonako-III were collected using stainless steel tubes down to below the PC2 complex. Using conventional sample preparation techniques, we extracted quartz and feldspar in the coarse-silt and/or fine sand (40-63/63-90 µm) range. Using conventional sample preparation techniques, we extracted quartz and feldspar in the coarse-silt and/or fine sand (40-63/63-90 µm) range. Dose rates were determined using high resolution gamma spectrometry and are typical for loess in Tajikistan (~3 Gy/ka to silt-size d quartz grains). High dose rates limit the use of the OSL signal from quartz to the last ~40 ka, but the high temperature feldspar signal (post IR IR measured at 290ºC after prior stimulation at 200ºC) has been used to provide a detailed luminescence chronology for Tajikistan loess-palaeosol site back to ~250 ka. Comparison with quartz ages over the first 40 ka is used to confirm the resetting of this more difficult to bleach feldspar signal.

High resolution luminescence dating has identified several hiatus in the sedimentary sequences: Kuldara shows major breaks of up to 100 ka, with the most of L2 and the entire PC2 and L3 units missing; a small hiatus was detected at Khonako-III (at the bottom of PC 1) of ~10 ka. These discontinuities had not been previously identified, leading to gross errors in palaeosol identification, and so in presumed chronology.

The Khovaling loess plateau sections are known to reflect the regional features of loess/palaeosol sequences. As a result of the development of a detailed numerical chronology for these sections, we are now able to correlate regional features with global events, and relate these to such important phenomena as pedocomplex formation, the development of petro- and paleomagnetic records, and human activity.

Session 28

Quaternary paleoclimate from Scandinavian to global perspective – a session in honor of Svante Björck

Session Chairs:
Raimund Muscheler,
Department of Geology, Lund University
Karl Ljung,
Department of Geology, Lund University
Dan Hammarlund,
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From ice-dammed lake to aeolian dunes in the Store Mosse area, SW Sweden

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Aeolian deposits surround and stretch across the Store Mosse (Great Bog) bog complex in southwestern Sweden. Both peat and aeolian sand are underlain by lacustrine sediment and the deposits record the area's transition from an initially ice-dammed lake to Ancient Lake Bolmen, which gradually drained, exposing sediments to wind erosion and allowing peat to start forming in basins.

Here, we present 25 luminescence ages from lacustrine/fluvial and aeolian deposits that range from the time of deglaciation (~14.5 ka) to the late Holocene (~3.5 ka). Most of the water-lain sediments are dated to 12-10 ka while the bulk of the dunes formed 10.5-6.5 ka ago, possibly during two phases in the early and early-mid Holocene, respectively. Single younger ages likely record limited re-activation of dunes during the mid-late Holocene. The relationship of the dune record to environmental changes and a regional peat-based palaeostorm record (Kylander et al. 2023) will be discussed.

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Deglaciation chronology, ice-free Greenland

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In 2002 Bennike & Björck published a new deglaciation chronology for the ice-free parts of Greenland, the continental shelf and eastern Ellesmere Island (Canada) in Journal of Quaternary Science. The chronology was based on a compilation of all published radiocarbon ages from Greenland, and included new material from southern, north-eastern and north-western Greenland. Although each age provided only a minimum age for the local deglaciation, some of the ages came from species that indicate ice-proximal glaciomarine conditions, and thus may have be connected with the actual ice recession. In addition to shell ages, ages from marine algae, lake sediments, peat, terrestrial plants and driftwood were also included. Only offshore and in the far south had secure late-glacial sediments been found. It was concluded that most of the present ice-free parts of Greenland were deglaciated in the Early to Mid-Holocene.

In the past two decades a number of important radiocarbon ages have been published from marine sediment cores collected from the Greenland shelf. Also, numerous exposure ages have been published. These data add to our understanding of the deglaciation chronology of ice-free Greenland.

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A multiproxy record from Sumatra indicates continuous Holocene warming but a Mid-Holocene rainfall maximum

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The maritime continent (MC) forms the central part of the Indo-Pacific Warm Pool (IPWP). This tropical region is a critical component of the global climate system by providing large amounts of latent heat to the higher latitudes via deep atmospheric convection. Paleoclimate information remains relatively scarce from the MC despite its global importance, calling for additional records from the region. We generated a multisite-multiproxy record from Sumatra, with a main focus on the glycerol dialkyl glycerol tetraethers (GDGTs) and leaf wax hydrogen isotopic composition (δD_{wax}) allowing reconstructions of past temperatures and rainfall. We investigated one homogenous peat core (Padang, 0-8 ka BP) and one paludified lake (Diatas, 0-11 ka BP), but also compared the GDGT results with those from a deep lake and of a soil altitude transect. Principle Component Analysis of these differently sourced GDGTs from the same region, allowed assessment to what extent their provenance (soil erosion, peat, lake) determine GDGT distributions, besides temperature. The GDGT sources remained constant at the Padang site, allowing a robust temperature reconstruction that shows gradual warming during the last 8 ka, including a plateau 3-5 ka BP

The finding of ongoing warming over the past 8 ka agrees with several climate model simulations for Sumatra and nearby marine SST reconstructions from the Indian Ocean (western IPWP). This trend is opposite to previous marine reconstructions in the eastern IPWP, which may be related to long-term changes in the Walker circulation. Of note is that there is little to no seasonal bias in our equatorial peatland site and bacterial lipid source, something that has been implicated as biasing temperature proxies.

The δD_{wax} values of both records indicate an increasingly humid Holocene with a maximum between 4-6 kyr BP. This mid-Holocene wet maximum is also apparent from higher Paq index values at Diatas, and highest $\delta^{13}C$, indicating a largest contribution of peat-forming aquatic macrophytes during this period. After 4ka BP all proxies indicate a decline in precipitation strength that is coincident with the reorganization and general drying and cooling of global climate at the start of the Meghalayan age. Our multi-proxy data set indicates that the last two centuries were seeing a return to wet conditions.

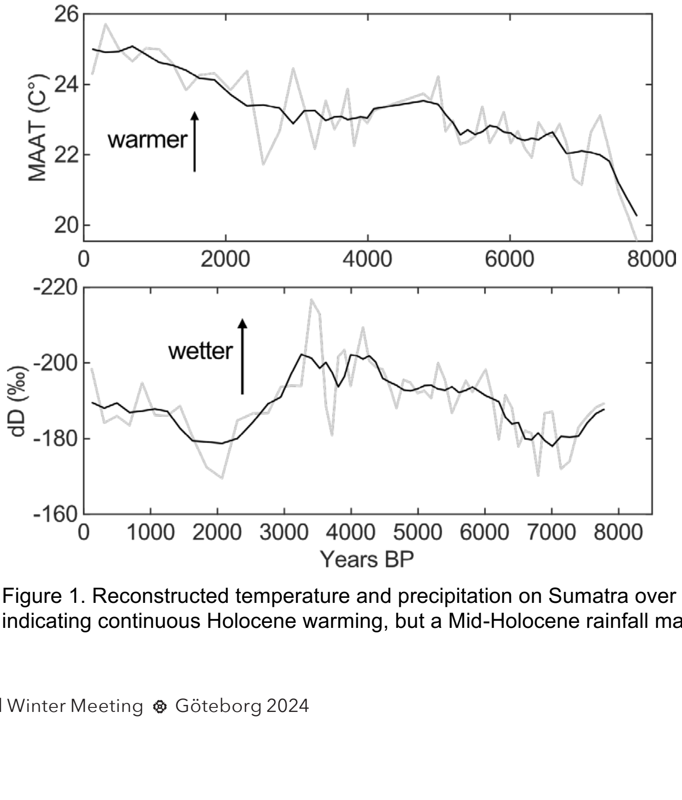

Figure 1. Reconstructed temperature and precipitation on Sumatra over the Holocene indicating continuous Holocene warming, but a Mid-Holocene rainfall maximum.

The formation of Valle Härad

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Valle Härad is a well-known location in Sweden displaying ice-collapsed, 'kame-and-kettle' topography. It contains eight nature preserves and lies in the newly established Platåberg UNESCO Geopark. It has been studied for over 100 years, initially with papers by Henrik Munthe and Hans W:son Ahlmann in the early 1900's. Because it is close to the drainage site of the Baltic Ice Lake, its genesis has also at times been linked to that event. Despite its fame as a dead-ice locality, it has long been understood that non-collapsed, gently sloping outwash surfaces are present. With the advent of LiDAR elevation models, it has been possible to map the landforms more precisely, and we present a new map. In addition to collapse hummocks and outwash plains, there are numerous eskers, two-large esker nets, and at least one clear push moraine present. Maximum clast-size analysis of the outwash surfaces in Valle Härad reveal that they exhibit the same downstream fining of grain size measured on modern outwash plains, indicating that the outwash plains were formed at the retreating ice margin. The outwash plains, end moraines, esker nets and clast-size information allow for the lateral correlation of the push moraines of the Middle Swedish end moraine zone into Valle Härad. For example, the Eggby outwash surface is correlated to the initial Skånings Åsaka ice-margin position. And the Eahagen ridge (a push moraine composed of outwash) can be correlated to the second Skåins Åsaka ice-margin position. These results show that the surface topography of Valle Härad was developed sequentially and parallel with subaquatic, push-moraine formation further west. However, two major features remain difficult to explain. The first is the esker-covered steep slope at the north end of Valle Härad at Lerdala. The second is the genesis of the 30-60 m of sand and gravel that underlies the surface landforms. We offer two hypotheses for the origin of this older sediment. First, the older sediment was deposited during the Younger dryas sequentially from south to north as a series of ice-contact deltas with each delta overridden by subsequent ice-margin oscillations. Second, the older sediment may represent drainage sediment from the late Allerød drainage of the Baltic Ice Lake, as first suggedted by Björck and Digerfeldt (1984).

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How lake succession influences paleoclimate records in small, subtropical high-mountain lakes

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Small high-mountain lakes in subtropical regions are usually not considered optimal paleoclimatic archives because the steep topography and rapid erosion leads to fast infill and low signal-to-noise ratios for many climate signals. In Taiwan, however, alternative climate paleoclimatic archives are scarce. The lithology of the actively forming mountain belt primarily consists of slates and meta-sandstones, making limestone caves and speleothem records rare. Additionally, the hot and humid climate accelerates the decomposition of fallen trees, limiting dendrochronological archives to the last 500 years. Furthermore, marine archives around Taiwan either offer low resolution or are heavily influenced by turbidites caused by earthquakes and frequent typhoons. Consequently, the most realistic approach of reconstructing climatic variability on Taiwan from the late Pleistocene to the Holocene relies on lacustrine records.

Here we present a detailed account of a small wetland in the Taiping Mountains in northeastern Taiwan. How the lake initially formed, how it gradually filled up and evolved into a wetland dominated by a wooded swamp with a smaller fen surrounding the open pond, and how understanding this succession can be used to optimize paleoclimatic studies.

To investigate the lake's history, we employed spade borers and Russian corers to create transects across the basin, aiming to determine when the lake first formed and how it evolved. Dry, yellowish clay with slate shards at the bottom of the holes was interpreted to represent subaerial valley deposits, and radiocarbon dates of about 12 ky from lacustrine, gray clays just above this layer therefore were interpreted to represent the approximate age of the lake formation. Because the modern wetland is situated in a valley between two cuestas formed by the uplift and tilt of metamorphic sandstone layers, the most likely mechanism of lake formation is landslide damming. From the distribution of lacustrine clay, gyttja and peat in the core transects, we conclude that the original lake gradually decreased in size primarily through lateral expansion of first fens, later followed by a wooded swamp environment. As the remaining open pond decreased in size, sediment input was focused on the remaining open area, accelerating sediment accumulation rates. This is reflected in sedimentations rates of almost 0.5 cm per year in the uppermost sediments from the last remnants of the open pond, in contrast to sedimentation rates as low as 0.016 cm/y in the oldest parts of the lake. Consequently, lithostratigraphic layers in the basin are diachronous, and it is not possible to directly compare paleoenvironmental signals between the cores. Nevertheless, by understanding the depositional environment and the succession of the lake, we conclude that the lacustrine clays deposited during the early stages of the lake evolution, before the fen and the swamp encroached, can serve as valuable and robust paleoclimatic archive of early to mid-Holocene climate changes, while the top sediments from the last remaining open waters provide a high resolution archive of the last few thousand years.

To summarize, in small high-mountain lakes it is important to understand the lake formation and lake succession before any attempts at interpreting paleoenvironmental trends are made. In particular, because the lithostratigraphic units of the lake develop diachronously, it is not possible to correlate between cores simply based on sediment composition. However, if the individual micro-environmental setting is understood in context of the pond’s evolution, useful climatic archives can be extracted.

From the Preboreal oscillation to solar storms – solar variability as a tool for climate studies

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Solar variability leaves its traces in cosmogenic radionuclide records in e.g. tree rings and ice cores. This allows us to reconstruct past changes in solar activity and study sun-climate linkages. In addition, the combined analysis of ice core ^{10}Be and tree ring ^{14}C records allows us to synchronize these records via to the common production signal and to disentangle production rate (solar and/or geomagnetic) and carbon cycle influences on the atmospheric ^{14}C variations as inferred from tree ring record. The potential of such studies for improving our understanding of the climate system captured immediately Svante's attention when we first met at a summer school in Hasliberg, Switzerland in 1999. It has subsequently led to a long, fruitful and very pleasant collaboration and we could infer solar influences on climate during the early Holocene period. More recently, it has been confirmed that extreme solar proton events can lead to significantly increased atmospheric production rates of cosmogenic radionuclides, again evidenced in tree ring and ice core radionuclide records. These events open up the completely new field of Paleo-Space-Weather with applications for studying the carbon cycle and the climate system in the past. Here I will review the present state of this emerging field and discuss the applications of Earth Sciences.

Interstadial stratigraphies in Jämtland – dating of newly discovered localities and connection to a MIS 3 ice margin

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Pre-Late Weichselian ice sheets and intervening periods between them have left geomorphic and stratigraphic evidence. In Jämtland, west-central Sweden, such evidence, in the form of interstadial sediments and glacial landforms, was preserved during subsequent frozen-bed conditions of the last ice sheet. Data from these sediments and landforms help us understand the timing and geometry of the pre-Late Weichselian ice sheets, which are essential to validating numerical ice-sheet models. Furthermore, this knowledge is vital to developing geological frameworks for the subsurface, which is helpful for sustainable land use planning.

We recently discovered a 'new' ice-marginal moraine, forming a discontinuous connection with the Veiki-moraines (ice-walled lake plains) in the north of Sweden with the Idre moraine 600 km south. Based on this spatial relationship and cross-cutting glacial landforms, this moraine was hypothesized to have formed during Marine Isotope Stage (MIS) 3 by the retreating MIS 4 ice sheet. The mapped ice margin is marked by distinct end-moraines only in a few places and is mainly comprised of landforms indicative of an ice-marginal dead-ice environment, such as dead-ice depressions and ice-walled lake plains. In a few places, however, the ice-marginal moraine appears to be a push moraine, sometimes in conjunction with crevasse-squeeze ridges, suggesting an active ice margin.

Two of these dead-ice depressions in eastern Jämtland, connected to the hypothesized ice margin, were cored using a Cobra Combi to retrieve cores for stratigraphic description and to sample for OSL dating. In both depressions, we found fine-grained sorted sediments covered by till. Based on preliminary OSL results, these stratigraphic sequences appear to date to MIS 3, although further work is needed to refine the results. In addition, some unpublished OSL and ^{14}C results from SGU's archives indicate MIS 3 ages for one more dead-ice depression along the hypothesized ice margin in southern Jämtland.

During recent surficial deposits mapping in the region in 2020-2023, five new localities were investigated and, where suitable, dated by OSL. These results also yield MIS 3 ages, which agree with our other preliminary results and previous studies. Finally, the westernmost site, located just east of Åre, indicates that the maximum extent of the ice sheet during MIS 3 was constrained to well inside the mountains.

Radiocarbon age of the Zero-Varve of the Swedish Time Scale

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Here we present radiocarbon ages of the drainage of a series of lakes in Jämtland that were dammed by the retreating Scandinavian Ice Sheet, one of which led to the deposition of the zero-varve of the Swedish Time Scale (cf. De Geer 1940).

The varve-based Swedish Time Scale is an unparalleled tool for documenting the retreat pattern of the Scandinavian Ice Sheet, along with associated palaeo-environmental changes, at an annual time scale. Its early construction was due to the enormous body of work by Gerard De Geer and collaborators and, while initially a relative chronology “floating” in absolute time, the time scale has since been linked to the present through Holocene and modern estuary varves. However, later works have revealed that ~900 varves are missing from the chronology, and it cannot be considered a true absolute time scale. To anchor his chronology, De Geer chose an exceptionally thick (~1 m) and coarse-grained “varve” in Döviken, eastern Jämtland, as a marker bed and zero-point of his time scale. De Geer interpreted this “zero-varve” as resulting from catastrophic drainage of the Central Jämtland Ice Lake, following a partitioning of the ice sheet around Storsjön. However, this correspondence was only assumed and, at the time, no geomorphological features from such a large drainage event had been found.

We present a reconstruction of not one but a series of connected and evolving ice-dammed lakes in Central Jämtland, and find independent evidence for catastrophic lake drainage event(s), including that which corresponds to the deposition of De Geer’s zero-varve. Using the isolation basin-method, we have dated the lake drainage that deposited the zero-varve to 10 003±76 cal. a BP. We hereby tie the varve-based Swedish Time Scale to the radiocarbon timescale with unprecedented precision, independent of intercontinental teleconnections, and show that 765±76 varves are missing in the part of the Swedish Time Scale younger than the zero-varve. We demonstrate that the zero-varve drainage, and other such lake drainage events, were rapid and the interpretation of the thick marker bed as a single varve is appropriate. Based on our new age, we discuss the implications for the timing of other deglacial events (e.g. final drainage of the Baltic Ice Lake) and palaeo-environmental shifts (e.g. Younger Dryas/Preboreal transition) previously observed in the Swedish varve chronology.

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Holocene variability of the Southern Hemisphere Westerly Winds on Amsterdam Island (37°S) from peat records

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The Southern Ocean (SO) is the main area on the planet where the deep ocean is connected to the atmosphere and where about 40% of the global oceanic uptake of anthropogenic CO_2 takes place (Gruber et al. 2019). Therefore, this part of the global ocean is a crucial, yet understudied, part of the Earth's climate system and carbon cycle. Crucial in this context are the rain-bearing Southern Hemisphere Westerly winds (SHW). The vigorous zonal winds strengthened and shifted poleward during the last decades of the 20th century, contemporary with an increase in atmospheric temperatures, and enhanced SO CO_2 upwelling (Gruber et al. 2019, Deng et al. 2022). This flux of "natural" CO_2 to the atmosphere forms a potential amplification of human-induced global warming, as the strength of the SO CO_2 sink will weaken (Toggweiler et al. 2006, Moreno et al. 2010). In addition, a more poleward position of the wind belt, directly impacts human society as large areas on the three mid-latitude austral continents are exposed to droughts (Perren et al. 2020). Therefore, in light of the ongoing large uncertainty in model projections of the SHW, a thorough understanding of the natural variability of the SHW is of vital importance (Bracegirdle et al. 2020, Perren et al. 2020). This project will reconstruct the Holocene evolution of the SHW on Amsterdam Island (37°S) located at the current northern edge of the SHW wind belt. Rain-fed peat bogs occur on Amsterdam Island providing unique paleo-environmental archives. From those we will study the SHW Holocene variability in effective precipitation (precipitation minus evaporation) through bog surface wetness (BSW) proxies: encompassing (i) water table depth reconstructions obtained from testate amoebae*,* (ii) plant macrofossil analysis and (iii) stable hydrogen isotope analysis of plant derived n-alkanes (δ^2H of n-alkanes). Here we present preliminary results of the latter along with a temperature record record based on the relative abundance of branched glycerol dialkyl glycerol tetraethers (brGDGTs), bacterial membrane lipids.

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Store Mosse Bog: Species distributions of the past and factors that drive them

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Northern peatlands are typically made up of mosses, sedges, dwarf shrubs, and trees. *Sphagnum* mosses are a key species in boreal peatlands since they can tolerate nutrition-poor and highly acidic environments, thus contributing significantly to carbon sequestration and peatland dynamics. Understanding the factors that drive changes in *Sphagnum* species distribution over time is therefore of particular interest, as this may impact peatland carbon storage in a changing climate.

Species distributions are commonly analyzed using species distribution modelling (SDM) based on contemporary species data and climate variables using extensive spatial scales, however, they often lack an extended temporal scale. By incorporating paleo-datasets in SDMs, we can test the relationship between climate and species distributions over time, and in turn assess potential long-term changes or time-lags in ecosystem responses, creating so called *paleo*-SDMs.

In combining a dataset from the peat-paleorecord with environmental factors driving species changes (e.g., moisture, dry periods, nutrient input, fire activity, and temperature), we aim to show how species changes have varied over time, including the relative contributions of the driving factors involved. Here we present the results from our first *paleo*-SDMs based on a high-resolution plant macrofossil reconstruction covering the last ~10 000 cal yr BP in Store Mosse bog, south-central Sweden.

"Anomalously mild Younger Dryas summer conditions" (Björck et al. 2002) as potential solution for the stadial meltwater paradox

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Finding first late-glacial lake sediments on Greenland

After first ice core studies from Greenland in the 1990s revealed abrupt annual temperature shifts of up to 20 degrees within ~10 to 20 years for the Younger Dryas (YD) stadial (GS-1), Svante Björck and colleagues sought to find lacustrine records on Greenland that could elucidate this event. After many unsuccessful attempts to locate and core a lake clearly pre-dating the YD (Bennike & Björck 1999), lake N14 from the Island of Angissoq in the very SW of Greenland was a match covering the period 14,4 to 10,5 ka BP. Considering the severe cooling found in nearby ice cores, the diatom-based inference of *'anomalously mild YD summer conditions'* was clearly a surprise. Although previous studies found evidence for the presence of short-lived warm summer episodes within the YD, it was not until Björck et al. (2002) to highlight the possibility that the whole YD might have anomalously mild summers throughout - at least south of the Greenland Ice Sheet.

Widespread warm *Stadial Björck-Summers* could resolve the stadial meltwater paradox

Two decades later, it becomes clear that Svante's study was not a local finding at all. It is echoed by reconstructions south of the Fennoscandian Ice Sheet in Europe (e.g., Schenk et al. 2018; 2020 with Svante as co-author). Toucanne et al. (2015) and Boswell et al. (2019) even found evidence for enhanced stadial ice sheet melting in Europe during some Heinrich Events. The widespread existence of warm *Stadial Björck-Summers* could resolve an apparent meltwater paradox in climate modelling: That models require most meltwater forcing during the coldest periods – to keep the AMOC off.

However, warm stadial summers are still in contradiction to most multi-proxy studies. Here we show that considering non-analogue stadial conditions may reconcile discrepancies. To define the non-analogue state, we use a direct reconstruction of the Gorczynski continentality index (CI_G) from subfossil chironomids from S-Sweden. Our reconstruction yields hyper-continental stadial climates comparable to central Siberia (CI_G 60-80%). Using continental training sets for chironomids and plant macrofossils yields stadial T_{July} >14-16°C in S-Sweden and 15-18°C in the Baltic States. Inverting the equation for CI_G allows calculating $T_{January}$ from proxies as a function of CI_G and T_{July} with stadial winters as cold as –40.5°C ± 7°C (mean –33°C ± 0.7°C). These non-analogue reconstructions confirm the qualitative diatom-based estimates by Björck et al. (2002) for mild summers with cold winters for the YD. Irrespective of regional ice sheet readvances, *Stadial Björck-Summers* appear to be much more widespread and constitute a key feature of rapid deglaciation that does not stop during stadials.

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Development of hypoxia in the coastal northern Baltic Sea during the Holocene thermal maximum using magnetic greigite as a proxy

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The Central Baltic Sea has the one of the largest hypoxic zones in the world (Fennel & Testa, 2018), and during the past decades, increasing hypoxic conditions have been obtained also in the coastal zone (Conley et al. 2011). While the Holocene development of repeated hypoxia in the Baltic Sea basin is well studied in multiple Central and Southern Baltic deep-sea cores, less is known about the development of the coastal zone during the Holocene thermal maximum (HTM). Understanding the driving forces for coastal hypoxia during HTM is topical, providing an analogy for assessing future development of hypoxia in a warming climate.

An ultra-high resolution (0.75 m/a) 40-m long sediment core from coastal Bothnian Sea (Kurikka, S. Ostrobothnia, Finland) was analysed with lithological and environmental magnetic methods. This core covers local deglaciation and basin evolution from a freshwater to brackish phase until isolation from the sea (~10.8–4.5 ka BP). Environmental magnetic methods and occurrence of magnetic mineral greigite (Fe3O4) was used to assess hypoxia variation (Snowball 1997, Roberts et al. 2015) along the sediment sequence.

Preliminary results indicate that hypoxia was common, but frequently interrupted during the HTM in the shallowing coastal Bothnian Sea. Two multicentennial predominantly hypoxic periods and two intensive decadal hypoxic events are observed with more regular oxic conditions in between. However, the greigite concentrations are variable throughout the hypoxic interval, indicating unstable oxygen conditions and perennial trends in hypoxia intensity. The pattern seen in Kurikka record corresponds with the description of a multicentennial nature of hypoxia variability in the Baltic Sea with oscillating intensity (Zillen et al. 2008, Jilbert & Slomp 2013, Carstensen et al. 2014), suggesting basin-wide regularity and drivers of hypoxia.

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Monitoring of Greenland lake temperatures reveals NAO influence on thermal stratification

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In the face of current global climate change, it is imperative to assess the role of atmospheric circulation patterns for changes in regional climate, in order to mitigate future weather extremes that we are already seeing examples of, such as record high temperatures, drought, and rainfall. The North Atlantic Oscillation (NAO) is the most important reoccurring weather pattern in the North Atlantic region, with a strong impact on temperature, storm tracks, precipitation amount and distribution, as well as length of seasons (Hurrell et al., 2003). A way to test the reliability of future scenarios is to look for analogies in the past, such as during the Holocene Thermal Optimum (Intergovernmental Panel on Climate Change, 2023). However, there are currently no reconstructions of NAO covering the entire Holocene, mainly because the NAO variation is not always captured by geological archives or is swamped by other factors, such as seasonality and regional spatial variability. The longest existing NAO reconstruction covers 5,200 years and is based on a Greenland lake sediment record (Olsen et al., 2012). Arctic lake sediments comprise valuable climate archives for proxy-based reconstructions of large-scale climate variability, as the lakes are commonly undisturbed for thousands of years, only affected by climatic and environmental changes. To make a robust NAO reconstruction, covering the entire Holocene, however, requires a better understanding of how weather patterns affect arctic lakes, i.e., their physical and chemical properties. Many climate-proxy reconstructions derived from lake sediments are based on very limited contemporary environmental/process data, because multiyear in-lake measurements are rarely carried out along with paleoclimate investigations.

In this study, we show how weather patterns affect arctic lakes, and how these interactions are reflected in the sediment record. We monitored temperature profiles continuously for six years in three lakes in Kangerlussuaq, Greenland, and compare our results to calculated NAO index and local meteorological observations from two associated AWS in the same period. Our results show that there is considerable variation in lake sensitivity to NAO-mode, even between lakes in close proximity, which highlights the importance of careful site selection in lacustrine paleoclimate studies. Furthermore, we show that the thermocline strength is coupled to NAO-variation, and as this impacts the cycling of redox-sensitive elements (Olsen et al., 2012), our results have direct implications for future use of sediment geochemical climate proxies to infer past climate variability in the Arctic. This study expands our understanding of the processes that link atmospheric circulation patterns and lakes and hence the derivation of quantifiable properties from arctic lake sediments, which will help clear the path for extending the NAO record into the early Holocene.

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Zonally symmetric shifts of the Southern Hemisphere Westerly Winds

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Peatlands preserve climate and environmental change over thousands of years, and arguably nowhere is this more important than the Southern Ocean region. This region has particular significance for understanding the evolution of the southern westerly winds, and their influence on ocean carbon flux, Antarctic sea ice, and regional temperature and precipitation patterns. Here we investigate shifts in the latitudinal position and strength of the Southern Hemisphere Westerly Winds using high resolution geochemical data from peat sequences in sub-Antarctic islands across the Southern Ocean. We measure bromine concentration, derived from sea-spray aerosols, as a wind-strength proxy over the Holocene, and find Southern Ocean-wide increases in bromine over the last 2000 years, indicating a zonally symmetric strengthening of the southern westerly winds during this time. This work has important implications for understanding the links between stronger and poleward-shifted westerlies and the outgassing of natural CO_2 from the Southern Ocean.

Unravelling the Holocene history of the Southern Westerlies: a latitudinal transect of terrestrial (peat) records from the South Indian Ocean

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The Southern Hemisphere mid- to high latitudes are strongly influenced by the rain-bearing Southern Hemisphere Westerly winds (SHW), acting on large-scale precipitation and temperature patterns, dictating the climate between the latitudes 30 to 60°S. Changes in the intensity and position of the SHW are believed to control wind-induced upwelling in the Southern Ocean (SO) and hence, the oceanic meridional overturning circulation and atmospheric CO_2 variations, during deglacial times, the Holocene as well as in recent times (i.e. Toggweiler, 2009; Moreno et al., 2010, Gruber et al., 2019). However, despite substantial research efforts during the last decades, proxy-based knowledge on the strengthening and/or latitudinal shifts of the SHW is still fragmentary and sometimes contradicting. A prerequisite for reconstructing latitudinal changes in zonal winds is the availability of well-dated terrestrial records that (i) reflect atmospheric conditions and (ii) are situated on a latitudinal transect covering the wind belt. We study the pre-anthropogenic (Holocene) history of the SHW, by investigating a latitudinal transect of peat lands on a series of sub-Antarctic islands in the Indian sector of the SO: from Kerguelen Islands (49°S) located in the core of the modern wind belt, over the Crozet archipelago (46°S), to Amsterdam Island (37°S) at its northern edge. Here we will discuss two case-studies of Holocene SHW changes based on multi-proxy analysis of peat cores [e.g. pollen and plant macrofossil, XRF core-scanning, biogenic silica (BSi)]. The first study is a record for past humidity and windiness changes from the Crozet archipelago (46°S). A shift to wetter and windier conditions occurred about 2800 years ago, caused by a strengthening of the SHW and coinciding with a major decline in solar activity (Homeric minimum). A second study on past humidity and windiness changes originates from Kerguelen Islands (49°S). Accumulation rates in a peat core are very low (~0.1 mm/yr) between 9 and 5.5 kyr BP (thousand years Before Present). From around 5.5 kyr BP onward, a change to more humid conditions caused renewed peat formation prossibly caused by increased SHW influence. Superimposed on this long-term trend, multi-centennial variability was found from about 4 kyr BP onward, showing periods of both (i) higher wind intensity (increased *Azorella selago* pollen and Ti content and (ii) increased humidity (increased *Botryococcus* sp. and BSi percentages) suggesting cyclic SHW intensity changes. This research was partly funded by a grant to Svante Björck who in his later career moved his research interests from Scandinavia and the North Atlantic region to a global perspective applying the unique potential of lacustrine and peat sediments for reconstructing linkages in the global climate system.

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Tephrochronology of the North Atlantic region – a tribute to Svante Björck

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Svante Björck was a pioneer in many fields of Quaternary science, including tephrochronology as a tool for dating and correlating palaeoclimate archives. A search in Google Scholar on "Svante Björck Tephra" returns almost 175 results with a main focus in the North Atlantic region, but also several papers and citations based on his research in remote localities in Antarctica and the southern oceans (e.g. Björck et al. 1991, Ljung et al. 2006, van der Putten et al. 2015).

In the North Atlantic region, Svante worked with many exciting island lakes, bogs and wetlands. Some sites were part of his Atlantis project, starting in 2002 (Björck 2019), but also his work on Icelandic lake records are today regarded as benchmark papers in the North Atlantic tephrochronology The sediment study from Lake Torfadalsvatn in northern Iceland was first effort to identify the terrestrial tephra equivalents of the North Atlantic Ash Zone I and reported evidence for the Saksunarvatn and Vedde tephras as well as several basaltic tephras (Björck et al. 1992). The tephra record of Lake Lögurinn in eastern Iceland contains no less than 157 tephra layers which is among the highest number in Europe (Gudmundsdóttir et al. 2016).

In this presentation, I will revisit some of the tephra records that I have studied in collaboration with Svante in Sweden (Late Weichselian; e.g. Wastegård et al., 1998), the Faroe Islands (Eemian and Holocene; e.g., Wastegård et al., 2005), the Azores (Holocene; Björck et al., 2006) and Jan Mayen (late Holocene; e.g. Björck et al., 2022). The results have been published between 1998 and 2022, from the first discovery of the Vedde Ash in a Swedish lake sediment record (Wastegård et al. 1998), to the tephrostratigraphy of sediments from Nordlaguna, the only permanent lake on Jan Mayen (Björck et al. 2022).

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Session 29

Quaternary geology and geomorphology: Open session

Session Chairs:
Gustaf Peterson Becher
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Can modelled ice conditions indicate geomorphology? Comparative pattern analysis of Norwegian Quaternary Geomorphology

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Pattern analysis of contemporary landforms versus modelled Quaternary glacial conditions

In this study we investigate the relationship of subglacial conditions - such as thermal regime and topography - to common subglacial landforms. We do this by comparing landforms detected using the outputs from a machine learning model (Barnes et al., in prep) and prior mapped features from the Norwegian Geological Survey (NGU, 2022), to modelled conditions at the bed of the Fennoscandian Ice Sheet (Patton et al., 2016; 2017). We then group landforms into respective categories: (a) glacial, (b) periglacial, (c) glaciofluvial and (d) glaciolacustrine, with (i) erosional and (ii) depositional subcategories. To gain a more comprehensive overview as to the value of this study in Norway, we take a transect across southern Norway, from Kongsvinger in the South-East to Kristiansund in the North-West. Thereafter we overlay model data and landforms to calculate zonal statistics for our transect, for example the mean modelled basal temperature for each feature group, for each 1000-year time-step of the numerical ice-sheet model. From this comparison we hope to learn about the conditions present during the formation of Quaternary landforms such as drumlins and ribbed moraines. Using this information, we provide new insight on the processes of formation of Quaternary landforms with debated origins, their timing of formation, and potential periods of preservation under cold-based ice.

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Rapid glacial sedimentation and overpressure in oozes causing large craters on the mid-Norwegian margin

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Along continental margins with rapid sedimentation, overpressure may build up in porous and compressible sediments. Large-scale release of such overpressure has major implications on fluid migration and slope stability. Here, we study if the widespread crater-mound-shaped structures in the subsurface along the mid-Norwegian continental margin are caused by overpressure which accumulated within high-compressibility oozes sealed by low-permeability glacial muds. We interpret 56,000 km ^{2} of 3D and 150,000 km ^{2} of 2D-cubed seismic data in the Norwegian Sea, combining horizon picking, well ties, and seismic geomorphological analyses of the crater-mound landforms. Along the mid-Norwegian margin, the base of the glacially-influenced sediments abruptly deepens to form 28 craters with typical depths of ~100 m, areal extents of up to 5130 km^2, and volumes of up to 820 km^3. Mounds are observed in the vicinity of the craters at several stratigraphic levels above the craters. We present a new model for the formation of the craters and mounds where the mounds consist of remobilized oozes evacuated from the craters (Bellwald et al., 2024). In our model, repeated and overpressure-driven sediment failure is interpreted to cause the crater-mound structures, as opposed to erosive megaslides (Riis et al., 2005). Seismic geomorphological analyses suggest that ooze remobilization occurred as an abrupt energetic and extrusive process. The results also suggest rapidly-deposited, low-permeability and low-porosity glacial sediments seal overpressure which originated from fluids being expelled from the underlying, high-permeability and high-compressibility biosilicious oozes.

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High resolution seismic investigation of lake Esrum Sø, Denmark – glacial morphology or wrench fault tectonics?

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The Esrum Sø is one of the biggest lakes in Denmark with a marked elongation trending N-S located in the glacio-morphological landscape of NE Sjælland and being close to the tectonic Tornquist–Sorgenfrei Zone, which is a wrench-fault system trending to the NW few kilometres NE of Esrum Sø. The water table in the lake is at 9 m a.s.l., and the lake is up to 20 m deep with very steep sides and occupies an area of c. 18 km^2. In the present investigation of the structures in the lake basin a shallow seismic mapping has been carried out for the first time and the data is of high quality. Four fieldwork campaigns (in the years 2013-2015 and 2022) has been carried out with an instrumentation of Teledyne high-resolution Chirp III subbottom profiler with a frequency band of 2-20 KHz. 82 seismic profiles (115 line km) has been acquired and carefully analysed using seismic interpretation software. An 8.5 m long drill-core from a borehole drilled in 1966 in the northern part of the Esrum Sø is included in the study and a correlation between the drill-core and two seismic profiles is carried out. The drill-core reach the Young Baltic till in 8 m depth below the lake floor and above this an alternating succession of c. 4 m consisting of clay, free of stones, with several sand layers is found. In this succession pollen zone, analysis was performed previously. The uppermost 4 m of the drill-core consist of calcareous gyttja.

The seismic data reveal a number of anti- and synform structural features in the Northern part of the lake and the mapping of these structures show N–S trending vertical fractures, fault escarps and fold crests, which in places are bent towards a NW direction. The seismic signal deteriorates significantly in some places of the lake where gas seepage is found in the gyttja and in most of the southern parts of the lake where gas occurs close to the lake floor.

Our investigation shows that the lake in Bølling to Pre-boreal time was a shallow fresh water lake with no tectonic disturbances and the major subsidence of the lake took place in Boreal to Atlantic period. Our interpretation favours a model of an extensional Post-glacial pull-apart basin related to the wrench-fault tectonic zone neighbouring the Sorgenfrei–Tornquist Zone.

Quaternary geology mapping in the Helgeland region, northern Norway – a multidisciplinary approach

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Quaternary geology maps provide data of great societal value. The distribution and characteristics of superficial deposits have direct implications for e.g. spatial planning, resource management and geohazard mitigation, and the maps provide information of educational and scientific interest. The ever-increasing need for better and more accurate maps and sub-surface geological information becomes particularly evident in geohazard related context, e.g. as land use in areas with sensitive clays require expensive ground investigations prior to development.

Here we present results from a Quaternary geology mapping project in the Helgeland region, northern Norway, carried out by the Geological Survey of Norway (NGU). In this project we have employed a variety of methods in order to gain a robust and comprehensive geological knowledge fundament for the area. In addition to our traditional terrestrial field reconnaissance and remote sensing mapping methods, we have conducted: a) geophysical ground surveys using electrical resistivity tomography (ERT) to explore the three-dimensional structure of sediment deposits; b) multi-beam echosounder and seismic surveys in the fjords to map the seafloor terrain and seismic stratigraphy; and c) study and radiocarbon dating of sediment cores from lake and bog basins, to investigate the relative sea level history and deglaciation chronology.

The results gained with a wider method approach include new insights into environmental changes in the region throughout the last deglaciation. For instance, the ERT data have helped uncover areas with sensitive marine clays on-land deposited during a time of higher relative sea level, and provide vital depth-to-bedrock data along with crucial information to local authorities regarding potentially slide-susceptible raised marine deposits. The newly acquired marine bathymetry data reveal the presence of several interesting features in the fjords, such as moraine ridges, glacial lineations, pockmarks and landslide features, including a hitherto unknown large subaqueous rockslide deposit (>100 000 m^3). Mapping of submarine moraine ridges and grounding zone wedges provides additional evidence to the terrestrial mapping for ice sheet positions during deglaciation. When combined with onshore mapping and results from the sediment core analysis, including radiocarbon dated shells within the Younger Dryas margin, the evidence indicates that the climatic deterioration of the Younger Dryas caused a ≥13km readvance of the ice sheet in Southern Helgeland, simultaneously producing up to 100-meter-tall moraines.

This project has thus far led to the production of eight new tiles of 1:50 000 scale geological maps (~650 km^2 each, 5200 km^2 total), with three more tiles in progress. The new geological maps and knowledge will be of great value for local management and development, and ultimately cost-saving for the municipalities in the region.

Mapping the way in the digital day. Improving Quaternary geological maps in Norway

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High-quality Quaternary geological maps provide vital information for a wide user mass of diverse needs, including land-use planning, environmental mitigation, natural disaster evaluation, policymaking, research, and education. The digital society requires accurate and precise maps. Older maps show displacements and inaccuracies caused by the digitalization process and lack of digital data at the time of making. Alongside ongoing mapping, NGU now initiates map improvement efforts using high-resolution digital terrain data, and explores new possibilities introduced by artificial intelligence.

Whilst ground truthing remains essential in new mapping, high-resolution digital terrain data increases mapping precision and accuracy. High-resolution images from airborne LiDAR reveal unexposed geomorphological details covered by vegetation, and thus enhances delineation accuracy and map applicability. The importance of high-quality maps becomes particularly evident in the context of geohazard detection, where inexact or absent boundaries can impair risk assessment in areas prone to landslides.

Today, automated processes increasingly enable assorted data derivation from Quaternary maps. However, maps made prior to the time of digitally comprehensive landscape analysis challenge the aptitude of such technological tools. Ripple effects occur in derived data sets as maps of an earlier age constitute a weighty component of integrated modelling operations.

Maps reflect the priorities and tools available at the time of making. As digital development advances, opportunities for upgrades arise. Still, less than a third of Norway is mapped at a satisfactory scale, and most maps predate the digital era. The countrywide variety of landscapes requires novel approaches to assessing both the cartographical and geological quality of published maps. As NGU tackles the task at hand, we consciously consider mapping methods, sufficient standards, and project prioritisation. Here we present lessons from a work in progress.

A surprisingly explosive volcanic history, Snæfellsjökull W. Iceland

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Iceland´s post-glacial explosive volcanic history is predominantly derived from investigations of soil sections as well as written archives, following human settlement *c.* 870 CE. While this approach provides detail to our understanding of past explosive volcanism, prehistoric knowledge is limited by the development and distribution of Iceland´s soil. Knowledge gaps exist during the Early Holocene (prior to extensive soil formation) and in relation to specific understudied coastal provinces (largely flanked by sea rather than soil). As a result, tephra from large explosive eruptions is regularly first identified overseas and locally lacks key details (e.g. specific source province, range in geochemical properties, eruption age). While tephrochronological investigations through the last century have mainly focused on historically active volcanic provinces (e.g. Hekla, Katla, Bárðarbunga-Veiðivötn and Grímsvötn), some volcanic provinces remain understudied. Even despite the risk of explosive eruptions (≥VEI 4), not only locally effecting Iceland, but potentially large parts of Europe. The Snæfellsjökull volcano, located on a peninsula extending 100 km off the west coast of Iceland (110 km north of the capital city Reykjavík) is a prime example of one of these understudied provinces. While the glaciated central volcano has no described historical eruptions, there are three explosive events known from the post-glacial era: *Sn-1* ~1.8 ka BP, *Sn-2* ~4.0 ka BP and *Sn-3* ~8-9 ka BP. It is suggested that tephra from at least two of these eruptions has been identified in European stratigraphic archives. Furthermore, numerous other (crypto-) tephra horizons have been identified in Europe that exhibit similar geochemical properties to the Snæfellsjökull province. However, we lack knowledge on the extent of its post-glacial explosive volcanism and the potential range in tephra geochemistry. In this study we present several lake records from the Snæfellsnes peninsula to improve understanding of post-glacial explosive volcanic activity effecting both regional and distal environments.

Hekla early Holocene tephrochronology: Potential new Hekla marker layers?

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The Icelandic tephrochronology plays a key role in the North Atlantic framework. Over 40 tephra marker layers have been established for the Holocene. However, only a few well-established marker layers have been identified in the Early Holocene. Tephra layers from Hekla volcano are the backbone of the Icelandic tephrochronology. Almost 20 tephra layers, half of the known tephra markers within the Holocene, originate from Hekla volcanic system.

The present study aims to improve the early Holocene tephra framework by exploring new tephra marker layers from the Hekla volcanic system. 166 tephra units older than Hekla 5, from eight soil sections around the volcano, have been sampled and analyzed for major element composition. Preliminary results show that over 50 tephra units originate from Hekla. Most of the tephra units are of basalt composition, characterized by two components: a relatively primitive basalt (TiO_2 < 3 wt% and Al_2O_3 >15 wt%) and a more evolved basalt (TiO_2 >3 wt% Al_2O_3 <14 wt%, MgO <6 wt%). In many cases both components are found within the same layer. Fewer layers are of basalt andesite to andesite composition. Of particular interest is a tephra unit, older than 8800 BP, identified northeast of Hekla and in North Iceland. This tephra unit, provisionally called “Hekla 6”, has a composition ranging from silicic to basaltic similar to the well-known Hekla 5, Hekla Ö, Hekla 4, and Hekla 3 tephra marker layers.

First cryptotephra study in Iceland reveals two previously unknown rhyolitic early Holocene eruptions of Hekla

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Icelandic tephrochronology consists of both silicic and basaltic, geochemically well-characterized and well-dated tephra horizons (e.g. Larsen & Eiríksson 2008, Guðmundsdóttir et al. 2016). Of these, the silicic major tephra marker layers traditionally form the core of the chronology and act as important anchor points for between-site correlations of tephra stratigraphies. Most of the marker tephras, however, form a visible layer only within a certain sector extending away from the source volcano (e.g. Larsen & Thorarinsson 1977, Larsen et al. 2014). The extent (of the dispersal area) of the visible tephra layer is determined both by the intensity and the length of the eruption as well as the prevailing wind directions during the eruption. Some amount of tephra grains is, however, expected to be deposited over a larger area and to be preserved as a cryptotephra layer. Here we present the results of our study that aims to improve the Icelandic tephrochronology, both through identifying new tephra layers and extending the known dispersal areas of well-established marker layers by using cryptotephra methodology for the first time in Iceland.

Our main findings include the discovery of two rhyolitic early Holocene Hekla tephras in an organic-rich soil section in Reitsvík, northern Iceland. Based on their stratigraphic position below the visible Hekla 5 layer (radiocarbon dated to 6935–7159 cal BP in Reitsvík) and their radiocarbon ages they predate the Hekla 5 eruption and represent the earliest silicic products of the Hekla volcano, originating from previously unknown eruptions. The younger of the two (ca. 7500 cal BP) is geochemically indistuingishable from the Hekla 5 tephra and its composition in Reitsvík is strictly rhyolitic (SiO_2: 72.46–76.05 wt%), whereas the older one (ca. 8900 cal BP) has a similar composition as Hekla 3 (SiO_2 65.57–73.44 wt% and FeO_{tot} > 3 wt% in the rhyolitic fraction). These results reveal that rhyolite production in Hekla has begun much earlier than previously thought, and showcase the benefits of extending tephra research in Iceland into the cryptotephra realm. We expect further cryptotephra research in Iceland to improve knowledge of the eruption history of different volcanic systems, as well as to refine the tephrochronologies of single sites.

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Tilting of Eemian sea notches on the Thai-Malay Peninsula

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Erosion of limestone in tropical marine environments can lead to the rapid formation of distinct sea notches marking the position of the average sea level. Fossil sea notches at far-field sites outside the areas directly influenced by glacio-isostatic adjustment processes can therefore be used to infer the position of past global sea-level high-stands.

The Thai-Malay Peninsula is often considered to be tectonically stable on time scales relevant for reconstructing late Quaternary sea level variations. However, here we demonstrate that in Phang-Nga Bay on the western side of the Thai-Malay peninsula, sea notches that formed during the last interglacial about 130-115 ka (Eemian) show a distinct east-west tilt. Clear sea notches, both modern and fossils, can be observed in the Permian Ratburi Limestone that crops out along SSW-NNE trending chains of karst towers in Phang-Nga Bay. Sea notches on the eastern side of the bay are about two meters higher relative to sea notches on the western side of the bay, with sea notches in the middle of the bay having intermediate values.

The elevation of the sea notches was measured using laser range finders and all measurements were tied to the local datum using GNSS with an error typically smaller than 10 cm. Only distinct sea notches that could be traced out horizontally were used. Because older sea notches are typically overgrown by tufa formations and flowstones, only clear measurements from notch ceiling and notch floor were used. A compilation of the measurements shows that sea notches across the bay show similar heights from floor to ceiling, but that there is a clear trend with higher elevations in the East relative to the West. No such trend could be seen in the north-south direction. Because sea notches are erosional features, absolute dating is often difficult. However, oysters found in situ in crevasses in the ceiling of the sea notches have infinite radiocarbon ages, demonstrating that these notches must have formed long before the Holocene sea-level high-stand, but the amount of overgrowth and the general erosion rate make it unlikely that the observed notches should be remains of the MIS 11 sea-level high-stand. Consequently, we conclude that the most likely age of the wide-spread upper sea notches matches the Eemian (MIS 5e) sea level high-stand.

Because the east-west difference in elevation of the Eemian sea notches is roughly perpendicular to the direction of the Khlong Marui strike-slip fault, we postulate that movement along the Khlong Marui fault over the past ca. 100 ky have resulted in about two meters of vertical movement of the landscape. Consequently, on longer time scales, the vertical movements of the Thai-Malay Peninsula must be considered when reconstructing past sea level variations.

The Norwegian tafone: A common, yet overlooked and poorly described landform

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Tafoni (Tafoni plural, Tafone singular), a term first used scientifically by renowned Norwegian geologist Hans Reusch after his excursion to Corsica in 1876, refers to cavities ranging from centimeters to meters in size that form in rock (Reusch, 1882). Despite Norway's long-standing tradition of studying these landforms, they have been largely overlooked, leaving gaps in our understanding of their distribution and formation processes within the Norwegian and Scandinavian contexts.

Internationally, Tafoni are quite well-documented, particularly in coastal, arid, and polar environments. Recent studies have revealed that coastal Tafoni in Norway can cause significant local weathering, leading to erosion rates of several decimeters per thousand years (Andersen et al., 2022). Furthermore, ongoing mapping efforts have shown that Tafoni are present both along the coast and in inland Norway (Øverland, 2020). They exhibit a wide range of sizes and morphologies and occur in various lithologies, making their formation processes elusive. Tafoni in their essence are not able to hold standing waterbodies. They need to be distinguished from other small-scale bowl-like depressions, of which there are plentiful.

Various formation processes for Tafoni have been proposed in international literature, with mechanical weathering, especially salt weathering (haloclasty), being a common factor. Haloclasty occurs when saline solutions infiltrate rock fissures and mineral grain boundaries, depositing salt crystals. As the rock dries and heats under solar radiation, these salt crystals expand differentially, exerting pressure on the surrounding mineral grains and causing the rock to disintegrate mechanically.

In a newly discovered, spectacular Tafoni site in Stjørdal, central Norway, detailed studies tell us that haloclasty plays a significant role in Tafoni formation here. Thin sections, XRD and XRF data indicate that phyllosilicates like biotite and clay minerals such as chlorite residing interstitially between the primary rock-forming minerals may also undergo physical expansion through weathering. This process aids both the disintegration of the rock and the infiltration of saline solutions. We propose that haloclasty in our opinion are the most likely contributor to physical expansion. Other mechanical and chemical weathering processes might also contribute to further development, but to a lesser extent. Our findings are likely transferable to other tafoni localities in Norway.

The formation of Tafoni is complex, requiring careful petrographic studies combined with analysis of rock geochemistry and environmental settings to fully understand their formation processes. Our findings and observations suggest that Tafoni are common geological features in Norway. They can cause rapid disintegration and erosion of bedrock, at geographically smaller areas. Their overall impact on the Norwegian landscape remains to be quantified.

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Mörtsjö fault – 'new' Glacially-triggered fault discovered following geomorphic analysis of the 'Hudiksvall seismic cluster', Sweden

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We present geomorphic, sedimentologic, and stratigraphic evidence of a previously unknown Holocene fault complex in central Sweden. The discovery was made in two steps: remote-desktop study with LiDAR-based imagery, and machine trenching of two suspected faults scarps. The study is funded by Swedish Nuclear Fuel and Waste Management Company (SKB) and is part of a larger project investigating the cluster of high seismic activity in the Hudiksvall area.

The first step focused on finding landforms influenced by glacially-triggered faulting, such as cross-cutting relations between scarps and raised shorelines or glacial features, as well as landslides in till. Features were mapped manually using the 1 m resolution, LiDAR-derived national height model. The distribution and character of landslide scars are a work in progress. Over six hundred such features were mapped, in step one, and the distribution can be correlated to known or suspected GTF's. The remote desktop study is summarized in an SKB report which is under review.

In the second step two sites were selected for machine trenching. The geomorphology shows cross cutting relations of the mapped scarps to raised shorelines and drumlins. Sedimentologic documentation reveals landslide events and folded, as well as, ripped fine-grained sediments sections. The sites, Snaten and Ers-Pers, are collectively referred to as the Mörtsjö fault complex.

Radiocarbon dates on samples from the Snaten fault landslide deposit are consistent with an average of 3180 cal yr BP. This 'maximum age' is by far the youngest fault rupture documented in Sweden. The varve stratigraphy at Ers-Pers shows that the landslide occured below water c. 40 yr after deglaciation, c. 10 600 cal yr BP. However, the sedimentology also indicates secondary movements suggesting that the fault has been active at least twice since deglaciation.

Mapping and late Holocene reconstruction of the Helags glacier in Härjedalen, Sweden

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Mountain glaciers are melting as a consequence of global warming. A warmer climate has a direct effect on the mass balance of glaciers, leading to major consequences for water supply, sea levels, tourism and local climate. By studying glaciers and their recession by the mapping of glacial landforms, we can gain an understanding of their current and past retreat, and make predictions and estimations about their future state. The Helags glacier located in Härjedalen, Sweden, is a retreating cirque glacier with numerous glacial landforms in its vicinity. No recent or detailed maps have been made and neither has an attempt to reconstruct the retreat of the glacier. This project will fill this gap by making in situ observations and measurements of the glacier and the surrounding landforms, with the aim to reconstruct the late Holocene glacial history of the Helags glacier.

Drone images of the glacier and the immediate area around it in addition to in situ observations, historical maps and photos, and LiDAR data, were used to make a detailed geomorphological map. The geomorphological map presents a variety of landforms and sediments including (but not limited to) end moraines and lateral moraines, glaciofluvial sediments, striations, talus cones, ribbed moraines and proglacial lakes. Measurements using lichenometry and rebound values using a Schmidt hammer were taken on selected mapped moraines below the glacier in order to investigate and ultimately define their exposure ages. Eight moraine ridges were measured in total, ranging in size, elevation and distance from the glacier. On each ridge, the diameter of the largest lichens were measured as well as the rebound value of boulders. The results show a general increase in lichen size and decrease in rebound value on moraines with increased relative distance from the glacier, indicating that those surfaces have likely been exposed for a longer period of time.

Furthermore, it is evident that the glacier has had multiple stages of retreat, standstills, and advances which affected the landscape by forming moraines of different intervals. However, it is also apparent that the landscape outside the immediate Helags cirque valley is characterized by landforms from the last glaciation, with the younger moraines overprinting. The results obtained in this study can be used to better understand the late Holocene glacial history and the rate at which the Helags glacier is, and has been, receding, while also help us to gain greater insight into similar glaciers and environments.

Mapping of red-listed marine clay gullies in Norway using Deep Learning

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Gullies and ravines are common landforms in raised marine fine-grained deposits in Norway. Gullies in marine clay are significant landforms indicative of soil erosion, natural hazards and are of high conservation value. As a result of the substantial impact of human intervention over the past century, marine clay gullies are now red-listed. To monitor the condition of these landforms we need to improve our understanding of their spatial extent, complexity, and morphology. We explore the applicability of automated approaches that uses a methodology of combining deep learning (DL), fully convolutional neural networks (FCNN), and a U-Net model with ArcPy libraries and ground truth data to derive a high-resolution map of gullies in raised marine fine-grained deposits. Predictors used comprise solely terrain derivatives to broaden the usage of the pre-trained model to other regions. Our best model achieved a precision score of 0.82 and a recall of 0.75. We find that our pre-trained model can successfully predict gullies in blind-test areas in regions with similar geological settings, scoring a length-weighted overlap of >72% with reference datasets. We also find that the applicability of the model increases when we post-process the predictions by eliminating noise, especially by using the predictions derived from ensembled models. We, therefore, conclude that the pre-trained models can effectively be used to supplement the geomorphological mapping of marine clay gullies in Norway. The outcome of this research contributes towards mapping the spatial extent and condition of red-listed landforms in Norway, as well as the development of monitoring systems for future landscape change.

Session 30

Sedimentology – organized by the Nordic Sedimentary Research Group

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The Fourth Slope – Mathematical correlation of shape and process on continental margins

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Clinoforms are the building blocks of sedimentary geology and their typical s-shaped geometry can be recognized in cm-scale ripples up to the kilometre-scale slopes connecting the shallow continental shelves to the deep abyssal ocean floor. To what extent there is a systematic relationship between the shape of clinoforms and the processes responsible for their formation, is addressed in this study based on curve-fitting of over 150 continental margin slopes. Previously three mathematical functions have been found to closely match many submarine slopes. The present study broadens the range of mathematical functions to improve the potential for prediction of along-strike variations between form and processes. Four mathetmatical functions are found to closely match most slopes: Linear, Gaussian, exponential and quadratic (positive and negative/inverse). The study reveals that the fourth slope, the quadratic, is by far the most common. While exponential and quadratic slopes are similar, there is a crucial difference in the way in which the declivity of the slope changes. Continental slopes are created through a complex interaction of destructive and constructive processes, although by and large they are sites of deposition hosting large amounts of the ocean sediment despite covering only 4% of the surface area. It is suggested that the even reduction of the angle in quadratic slopes represents systematic decay of sediment with distance, previously attributed to exponential slopes. Exponential slopes, meanwhile, are suggested to result from slope readjustment, with upper slope sediment bypass and lower slope aggradation. There is a clear link between abrupt shelf-edges and long slope-aprons, which supports connection to erosional processes. This in turn means that the quintessential sigmoidal (s-shaped, Gaussian function) slope, with a smooth rollover, represents a fundamental depositional slope profile. The even, fairly uncommon, linear slopes, are typically the longest and lowest angle slopes, and likely form in response to high sediment input. The ability to understand the governing processes, sediment type, rate, and transport mechanisms, influence of antecedent geology, and ensuing slope stability, has wide-stretched economic and environmental implications relating to marine life, resources, climate change and sea-floor infrastructure.

Detrital zircons in reworked tephra deposits – a proxy for contourites?

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Detrital zircons of up to nearly 200 µm have been found in reworked tephra and shale samples from finely laminated mudstones from the Vikinghøgda Fm. of earliest Triassic age in Svalbard (Zuchuat et al. 2020). The mudstones are interpreted to have been deposited on distal offshore shelf below the storm-wave basis. The mudstone deposition is only interrupted by tephra-bentonite deposition, with layers of up to 5 cm (post compaction), and one or two thin, slightly silty beds. Many of the zircons preserved in the sedimentary rocks are perfectly euhedral and are preserving pyramidal terminations and/or remaining coherent despite the presence of nearly through-going fractures and large inclusions. Ages of these zircons, dated by chemical abrasion isotope dilution thermal ionisation mass spectrometry (CA-ID-TIMS), range from Paleo-/Eoarchean to Carboniferous. Perfectly euhedral grains range from Proterozoic to Devonian, compatible with a relatively local source (Svalbard). However, the depositional setting requires substantial transport of the grain. The fact that many of the zircons do not show any indications of mechanical abrasion point to transport in suspension. As zircon is a high density mineral (~4.67 g/cm^3), this would require high-energy currents not compatible with the general depositional environment indicated by the mudstones of the succession. We therefore propose that the zircon-bearing layers are reflecting contourite deposits and that the preservation of euhedral heavy minerals can be used as a proxy for such deposits in sedimentary successions where diagnostic macroscopic structures are difficult to identify.

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Glacial source-to-sink systems on the formerly glaciated North Atlantic margin

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The common understanding of source-to-sink systems is dominated by terrestrial processes with glaciated catchments, supported by a vast body of evidence (Castelltort and Van Den Driessche, 2003; Tofelde et al., 2021). However, there remain significant knowledge gaps regarding completely glaciated source-to-sink systems, for example those dominated by extensive ice-sheets (Sejrup et al., 1996; Jaeger and Koppes, 2016). The aim of this contribution is to summarize glacial source-to-sink systems along the formerly glaciated European margin, with a focus on depositional environments (Bellwald et al., 2023). We integrate new extensive and detailed geological, geophysical and geotechnical evidence collected to support the rapidly growing offshore renewable industry.

We show deposits and processes representative of a complete glacial cycle on emerged continental shelves during sea-level lowstands: i) subsurface weathering before the glacial onset in the periglacial environment, ii) accumulation of glacial till, glacio-tectonic deformation, and erosion of channels in the subglacial environment, iii) glacio-lacustrine deposition and outwash sedimentation in the proglacial environment, and iv) fluvial incision, lacustrine deposition, and sediment reworking in the ice-free environment.

We compare the types of sedimentary environments with processes active in Southern Iceland and Svalbard, which act as modern analogues for the European margin (Evans, 2017). Our study highlights that there are strong links between the Quaternary ice-sheet driven source-to-sink systems and their classical counterparts that cover longer time periods, and that there is much to learn from data integration between glacial geologist and sedimentologists.

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Svalbard Warm Arctic Palaeoclimate Laboratory – sedimentology as a tool to forecast the future

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The Svalbard archipelago, currently located at c. 78-80 degrees N in a high Arctic climate, contains a unique record of terrestrial to coastal response to a warm Arctic climate from the Paleocene to Eocene. More than 500 drill cores, originally obtained for coal exploration, provide densely spaced data points through a paralic succession particularly from the Paleocene but some also spanning the PETM (Paleocene-Eocene thermal maximum). The Palaeogene “Central Tertiary Basin” in Svalbard formed as a foreland basin in response to the Eurekan orogeny (Piepjohn et al. 2015). At the time of deposition Svalbard was located at c. 75 degrees north in a world with pCO2 levels rising from c. 400ppm to between 1000-2000 ppm, and global temperatures 8-10 degrees warmer than present (IPCC AR6 Technical Summary). The Van Mijenfjorden group comprise 1900 m of clastic sediments from terrestrial to marine environments recording tectonic and climatic changes from the Palaeocene to Eocene of Svalbard, with the terrestrial to paralic formations providing unique insight into land surface characteristics and changes in a warm world Arctic, characterized by extreme seasonality (midnight sun and polar night) and with no modern analogues.

The terrestrial landscape was characterized by low-gradient hills and valleys and extensive forested peat- and wetlands. The high-resolution grid of data across the basin allows for detailed studies of response of wetlands to terrain, shoreline position, coastal palaeo-geomorphology and changes in drainage patterns. We present case studies from the Paleocene Firkanten Formation showing current work to understand the accumulation, stability and demise of peatlands in a warm Arctic setting. We show how the palaeo-peat (coal)-record is in itself a high-resolution palaeoclimate record of atmospheric dust, charcoal from forest fires and possibly of other proxies. And we discuss the potential for using the Palaeogene Foreland basin in Svalbard as a terrestrial palaeoclimate laboratory for a future warm Arctic.

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Nature of acoustic basement and the sedimentary successions in the southwestern Eurasia Basin, Arctic Ocean

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The Eurasia Basin, one of two major oceanic basins of the Arctic Ocean, is composed of the Amundsen and Nansen sub-basins, which were created due to the slow and ultra-slow seafloor spreading at the mid-oceanic Gakkel Ridge initiated during the Paleocene-Eocene transition (53-56 Ma). Since the beginning of the current millennia the Gakkel Ridge and the Eurasia Basin have been subject of marine geological and geophysical studies leading to the collection of diverse datasets including rock samples, seismic, and potential-field datasets. It is considered that this polar region may hold important clues for the understanding of global processes such as passive margin formation, and the complex links between plate tectonics and climate. One of the existing hypotheses (Lutz et al., 2018) postulate corridors of exhumed mantle formed across the southwestern Eurasia Basin and within the western corner of the Nansen Basin because of the magmatic segmentation imposed by the Gakkel Ridge. Consequently, the oceanic basement of this area should be prone to hydrothermal alteration and serpentinization. However, little is known how such mechanism would affect the sedimentary units above or whether serpentinization occurs and to what extent.

New marine seismic data become available in the SW Nansen Basin in the very last years, including data acquired by the Norwegian Petroleum Directorate in the context of the UN Law of the Sea, seismic lines by Alfred Wegener Institute (AWI), Federal Institute for Geosciences and Natural Resources (BGR), and recent results of the GoNorth program (collaborative efforts of several Norwegian research institutions and Geological Survey of Denmark and Greenland, GEUS). During October-November 2022 the first High Arctic GoNorth marine expedition collected new seismic reflection and refraction, as well as gravity and magnetic datasets. Two multi-channel seismic reflection profiles (L3 and L9) provide an image of the sedimentary structure and the upper crust, within the oceanic crust and the continent-ocean transition (COT) between northern Svalbard margin and Eurasia Basin. As indications of relatively recent tectonic activity, landslides have developed along the shelf edge and slope areas of the Arctic basins (e.g. the Hinlopen Slide) as response of Neogene-Quaternary (<3 Ma) degassing of methane hydrates and dewatering from the deeper buried sedimentary units across the Eurasia Basin. The compilation and preliminary analysis of reflection and potential-field data indicates that the sediments and basement structures within the southwestern corner of the Eurasia Basin have been modified in a unique manner due to an underlying geothermal anomaly sourced from underneath the lithosphere.

In addition, the wide-angle deep refraction data (Profile T1) consisted of a N-S-oriented 240-km-long transect passing along the shelf-edge of the Barents Sea into the Eurasia Basin, and employing 24 ocean bottom seismometers (OBS), provides new insights into the seismic velocities up to the Moho, and a complete image of the crust and the COT in the region. A better constrained crustal structure model represents an important piece of information to understand tectonic processes responsible for the opening of the Eurasia Basin and the subsequent connection of the NE Atlantic and Arctic oceans through the Fram Strait.

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Sedimentological context and distribution of quick clay around ice-marginal positions in Trøndelag and Finnmark, Norway

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Quick-clay landslides pose a significant geohazard in regions that were previously glaciated and located below the marine limit. In Norway alone, over 100,000 residents inhabit areas with definitive evidence of quick clay, while a much larger population resides on marine clays that are potentially quick. Quick-clay landslides occur annually in Norway, sometimes leading to fatal outcomes. Therefore, mapping and predicting the distribution of quick clay is of high societal importance.

The occurrence of quick clay is commonly explained by the change in porewater chemistry of marine clay deposits due the leaching of ions through long-term groundwater seepage. However, both syn- and post-depositional processes play a role for the occurrence of quick clay. Coarser-grained layers in association to the clay potentially enhance the leaching process and thus play a role for the distribution of quick clay.

The present study aims to enhance our understanding of how and where quick clay occurs within a sedimentological and geomorphological context. Also, this study aims to explore the potential of using soil index properties (e.g. grain size, water content, Atterberg limits and sensitivity) alongside field methods in sedimentological studies. This is achieved through statistical analysis of data from geotechnical drilling reports, and sedimentological field investigations. Such data compilation will help to assess whether and how the regional sedimentological settings and internal structures influence the distribution of quick clay in the selected study areas.

Our focus areas are the marine deposits surrounding major ice-marginal deposits in Trøndelag (Tillerryggen) and Finnmark (Alta), Norway. Both regions feature widespread evidence of landslides involving quick clay. The sedimentological setting in these areas is complex due to readvancing glaciers potentially overconsolidating proximal marine deposits while simultaneously depositing coarse-grained glaciofluvial material that interlayers with fine-grained marine material. Preliminary results from this study will be presented. This will aid in discussing if and how the distribution of quick clay can be correlated to the distribution of course-grained deposits.

Plastics in the sediment record

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Sediments are considered a main sink of plastic in the aquatic environment (Woodall et al., 2014, Bergmann et al., 2017). The apparent recalcitrance of plastics implies a sediment archive of a distinctly anthropogenic material and raises discussion of plastics as a marker of our presence on Earth (Zalasiewicz et al., 2016). However, the extraction and identification of plastic from sediment is challenging. Particularly, small grains remain in suspension and can form aggregates. Plastic degradation in oxygenated and light-penetrated environments is better understood than their stability in sedimentary environments that act as sinks. The efficacy of sampling methods and uncertainties in degradation processes in sediment therefore present key challenges to defining a sediment record of plastics and its long-term stability in these systems.

Herein, we present our work on the plastic record in Greenlandic sediment, targeting micro-and nanoplastics (MNP) in fine-grained sediment (Parga Martinez et al., 2023). We discuss our findings as well as limitations to reconstruct reliable records of this pollutant in the complex sedimentary system. We also present the biogeochemical influence of plastics deposition in the sediment and the implications for transformation of the polymers over time (Rogers et al., 2020, Dodhia et al., 2023). We conclude with insight to current and future work.

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Microstructure and sedimentation processes interpreted from muddy turbidites along the Antarctic continental rise

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Ocean floor drill cores collected from the Amundsen Sea, West Antarctica during International Ocean Discovery Program (IODP) Expedition 379 recovered sediments of Holocene to late Miocene age within a sediment drift located on the continental rise. The dominant lithofacies assemblages are cyclic and alternate between planar thinly laminated grey silty clay and massive and bioturbated greenish-grey silty clay. The grey laminated lithofacies is interpreted as a distal silty mud turbidite deposit corresponding to glacials and periods of West Antarctic Ice Sheet (WAIS) growth while the massive bioturbated lithofacies may correspond to interglacial periods and WAIS shrinkage. Laminations consist primarily of terrigenous detritus likely sourced from ice advance towards the continental shelf edge and then transported by both gravity-driven and bottom current processes on the continental slope and rise. The interpretation of deep-water depositional processes of fine-grained sediments in such settings remains controversial but few studies of the microstructure of these types of turbidites exist. In order to use these sedimentary archives as a record of WAIS behaviour back through time, sedimentation processes at the drill site need to be identified. Results are presented from a micromorphological investigation of the laminated distal glaciomarine facies recovered at the drift site. Grading patterns as well as other textural and structural data suggest sediment was sourced from turbidity currents which then formed thinly laminated normally graded lithofacies. Laminations often display different types of heterolithic bedding indicating pulsed sediment supply. In addition, deformed laminations along with load structures, water escape structures, lonestones and "traction carpets" indicate subtle changes in prevalence of sedimentation corresponding to traction and fallout from lofting plumes. The relative rarity of reverse grading suggests limited contouritic deposition during late Miocene to Pleistocene glacials along the continental rise of the Amundsen Sea.

Controls and geometries of small-scale nested clinoforms within a larger clinothem in the Sobrarbe Deltaic Complex, Ainsa Basin, Spain

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Clinoforms are basinward-dipping chronostratigraphically significant surfaces generally displaying sigmoidal shapes (Rich 1951), which bound sedimentary units in a wide range of spatial scales and environments (Patruno & Helland-Hansen 2018). As clinoforms develop in response to sediment transport and distribution, their geometry and stacking architecture constitute a fundamental record of depositional conditions and processes (Pellegrini et al. 2020). This work investigates nested clinoforms within the mixed siliciclastic-carbonate Eocene Sobrarbe Formation of the Ainsa Basin. The aim of the study is 1) to analyze sedimentological variations at two different clinoform scales, and 2) to assess the impact of lithological and process variations on clinoform geometries. The work details two sets of small-scale clinoforms and discusses their formation and preservation in relation to the large-scale clinothem containing them. Twelve stratigraphic sections with a combined thickness of 155 m were measured at 1:100 cm scale targeting the small-scale clinoforms, and a 120 m section was measured at 1:500 cm scale across an entire deltaic cycle to place both clinoform scales into a sequence stratigraphic context. In addition, small- and large-scale clinoform surfaces were mapped using a 3D outcrop model constructed from drone-based aerial photographs to quantify clinoform geometrical parameters. The low-resolution stratigraphic section covers an ~80m thick clinothem comprising carbonate-rich mudstones with occasional intercalated sandstones (prodelta), passing upwards into very fine-grained bioclastic-rich bioturbated and, in places, deformed sandstones (lower delta front), and culminating with dominantly coarser grained channelized and cross-bedded deposits (upper delta front). These three facies associations tend to dominate the bottomset, foreset and topset respectively of the large-scale, approximately 7 km long clinothem. The small-scale clinoforms correspond to up to 15 m thick packages of lower delta front deposits, and extend between 100 and 200 m. The two identified scales of clinoforms display foreset angles of ~2 degrees, in the case of the larger scale clinoforms, and between 5 and 10 degrees, in the case of the small-scale clinoforms. We attribute this difference in steepness to the highly cemented character of the small-scale clinoforms, which could be related to their high bioclastic content and early diagenetic processes of cementation. This suggests that cemented horizons could be promoting the preservation of steeper clinoform foresets in fine-grained delta front environments, which are therefore not to be only associated to coarser Gilbert-type deposits. The cemented horizons could be helping the deltaic system to prograde by preventing frequent collapse, but would create permeability barriers/baffles for fluid flow in subsurface reservoirs. These preliminary results contribute to the understanding of intra-clinothem sedimentological variations, by better constraining observed relationships between geometric expressions of clinoforms and constituent lithologies.

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Depositional architecture of the Neogene Skade and Utsira sands between 58° and 62° N, northern North Sea

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The Neogene Utsira and Skade formations of the northern North Sea have been challenging and difficult to understand since their first definitions in 1977 and 1989, respectively. Recently, Eidvin et al. (2022) presented a revised lithostratigraphic scheme for the Eocene to Pleistocene succession, including a new Utsira Group, addressing errors in the nomenclature. Our study presents new findings on the depositional architecture of these sand-prone lithologies. The study is based on integrated interpretation of regional 2D seismic data, wireline logs from exploration wells, and biostratigraphic and Sr isotopic dating of the Neogene strata in selected wells (Rundberg & Eidvin 2005; Eidvin & Rundberg 2007; Eidvin et al. 2013).

The Skade Formation (Aquitanian-Burdigalian, 23.0-16.0 Ma) represent a sandy system shed from the East Shetland Platform (ESP) comprising shallow marine prograding facies in UK and parts of Central Viking Graben, Frigg Field area (CVG), slope and channel sand facies fringing the prograding shelf margin, and thick strata of basin-floor gravity sands that accumulated in Viking Graben and adjacent areas between 58°30' - 61° N. The outline and pinchout of the sands suggest that deepest marine setting occurred in the Southern Viking Graben (SVG) and Utsira High (UH).

During Langhian-Serravallian (16.0-11.6 Ma), sand deposition was mainly directed towards the Northern Viking Graben (NVG), whereas fine-grained sediments accumulated in SVG and UH. In NVG, three distinct sandy units of the Utsira Group (U1-U3) were deposited during these stages, each with thickness exceeding 100 m. These units are illustrated along a SW-NE oriented transect from the ESP margin near the Frigg Field towards the Gjøa Field. The two lowermost units are bounded by distinct mudstone layers (5-10 m thick) that become truncated towards the shelf margin. The depocenters of units U2 and U3 switch laterally to the west and east of U1. U1 and U2 are inferred to represent Langhian T/R-sequences where much of the transgressive shallow strata are eroded. U1 forms the basal part of the Utsira Group and also the top of the Hordaland Group.

During Tortonian – Messinian (11.6 – 5.3 Ma), sandy deposition resumed in SVG and UH where thick (+100 m) Utsira sands (B1) with thin interbeds of mudstones accumulated. Simultaneously, sand deposition also took place in NVG and Tampen Spur areas, where Utsira sands (U4, U5) attain thickness exceeding 100 m. Input from the Norwegian mainland also occurred during these stages.

In SVG and UH, Utsira sand (B1) deposition continued during Zanclean (5.3 -3.6 Ma). Along the SVG, these piled up on the upper Miocene B1sands to a combined thickness of about 200 - 300 m. Eastwards on the UH, the B1 sands pinch out and overlie inclined lower Miocene strata. The B1 sands were sourced from the ESP via a wedge unit (B2) with distinct coarsening-upward GR log profiles in wells. The B1 sands are interpreted as gravity sands, laid down by turbidity currents which contrasts to the shallow sand bar model of Galloway (2002).

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Session 31

Ikaite and its pseudomorphs (glendonite) – a cold climate mineral indicator

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Isotope hydrology (^{2}H and ^{18}O) of water from the arctic Ikka Fjord, SW Greenland, and its relation to ikaite formation

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The small Ikka Fjord in arctic SW Greenland is home of more than a thousand submarine tufa columns originally composed of the metastable carbonate mineral ikaite ($CaCO_3 \cdot 6H_2O$, Buchardt et al. 1997). Several expeditions have visited the fjord between 1995 and 2021 with focus on geology, topography, biology, and hydrology of the columns. As part of the program more than 350 water samples have been collected over a period of 25 years from streams, springs, and lakes in the catchment areas of the fjord and from the fjord itself and analysed for ^{18}O- and ^{2}H-concentrations. This work presents the results from isotope studies of the different water types. The following conclusions can be made: 1) Seasonal effects of approx. 13‰ δ^2H and 2‰ δ^{18}O exist in isotopic composition of stream samples between early field campaigns (June and early July, depleted) and late field campaigns (late July and August, enriched). 2) A negative altitudinal effect (-12‰ δ^2H and -1.5‰ δ^{18}O) can be seen in different stream waters sourced from close to sea level and up to 900 meters of elevation reflecting the precipitation at the source areas. 3) The freshwater samples define a local meteoric water line (LMWL: $\delta^2H = 6.4 \cdot \delta^{18}O - 11.6$, $R^2 = 0.97$) different from the general Global Meteoric Water Line. No significant secular changes in the isotopic compositions of the different freshwater systems have been noticed over the 25 years of sampling. 4) Samples from the fjord system exhibit a well-defined linear mixing between sea water from the Davis Strait (δ^2H ≈ -9‰, δ^{18}O ≈ -1‰) and stream water flowing into the fjord from the surrounding highlands (δ^2H between -100‰ and -115‰; δ^{18}O between -12‰ and -16‰). 5) The composition of submarine spring water sampled from the Ikka columns is strongly influenced by sampling method and reflects the degree of contamination from fjord water. The least contaminated samples (drawn by syringes embedded in the columns) have isotopic compositions (δ^2H between -88‰ and -95‰; δ^{18}O between -12.5‰ and -13.4‰) close to that of the most depleted stream waters and support the hypothesis that columns are fed from precipitation falling at elevated altitudes.

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Sub-bottom profile survey Ikka Fjord, South Western Greenland – has the ikaite column garden resurrected?

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The Ikka Fjord in southwestern Greenland has gained wide interest from scientists in may fields for its world-unique ikaite columns protruding from the seafloor. The current understanding of column formation in the Ikka Fjord is that the mineral ikaite forms at low temperatures (<6°C) from the interaction of carbonate-rich groundwater with Ca-rich sea water creating supersaturation of calcium carbonates in the mixed solution (Buchardt et al. 2001). Seawater is containing Mg^{2+}, too, which inhibits the formation of anhydrous calcite (Stockmann et al. 2022). The groundwater aquires its high carbonate concentration from percolation from high elevations through the carbonatite bedrock of the Grønnedal-Íka igneous complex, and seeps out in the fjord floor following existing faults and fractures. Ikaite precipitates around the outflows in chimney-like structures because the continuously supplied low-density ground water floats upwards. When exposed to higher temperatures (>6°C), ikaite breaks down to less hydrated forms of calcium carbonate minerals (Stockmann et al. 2022). The existence of the Ikka Fjord columns is therefore climate dependent, and they likely did not exist during previous warmer periods. A multibeam sonar mapping survey in 2019 (Seaman et al. 2022) revealed at least 938 columns, ranging in height from 0.5 to 20 m above the sea floor, restricted to a area in the inner Ikka Fjord. The multibeam mapping showed column clusters aligned with observed fault lineations (Seaman et al. 2022), supporting ground water outflow as a responsible mechanism. However, little is known about the sediments surrounding the columns, regarding thickness, stratigraphy, composition and distribution in the Ikka Fjord, which is crucial for our understanding of the ikaite column history and their fate under changing climate conditions.

Here, we present results from a sub-bottom profile survey performed in in August 2021. We surveyed the entire Ikka Fjord with ~75 m line spacing (5 lines along and 24 across the fjord). The inner ~500 m of the fjord is occupied by coarse river sediments. Shallower areas are covered by <2 m soft sediments, and the ikaite column distribution shows no apparent relationship with sediment thickness. The deep (<29 m) inner basins show up to 13 m thick soft acoustically laminated sediments, whereas the outer deep basin only show ~5-7 m thick sediments without lamination. The thick sediment deposits are likely a result of fine grained siliciclastic material from the river mixed with organic matter from the rich biota encrusting the columns, which in turn trap sediment from transport to the outer fjord. In areas close to columns, the profiles show strong and irregular acoustic reflections in the sea floor (5-10 m bsf) , which we interpret as carbonate layers. If correct, this indicates that columns have existed and broken down previously, likely in response to cold followed by warmer sea temperatures. The acoustic profiles will be used to find suitable sediment coring locations in the Ikka Fjord, in order to ground truth the sub-bottom profile interpretation and to study the sedimentary history in more detail.

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Advances in glendonite understanding despite precursor ikaite remaining enigmatic

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Geologists have long debated the relationship between the metastable ikaite mineral ($CaCO_3*6H_2O$), found today in various polar and cool-water environments, and the calcitic glendonites, found in many intervals of the Phanerozoic sedimentary record (e.g., Rogov et al., 2023). Although the large sub-merged ikaite tufa pillars of Ikka Fjord bear no resemblance to glendonite, large yellow/orange euhedral ikaite crystals resembling glendonite morphology were first found in the Bransfield Strait, offshore Antarctica (Suess et al., 1982), represented in high detail in (Whiticar et al., 2022). Ikaite rapidly breaks down above ~7 °C into less or non-hydrated polymorphs of $CaCO_3$, which has hindered traditional crystallographic investigations. These calcite granules form a mesh of mm-large grains, coined as "guttalatic" texture (Scheller et al., 2022). The guttulatic structure is present in many different aquatic and terrestrial systems and yet appears a defining and common feature of glendonites from marine settings (Scheller et al., 2022; Schultz et al., 2023a). Marine sediment-formed euhedral ikaite is now unequivocally identified as the parent mineral to glendonite, whereby guttulatic microstructure is observed in recrystallized ikaite (Schultz et al., 2023b). The Eocene-aged Fur Formation mega-glendonites, Paleocene and Eocene glendonites of Svalbard, and, more recently, those of the Paleocene-Eocene Thermal Maximum interval retrieved during IODP Expedition 396 (summarized in Rogov et al., 2023), appear inconsistent with cold temperature formation of ikaite; supporting findings from laboratory studies that ikaite may precipitate at warmer temperatures under certain chemical conditions (Tollefsen et al., 2020). Ikaite might also lead to new possibilities for carbon storage. Indeed, ikaite might be used as a catalytic precursor for subsequent precipitation of stable calcite. However, this requires better understanding of the catalysing agents that favour the formation of ikaite, a problem that has so far remained unsolved.

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High-resolution multibeam Sonar mapping of the submarine ikaite columns and structures in Ikka Fjord, SW Greenland

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Ikka Fjord in SW Greenland is renowned for the hundreds of impressive submarine tufa columns and structures found scattered about its shallow length. These life-encrusted, stalagmite-like structures are up to 20m high and composed significantly of the 'rare' cold-water carbonate mineral ikaite ($CaCO_3 \cdot 6H_2O$). The fjord is the type locality for this mineral after which it is named. Ikka Fjord and the fragile and beautiful columns it contains has been the focus of multidisciplinary studies by scientists from predominantly Nordic countries who have come to refer to themselves and 'The Ikka Projekt'. The earlier phases of the investigations of the locality were aimed at understanding the processes behind the formation of the deposits, mapping their distribution and recording the abundant life-forms found living on and within the columns and structures. Recent discoveries of ikaite formation in Arctic and Antarctic sea ice and new laboratory studies has led to a resurgence in interest in Ikka Fjord and ikaite as these findings suggest that this rapidly precipitating carbonate mineral has the potential to be used as a carbon sequestration medium. With much still to learn about the precipitation of ikaite in Ikka Fjord, recent expeditions have been conducted to acquire new samples and to better map the deposits and the marine and terrestrial environment of the fjord. To this end a high-resolution multibeam sonar bathymetry survey was made in Ikka Fjord in the summer of 2019. This survey provided highly detailed maps of the floor of the fjord and data that could be used to chart column heights and distributions. The data also identified several hitherto unknown pockmarks on the seabed. A total of 938 individual columns and structures ranging 0.5–20 m in height measured from the sea floor were identified. The results supported previous observations that the columns are restricted to the spatial extents of the Grønnedal-Íka igneous complex. Column distribution exhibits lineations and variable density over the fjord floor. The tallest columns are observed to reach and then terminate at the levels of a halocline at approximately 2–4 m water depth. If the halocline marks the limit of growth, then majority of columns have reached only 15–50% of their growth potential. The 60 or so columns achieving their maximum growth potential stand in clusters, interpreted as representing exceptionally favourable growth settings. New data collected in 2019 shows a worrying increase in seawater temperature compared with measurements made in 1995 and 2007–2009. Given that the formation and stability of ikaite favours low temperatures, increases in seawater temperature could potentially affect the stability of the delicate columns of Ikka Fjord.

The transformation of ikaite into less hydrated $CaCO_3$ minerals controlled by fluids and temperature

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Recent years' research on the tufa columns in Ikka Fjord, SW Greenland have shown a change in mineralogy from almost pure ikaite ($CaCO_3 \bullet 6H_2O$) into less hydrated calcium carbonate minerals of monohydrocalcite (MHC), aragonite, and calcite (Stockmann et al. 2022). These dehydration reactions are interpreted as a response to an increase in seawater temperature supported by *in-situ* observations of summer 2019 of temperatures ranging from 6 – 9 °C in the submarine column area. An upper stability threshold of 6 °C was previously suggested for the ikaite columns based on past *in-situ* temperature recordings from Ikka Fjord. In recent laboratory experiments, small pieces of ikaite columns were heated incrementally while submerged in natural seawater from Arsuk Fjord, SW Greenland. They were mounted in a special-designed thermal cooling stage at the University of Gothenburg that allows for contemporaneous Raman analysis. The aim of the experiments was to discern the role of fluids for the transformation of ikaite with respect to temperature and alteration mineralogy. In one series of experiments, a sample of pure ikaite was submerged in seawater throughout the experiment conducted at 2.5 – 23.0 ± 0.1 °C for 2.5 months. This caused a mineral transformation into MHC initially at 10 – 11 °C. With increasing temperature, ikaite disappeared completely by altering into MHC. A further transformation of MHC into aragonite and minor calcite occurred at 22.0 °C. In a second series of experiment, the ikaite column sample was dried out at 6 °C, which caused a complete and instant alteration into aragonite. For comparison, a piece of ikaite column was taken straight from the freezer and left to dry at a laboratory temperature of ~22 °C for four days. The alteration product was almost pure calcite. Thus, we conclude that fluids and incremental heating are paramount for a prolonged stability of ikaite and has consequential effect on its mineral alteration assemblage.

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Unlocking ikaite's potential: A novel approach to carbon capture and transformation into premium calcium carbonate

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Harnessing Nature's Design: Laboratory Advancements in Ikaite Synthesis for Climate Mitigation

Ikaite, a rare and metastable calcium carbonate mineral, forms under very specific micro-environmental conditions, when high pH, carbonate-rich waters mix with cold seawater. A prime example of its natural occurrence is the Ikka Columns in Ikka Fjord, Greenland, which house over a thousand extensive columnar formations. These structures are in a constant state of evolution: while new ikaite material forms, older structures gradually recrystallize into other carbonate minerals as calcite and monohydrocalcite (Pauly 1963, Buchardt et al. 2001). Ikaite has previously been proposed as having a carbon mineral storage potential (Stockmann et al. 2018). Research into this natural ikaite system has revealed its potential as a model for an advanced carbon capture, storage and utilization (CCSU) methodology. Laboratory simulations, combined with extensive optimizations of the ikaite synthesis process, have showcased a method of CO_2 capture characterized by efficiency and low energy consumption, utilizing CO_2 as the primary carbon source. In the face of rising global temperatures, there's a pronounced emphasis on the importance of rigorous scientific and policy measures to combat the effects of anthropogenic climate change. This research underscores a series of carefully controlled reactions that involve ikaite synthesis via specialized membranes. These reactions effectively capture CO_2, whether sourced from flue gas or purer CO_2 forms, with the carbon securely embedded within the molecular lattice, leading to the formation of carbon-negative Calcium Carbonate. By harnessing green energy, technological advancements, and the inherent scalability of this method, it holds promise as a pivotal strategy in climate change mitigation, especially for major CO_2 emitters. The ultimate outcome is the capture of CO_2 and its conversion into premium-grade Calcium Carbonate, suitable for a wide array of industries and products.

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Mineral-trapping of methane in Arctic glendonites

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Glendonite, a calcium carbonate pseudomorph after ikaite, occurs in vast amounts in Mesozoic successions in the Arctic. Because of the low temperature stability of ikaite, glendonite is commonly taken to indicate “cold snaps”, even if this interpretation conflicts with other evidence for greenhouse warmth. Based on extreme bulk carbonate C-isotope heterogeneity, the (bio)geochemistry of Mesozoic glendonites from Siberia and Svalbard appears to be highly complex and strongly influenced by both methane oxidation as well as CO_2 reduction. All investigated glendonites contain methane gas with enriched $\delta^{13}C$-CH_4 signatures, depleted $\delta^{2}H$-CH_4, and large proportions of C_2-C_5 gas indicative of thermogenic methane. Organic geochemistry of Cretaceous glendonites from Svalbard shows the presence of a suite of hopanoids, among which are bisnorhopanes with isotopic signatures indicating activity of sulfide oxidizing bacteria. Extremely elevated bulk $\delta^{34}S_{cas}$ values further implicates sulfur cycling related to anaerobic methane oxidation. Their consistent presence in transgressive intervals also suggests their growth is related to sea level rise perhaps in the aftermath of cold episodes. Thin section analyses shows that methane is trapped within mixed gas-fluid inclusions in the primordial phase that formed after dehydration of the ikaite. This highly porous phase is also known from lab experiments producing synthetic ikaite. Using nature as a template, ikaite and its pseudomorphs may be considered as a potential mineral for trapping methane and perhaps other greenhouse gases. Deep time evidence shows that large amounts of methane were stored for more than 185 million years in Arctic glendonite.

The largest Early Cretaceous glendonites ever recorded

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The Lower Cretaceous succession of Svalbard is known to contain numerous glendonites, particularly in intervals of Hauterivian–Barremian and late Aptian age (e.g., Vickers et al., 2019). These are reported as ranging from centimeter to decimeter-scale in size (Vickers et al., 2018), which is within the usual size range for ancient glendonites and modern ikaite in marine sediments (Rogov et al., 2021). Recent fieldwork in central Spitsbergen recovered giant glendonites of half meter-scale size, comparable to outlier glendonites found in the early Eocene-aged succession of northern Denmark (e.g., Schultz et al., 2020). Unlike the Danish glendonites, and the smaller glendonites found in the Lower Cretaceous strata of Svalbard, these new finds appear as single or crossed blades. We present the locality in which they were found, their appearance and geochemistry, and discuss possible drivers of their formation in the Early Cretaceous high-pCO_2 world.

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Session 32

Advances in reconstructing past life, environments and climate from the sedimentary rock record

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Sam Slater,
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Shelf ecosystem response to the Eocene-Oligocene Transition

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The Eocene-Oligocene transition (EOT) is one of the most dramatic climate shifts of the Cenozoic with severe consequences for reef ecosystems. The onset of continental Antarctic glaciation is associated with widespread environmental change, resulting in a global peak in biotic turnover. Whilst numerous studies of the biotic response to the changes at the EOT have been carried out, most high-resolution studies consist of open ocean records of foraminifera and nannofossils. However, this is not representative of the ocean system as a whole. The shelf seas and reefs are some of the most diverse and fundamentally important ecosystems of the oceans. Long-term diversity loss across the EOT has been shown in several macrofossil studies, but mainly at low resolution, and recovery is not well understood. Larger benthic foraminiferal records provide a higher resolution insight to this event, both in terms of biodiversity, physiology and shallow water geochemical records. Additionally when integrated with records of other shelf organisms (e.g. molluscs, algae, bryozoa) this provides a powerful overview of whole ecosystem response. Many shelf species are ecosystem engineers whose loss and recovery have profound implications for the entire ecosystem. Understanding these interactions will provide insights into shallow marine ecosystems and their response to major climate perturbations.

The Tanzanian Drilling Project EOT record (TDP 11, 12, 17) is recognised globally for its completeness and exceptionally preserved calcareous microfossils. It is most importantly, though, a rare record of both shallow water organisms and open ocean plankton. Here we draw together a unique dataset of high-resolution larger benthic foraminifera, planktonic foraminifera, mollusc, Dasycladaceae, bryozoan, coral, shallow water trace element and isotope records from the EOT. The response and recovery of these species is compared with known, modern physiology of each group to provide a complete picture of the shallow marine ecosystem response. Following rapid extinctions in the larger foraminifera at the Eocene/Oligocene boundary, molluscs, Dasycladaceae and bryozoans all show increases in abundance, indicating a major shift in shelf ecosystem composition. These assemblage changes are coincident with a period of more positive values in □13C of planktonic foraminifera and changes in trace element values. Comparison with the open ocean record of planktonic foraminiferal, pteropod, and nannofossils confirm fossil increases are a biological, rather than sedimentological response and additionally support a transition to more eutrophic conditions during the transition. The interaction of these groups, within an environmental framework of traditional and novel geochemistry indicate that increased nutrient fluxes, rather than the temperature change directly, played a pivotal role in restructuring shelf ecosystem dynamics, and offer new insights into our understanding of the EOT.

Geochemical stratigraphy in the Sturtian Port Askaig Formation – testing palaeoenvironmental implications for the Snowball Earth Hypothesis

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Snowball Earth (Hoffman et al. 1998) refers to a deep-frozen Earth, initiated by low pCO_2 and characterized by high albedo. Late Neoproterozoic major glaciations with ice sheets extending to sea level near the equator have been evidenced by analysis of sedimentary successions characterized by numerous diamictite beds and associated cryogenic phenomena on most continents. The original Snowball Earth Hypothesis predicted a multimillion years hiatus when the Earth's anoxic and ferruginous oceans were completely frozen over and the hydrological cycle was shut down. Although compelling, the hypothesis is still debated, particularly for the long Sturtian episode (716-660 Ma).

The Port Askaig Formation (PAF) is a ~ 1,100 m thick, well exposed Sturtian deposit which crops out over ~700 km in NW Ireland, the Hebrides and mainland Scotland and consists of 48 diamictite beds interlayered with non-glacial rocks (Spencer 1971, Ali et al 2018). As part of research by a diverse multinational team led by A.M. Spencer the geochemical study presented here will constitute one chapter of a Memoir planned to be published by the Geological Society of London.

A geochemical log based on 300 stratigraphically positioned samples from Scotland and Ireland, covering the entire sequence of the PAF, was used to analyze the character and stratigraphic pattern of the PAF sediments, with these palaeoenvironmental and provenance interpretations:

At a level of ~ 15% of the stratigraphic thickness of the PAF there is an abrupt break in the element composition of the diamictites. New components, precipitated iron and manganese and granitic detritus are added, and limestone supply is suddenly cut-off. The mix of compatible to incompatible elements also changes here. A Snowball Earth deep-freeze hiatus just below this level would allow processes on tectonic time scales to explain these changes in sediment supply.

Studies of chemical weathering using quantitative indices show a glacial clay composition in the lower diamictite beds, above which there is a sudden shift to a well-weathered shale just below the stratigraphic break. A fast return to an un-weathered state is then followed by a gradual move towards shale at the top of the PAF.

The palaeoenvironmental mechanisms controlling the PAF sediments have generated the same stratigraphic geochemical pattern over a lateral distance of more than 250 km, including the replacement of carbonates by siliciclastic detritus and the occurrence of precipitated iron beds. This negates localized causes for the stratigraphic break in sediment supply.

Five cyclic changes following a saw-tooth pattern are seen in elements associated with glacial silt in the diamictite beds, possibly indicating a variation between glacial and glacifluvial processes. Together with the interlayered non-glacial sand- and siltstone beds in the PAF and observations of periglacial sandstone wedges and frost-shattered stones, they point to an active hydrological cycle.

In summary, findings from this geochemical study of the sediment stratigraphy of the PAF can both support the multi-million years hiatus of the Cryogenian Snowball Earth Hypothesis, but also disprove the shut-down of an active hydrological cycle then.

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250 years of history, and 2.5 billion years of prehistory – introducing the fossil collections of the Swedish Museum of Natural History

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The Department of Palaeobiology at the Swedish Museum of Natural History (NRM) is the home of around two million fossil animals and plants, from the arctic to Antarctica. Some of these were collected as early as in the 18th century and the collection is still growing today, through expeditions as well as donations. Our vertebrate collection, most notably, contains a large number of historically important fish fossils, mainly from the Devonian period, as well as one of the largest collections of Pleistocene mammals from South America. We have a broad collection of fossils from all over Sweden, and the world’s largest collection of fossils from Gotland. Another significant source of material is the Mesozoic of Skåne, from which we have cephalopods, bivalves, brachiopods, echinoderms, shark teeth and mosasaur and plesiosaur remains, to name a few. Furthermore, we have one of the world’s largest collections of fossil plants, and palaeobotany is one of the main topics of research at the department. For example, sedimentary successions from Skåne have yielded exceptionally well preserved fossil flowers and a large number of Mesozoic plant remains. The fossils of our collections have been the subject of over 1700 publications to date, and the number is constantly growing. A significant part of our collections are registered in databases and searchable through our website. We encourage researchers of all fields who are interested in studying our fossils to get in touch and visit our collections.

How seals made *Nautilus* a 'Living Fossil'

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The Cenozoic distribution patterns of pinnipeds and nautilids from the Oligocene onward show the local extinction of nautiloids in the areas where pinnipeds appeared, eventually resulting in the present-day restriction of *Nautilus* and *Allonautilus* to the central Indo-West Pacific Ocean. In addition, the development of oxygen minimum zones due to enhanced ocean circulation in the Oligocene prevented nautiloids to escape predation by retreating to deeper waters, resulting in their disappearance especially from the west coast of the Americas. The demise of the nautiloid *Aturia* due to predation pressure was less immediate, probably because it avoided predation by fast swimming rather than retreating to greater depths. Ultimately, however, this might have resulted in *Aturia*'s end-Miocene extinction, because its adaptations to fast swimming prevented it from retreating to depths that allowed *Nautilus* to escape the ever-increasing predation pressure. An immediate role of echolocating whales in the demise of shelled cephalopods is not apparent; their long, delicate snouts with numerous teeth likely were ill-suited for handling large shelled nautilids. A possible exception are short-snouted Simocetidae and Agorophiidae in the Oligocene of the North American Atlantic and Pacific coasts, which appeared in this area at the same time as the nautilids disappeared (Kiel et a. 2022).

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Increasing the digital availability of the palaeontological collections of the Swedish Museum of Natural History

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Historical palaeontological collections provide a glimpse into the Earth's fossil archives and have been utilized by researchers around the world as a source of information for various scientific studies for centuries. The fossil collections of the Department of Palaeobiology, at the Swedish Museum of Natural History (NRM), comprise around 2 million specimens from all over the globe and throughout geological time, from the earliest traces of life until recent times, collected by professionals and dedicated amateurs during more than 250 years. These fossils have been, and still are, frequently studied and published on and today the collections house thousands of type specimens and other scientifically valuable items.

New techniques allow us to examine fossils in new ways, database registered collections offers possibilities to easily compile extensive data sets for large-scale analyses, and digitization provides increased availability to collections both near and far. Furthermore, digitization prevents the loss or disassociation of information connected to the fossils, which is vital to their scientific value. Natural history museums, and other collection-holding institutions, have strived to database their collections for decades, a time-consuming process that demands prioritization and allocated resources. In some cases, there are automated mass-digitization solutions available, and AI-tools developed for *e.g.* transcribing information from specimen labels. However, the preparation of collections prior to registration and most often the entry of data itself still requires manual handling by skilled and dedicated staff members, with expertise within the specific scientific field. The collections databases of the Department of Palaeobiology at NRM date back to 1995. More than 90% of the vertebrate and plant fossils, and over 95% of all types and published specimens in the collections are registered in well maintained databases. The invertebrate fossils, mainly deriving from Sweden, make up the bulk of the collection with approximately 1.3 million specimens, and a bit over one fifth (almost 285 000) of these have been registered in the department's database for fossil animals. The majority (about 250 000 specimens) have been registered during the last 7 years, as a result of increased registration efforts.

The Covid-19 pandemic put an abrupt and long-lasting stop to researchers visiting the Department of Palaeobiology to browse the extensive fossil collections or to study, for example, type specimens.This made the necessity for digital availability of the collections clearer than ever. Therefore, the launching of NRM's collections web portal in 2022 was a major milestone for the museum in general and for the Division of research and collections in particular. Today, nearly all registered fossils are searchable through the NRM website at www.samlingar.nrm.se, which is updated regularly with newly registered specimens. Within the near future, many of the posts will also include photographs. All with the aim of making our collections increasingly available both to the public and to the scientific community.

Biotic responses to large igneous province volcanism during the end-Triassic crisis: Mass rarity, mutations and extinctions

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Greenhouse gas emissions from large-scale volcanism in the Central Atlantic Magmatic Province is considered to have caused the end-Triassic mass extinction (201.5 million years ago). Abundance changes in spores and pollen and marine dinoflagellate cysts in the Danish and North German basins record the devastating effects this volcanic induced climate crisis had on both the terrestrial and marine environment (Lindström et al. 2019, Lindström 2021, Gravendyck et al. 2020, Lindström et al. 2023, Bos et al. 2023, Lindström 2023). Combined stress from global warming, volcanic pollution and sea-level changes resulted in mass rarity, mutations and extinctions in land plants, as well as severely decimated phytoplankton diversity with the extirpation of many dinoflagellate species. The devastation of the terrestrial habitats was further amplified by increased wildfire activity and enhanced soil erosion in NW Europe (Belcher et al. 2010, Petersen & Lindström 2012, van de Schootbrugge et al. 2020). Here, we demonstrate how two high-resolution palynological data sets; Stenlille in the Danish Basin and Schandelah in the North German Basin, that together cover the entire Rhaetian to Sinemurian succession allows a more comprehensive view on the ecosystem changes on land as well as phytoplankton changes in the ocean during the end-Triassic crises and how these changes correlate to the volcanic activity in the Central Atlantic Magmatic Province.

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Reconstruct fossil mammal communities by recommender systems, and its improvement on paleoenvironmental estimations

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The fossil record is incomplete due to various natural and human biases. Each fossil assemblage represents only a small fraction of all species that have ever lived, making it challenging to reconstruct the planet's history accurately.

We apply a new machine learning approach to reconstruct fossil community structures at fossil sites. The proposed recommender systems modelling (Zliobaite, 2022) corrects for sampling or preservation biases by building a computational modelling of co-occurrences across a wide range of sites. The main predictive power bases on the assumption that what occurs together (due to affinity to similar environments) is likely to occur together again. Co-occurrences link incomplete data of different sites, and the recommender outputs likely fill in missing taxa at each site based on cooccurrence patterns within database of mammal sites.

We demonstrate the potential of this approach for reconstruct past mammal community on a case study of Pleistocene fossil sites in Nihewan basin, a famous early Pleistocene hominin occupation region in North China. Most Pleistocene fossil assemblages in the Nihewan basin indicate low diversity of faunal communities. Some estimations of paleo-temperature and paleo-precipitation based on dental traits of real fossil occurrence (Liu et al., 2012) give unrealistic estimations of precipitation and temperature. The recommender systems modelling riches effectively the Nihewan mammal communities by filling in missing taxa, and thereby, smooths the dental trait distributions for fossil sites and improves estimations of paleoenvironments.

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Enhanced exhumation in the East Karakoram during the mid-Pleistocene climate transition: A detrital provenance assessment

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Around the Nanga Parbat massif in the west and the Namche Barwa massif in the east, the Himalayan orogen exhibits an abrupt strike change from roughly E-W to N-S, forming two structural syntaxes. Each syntaxis is drained by a major trans-orogenic river system: the Indus and Ganges-Brahmaputra, respectively. The syntaxes record rapid exhumation rates (up to c. 10 mm/a), together with Plio-Pleistocene mineral (re)crystallisation and cooling ages (Bracciali *et al.*, 2016; Crowley *et al.*, 2009; Guevara et al., 2022; Zeitler *et al.*, 1993). The Namche Barwa massif supplies c. 65% of Brahmaputra bedload (Enkelmann *et al.*, 2011). In contrast, the Nanga Parbat massif supplies c. 10% of modern Indus bedload, which instead is dominantly sourced from the East Karakoram (Clift *et al.*, 2022).

We present detrital rutile and zircon U-Pb data from the Indus fan, sampled by IODP expedition 355 and ODP leg 117. These data record abrupt increases in the proportion of sediment sourced from the Nanga Parbat massif between c. 8-6 Ma and again at c. 2 Ma, coherent with bedrock studies (Crowley *et al.*, 2009; Guevara et al., 2022; Zeitler *et al.*, 1993). The Nanga Parbat massif then dominates sediment supply until c. 1.5-0.6 Ma, followed by an abrupt switch to East Karakoram sourcing.

The East Karakoram includes some of Earth's highest peaks, and largest extra-polar glaciers. Therefore, a provocative possibility is that the jump in erosion focus was driven by the well-documented switch from c. 41 ka, obliquity-dominated, to 100 kyr, eccentricity-dominated orbital forcing (the Mid-Pleistocene Transition). This transition occurred at c. 1 Ma (Clark *et al.*, 2006), and could have driven enhanced glacially-mediated erosion in the east Karakoram, outpacing Nanga Parbat exhumation.

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Plant-arthropod interactions through the Permian-Triassic transition at southern high latitudes

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The Sydney-Gunnedah-Bowen Basin complex, a retroarc foreland basin system in eastern Australia, incorporates a relatively continuous marine to continental early Permian to Middle Triassic sedimentary succession. Multi-disciplinary studies of bore-core and outcrop sections over the past six years are providing precise constraints on the age, depositional settings, geochemical characteristics, palaeoclimate and fossil content of this succession, particularly targeting events around the end-Guadalupian and end-Permian biotic crises. Importantly, this basin complex represents one of the very few successions in the world hosting relatively rich Early Triassic plant macrofossil assemblages that, in tandem with palynological data, enable analysis of the recovery of plant communities in the aftermath of the major Permian crises. Sydney Basin middle and late Permian plant fossil assemblages are overwhelmingly dominated by deciduous broad-leafed glossopterid gymnosperms typifying extensive high-palaeolatitude micro- to mesothermal wetland communities. These floras host a moderate to high intensity and diversity of herbivory damage. Little change in the floras or associated arthropod damage is obvious through the end-Guadalupian event. By contrast, the end-Permian event is marked by an abrupt collapse in glossopterid-dominated ecosystems, cessation of peat accumulation, and a drop in the diversity and complexity of arthropod feeding types. The lower Triassic succession is characterized by a coal gap globally. Plant assemblages immediately overlying the uppermost Permian coal seam are characterized by an influx of peltaspermalean seed-ferns and voltzialean conifers with generally small sclerophyllous leaves. Pleuromeian lycophytes are also present together with very rare hold-over elements of the preceding Permian communities. Slow, but progressive diversification of plant assemblages is evident through the Lower Triassic succession, with umkomasialean (corystosperm) taxa attaining dominance during the Olenekian. A general increase in leaf size among the dominant plants together with the re-appearance of coaly laminae suggest a return to more humid conditions around the Early to Middle Triassic transition. A similar pattern of vegetation turnover is apparent in the less intensely sampled Permian-Triassic succession in the Prince Charles Mountains, East Antarctica. Arthropod damage on earliest Triassic plant remains is sparse and dominated by simple margin-feeding injuries. From the late Olenekian to Late Triassic, foliar damage types are notably more abundant and complex attesting to synchronous recovery and diversification of plant and terrestrial herbivorous arthropod communities.

Dietary analysis of hare-sized fossil Clade Cainotheriidae (mammalia, artiodactyla) revealed fruit-dominated diet

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Diet of both extinct and extant mammals can be observed by observing distinct dental microwear left on occlusal surfaces during feeding. We analyzed the dental microwear of four species of Cainotheriidae, a clade of extinct, small-bodied artiodactyls ranging from the late Eocene to middle Miocene of Europe. Owing to their small body-size, previous studies have theorized their diet to be like that of extant mouse-deer (Tragulidae), small-bodied rainforest-dwelling ungulates which are highly frugivorous (Blondel, 2001). We compared the microwear of Cainotheriidae to that of mouse-deer, as well as dik-diks (*Madoqua*), a clade of small seasonal mixed-feeding antelopes inhabiting arid habitats in Africa. Two hypotheses were tested: 1) The Cainotheriidae diet being comparable to mouse-deer and differing from dik-diks, 2) Differing microwear expressions indicating possible climate related shifts in the cainotheriid diet between the late Oligocene to middle Miocene species. We analyzed four cainotheriid species of southern France and Germany: *Caenomeryx filholi* (Oligocene), *Cainotherium commune* (late Oligocene/Early Miocene), *Cainotherium laticurvatum* (early Miocene), and *Cainotherium huerzeleri* (middle Miocene). Analyzing cainotheriid occlusal surfaces at 70x magnification, we primarily observed them as coarse with an abundance of large pits, including deep puncture pits, as well as both coarse and hypercoarse scratches. Cainotheriidae showed strong resemblance to Tragulidae with regards to pitting, with the latter however having slightly more scratches. Both groups showed significant differences in microwear expression when compared to *Madoqua*. Our results show Cainotheriidae as having dietary preferences similar to that of extant mouse-deer as primarily frugivorous browsers, with both differing from dik-diks, supporting our first hypothesis. No significant differences in dental microwear expression indicative of dietary changes were observed between the late Oligocene, early Miocene, and middle Miocene species, thus rejecting our second hypothesis.

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Plant macrofossils from the aftermath of the end–Triassic extinction, Skåne, southern Sweden

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The end–Triassic mass extinction event (ca. 201 Myr ago) has received particular attention over recent decades since Sepkoski in the early 1980s classified it as one of the ‘‘big five’’ biotic crises in Earth's history. In the geological record of Greenland and Sweden, 80% of the species of terrestrial plants disappeared at this boundary. In the last two centuries, Triassic–Jurassic plant remains from Skåne, southern Sweden, have been collected, curated, and studied. However, the paleoflora from the lowermost part of the Helsingborg Member (Lower Jurassic: Hettangian) is poorly understood. Here, a taxonomic/paleoecological study is presented of two novel plant assemblages collected from the Boserup beds (basal Hettangian) in Norra Albert Quarry, Skåne. The exposures in Skåne are among the few localities in the world that record the terrestrial ecosystem aftermath of the end–Triassic extinction event. Plant macrofossils were studied using macrophotography and fluorescence microscopy. The flora is composed of sphenophytes (*Neocalamites* sp.), ferns (*Cladophlebis* sp., cf. *Eboracia*), ginkgophytes (*Czekanowskia* sp., cf. *Pseudotorellia*, cf. *Ginkgoites*), and conifers (*Pityophyllum* sp., *Brachyphyllum* sp.). A comparison with the Rhaetian Bjuv Member and the Hettangian Helsingborg Member floras is presented, revealing a relatively low-diversity -flora in the aftermath of the end-Triassic extinction but a fast recovery later. Furthermore, to clarify the regional plant distribution across the Triassic-Jurassic transition, the floras of the correlative lowermost Jurassic beds in East Greenland and Poland are compared, revealing that ginkgophytes and sphenophytes were widely distributed across the northern region of Pangea in the aftermath of the end-Triassic biotic crisis.

Drastic change in weathering processes during the Upper Triassic and its link to the emergence of pelagic calcification

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The Late Triassic time interval witnessed several important biological turnovers, extinctions and onset of new life forms. Among these events, the extinction around the Norian-Rhaethian Boundary (NRB) was of major importance and have been largely overlooked until now. The nectonic marine fauna have been the most affected, although some sensitive organism such as scleractinian corals or the newly appeared coccolithophorids were preserved. In order to better constrain the tectonic, climatic and oceanographic framework during this time of changes, we collected new $\delta^{13}C_{carb}$, $^{87}Sr/^{86}Sr$ and $\delta^{44/40}Ca$ dataset across the late Norian - Hettangian interval, established from carbonate successions in Austria, Turkey and Emirates. A characteristic change in the $^{87}Sr/^{86}Sr$ record is a sharp trend towards unradiogenic values, which started in the latest Norian and continued across the lower Rhaetian. The $\delta^{44/40}Ca$ shows as well a marked decrease at this level.The strong correlation between the strontium and calcium isotopic systems indicates that they are coupled through the same driving process. The $\delta^{13}C_{carb}$ is in contrary quite stable around this interval, at odd with several negative peaks in $\delta^{13}C_{org}$ as recorded in the literature. The $\delta^{44/40}Ca$ measurements helped to exclude the hypothesis that the early Rhaetian decrease in $^{87}Sr/^{86}Sr$ would have been driven by volcanism, elevated hydrothermal circulation or enhanced silicate weathering. Indeed, the two first of these processes seems to have a negligible effect on Ca-isotopes, while the second would result in a radiogenic $^{87}Sr/^{86}Sr$ trend, the opposite of the observed pattern. Instead, a large increase in chemical weathering of carbonates and evaporites as consequences of a major sea-level fall at the NRB is proposed. This new hypothesis could as well explain the stability of the carbon cycle during this interval as recorded in the $\delta^{13}C_{carb}$, and the variability of the $\delta^{13}C_{org}$ more prone to terrestrial influences.

Deadly kiss of the LIPs: Causes and consequences of Large Igneous Province emplacement – A case study from the Early Toarcian

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Past Large Igneous Province (LIP) emplacement is commonly thought to have been caused by mantle plume upwelling, and is proposed as a likely driver of past global change events because of volcanic carbon emissions. One of Earth's largest past environmental perturbations, the Early Jurassic Toarcian oceanic anoxic event (T-OAE; ~183 Ma), has been linked to emplacement of the Karoo-Ferrar LIP. However, the role of mantle plumes in controlling the onset and timing of LIP magmatism is poorly understood.

Here, utilizing global plate reconstruction models, and Lower Toarcian sedimentary mercury (Hg) concentrations from the Mochras borehole (Wales, UK) we demonstrate (1) that the Early Toarcian OAE occurred coevally with Karoo-Ferrar LIP emplacement, and (2) suggest that the timing and duration of LIP-emplacement was governed by a reduction in local Pangean plate motion associated with a reversal in plate movement direction. With this, we present a new model that mechanistically links Earth's interior and surficial processes, and we show that this mechanism may be consistent with the timing of several of the largest LIP volcanic events throughout Earth history and thus, by inference, the timing of many of Earth's past global climate change and mass extinction events.

Furthermore, the Toarcian oceanic anoxic event is characterized by one of the largest carbon cycle perturbations of the Mesozoic Era, with associated climatic and environmental change, most notably the widespread development of anoxia in epicontinental marine basins. On land, an enhanced hydrological cycle led to the development of major lakes, or significantly elevated lake levels, in continental basins, such as in the Sichuan, Tarim and Junggar basins (China). Stratified lacustrine water columns and the development of anoxic–euxinic lake bottom- water conditions initiated a negative feedback mechanism in Earth's climate system through increased lacustrine (lake) carbon burial. The sheer size of these lakes and associated carbon burial fluxes allowed for lacustrine carbon drawdown to have a demonstrable impact on Earth's carbon cycling at that time. Here, we show new geochemical data from the Sichuan Basin and show that lake levels rose at the onset of the T-OAE. Importantly however, lake levels were likely not stable, but rather fluctuated on astronomical timescales, possibly in response to periodic changes in the hydrological cycle and the transport of moisture into continental interiors.

Oldest record of a seagrass ecosystem: evidence of herbivory in marine angiosperms from the mid-Cretaceous of México (N America)

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Seagrasses are marine angiosperms and are widely distributed in modern shallow marine environments forming some of the most productive ecosystems on Earth, rivaling tropical rain forests and coral reefs (Costanza et al. 1997, Fourqurean et al. 2012). Seagrasses have an extremely sparse fossil record. So far, the oldest indisputable fossils of this group are from the latest Cretaceous (Maastrichtian) of Europe. The fossils in our study derive from the El Chango site, which exposes a Konservat-Lagerstaten belonging to the Cintalapa Formation of the Sierra Madre Group. This unit is mid-Cretaceous in age (most likely Cenomanian); it represents an opportunity to study the dynamics of plant-invertebrate interactions in early marine angiosperms during the KTR (Cretaceous Terrestrial Revolution). Deposits at this site are interpreted to have been laid down in a paralic environment. They host a varied range of fossils, including plants, mollusks, fishes, arthropods, and echinoderms. Our study documents the oldest evidence of seagrass meadows worldwide, including vegetative and reproductive remains, these fossils come from low-latitude, mid-Cretaceous (Albian–early Cenomanian) deposits of North America, about 30–40 Myrs older than the previous records. Additionally, evidence of herbivory and other seagrass-animal interactions are recorded in this material, supporting the hypothesis that these angiosperms invaded marine ecosystems early in the radiation of flowering plants and played an important role in shallow marine food webs before the end of the Mesozoic. Our results indicate that during the Cretaceous Terrestrial Revolution, marine herbivores had managed to adapt their feeding behavior to this new botanical group.

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Cretaceous biozonation schemes – comparison and correlation between Ukrainian and Swedish dinoflagellate assemblages

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This project aims at clarifying some key events in Earth history through studies of dinoflagellate assemblages. In order to achieve this, we need to a synchronize research methodologies and biozonation schemes between Western and Eastern European science communities.

The Cretaceous is a period of appearance and rapid diversification of several faunal and floral groups including microscopic algae and phytoplankton. Dinocysts are important biostratigraphic tools as they are widespread and generally comprise a significant number of index-taxa and can further correlate to high-resolution marine invertebrate zonation, including ammonite- and belemnite zonation. Importantly, the dinoflagellate assemblages may also be linked to the terrestrial biota through comparisons with continental palynomorphs identified in near-shore marine settings.

Here we compile the dinocyst occurrences and compile a zonation, for the first time established for the entire Cretaceous sequence of Ukraine. The zonation is based on samples from 15 cores and over 50 outcrop sections (Shevchuk 2020). Eleven dinocyst zones were established (Figs. 1, 2) for different parts of Ukraine. The Cretaceous deposits of **1.** Western Ukraine span the middle Albian to Santonian and seven zones and two intervals with zonal and characteristic species were established for this region (Figs. 1, 2). **2**. Successions of central and eastern parts of Ukraine span the middle Campanian - early Maastrichtian with two intervals with zonal and characteristic species established. **3.** Southern region of Ukraine including the southern Ukrainian monocline and Crimea span the late Tithonian – early Cenomanian with five zones and one interval with zonal and characteristic species established.

This is compared to the dinoflagellate occurrence in the Cretaceous deposits of Skåne, Sweden (Westin 1992; Guy Ohlson 1982; Lindström & Erlström 2007, 2011; Shevchuk & Vajda in prep).

We show that common Cretaceous zonal taxa includ – *Gochteodinia villosa*, *Pseudoceratium pelliferum*, *Odontochitina operculata, Senoniasphaera rotundata,* intervals with *Florentinia* spp., and *Palaeoperidinium cretaceum.*

Regarding the differences, it is necessary to recognize the insignificant number of *Muderongia* and *Vesperopsis nebulosa* in the Ukrainian successions compared to the Swedish ones and the earlier appearance datum of *Chatangiella* (Cenomanian) in Sweden, while Turonian in Ukraine.

Integrating fossil assemblages is important and has implications for regional (northern hemisphere) paleoclimatological/paleoecological interpretations, biodiversity studies and for dating sedimentary successions.

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Nannofossil imprints through past global warming events

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Here we present an understudied mode of fossilisation – nannofossil imprints preserved on organic matter. Nannofossils are the microscopic remains of calcareous nannoplankton, a group of single-celled marine planktonic organisms that produce calcium carbonate ($CaCO_3$) hard parts. Nannofossils are generally studied from their $CaCO_3$ 'body fossil' remains, but here we present fossil assemblages of their imprints, preserved in exquisite detail. These fossils were recently found through geological intervals spanning several past global warming events that took place during the Mesozoic (Slater et al. 2022). Here we show, for the first time, imprints preserved through the interval spanning the Paleocene-Eocene Thermal Maximum (PETM), a rapid global warming event that took place ~56 million years ago. The abundance, richness and quality of preservation of imprints, varies considerably among the studied events. Interestingly, imprint and body fossil records through the Mesozoic events differ substantially, with imprints commonly preserved in abundance in rocks devoid of body fossils. This pattern is different through the PETM – body fossil assemblages (Self-Trail 2011) preserve a much more complete record of nannoplankton through that event. The variable records of nannoplankton body fossils vs. imprints from different events highlights that this relatively new approach represents a tool with which to provide a more complete picture of how nannoplankton communities responded to past episodes of extreme environmental change.

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An example of the importance of detailed biostratigraphy to resolve complex geology – the Paleocene-Oligocene succession of island of Fur, Denmark

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Fur is a small island (22 km^2) in the Limfjord, Denmark, which is well known for exposures of diatom-rich deposits (known also as ´moler') interbedded with ash layers of earliest Eocene age, and encompassing the Paleocene-Eocene Thermal Maximum. These deposits are referred to the Fur Formation. The Paleogene succession in the area is heavily faulted due to an intense glaciotectonic influence. The upper Paleocene to Oligocene succession outcrops in several cliff-sections and inland quarries. Sediment cores are very limited.

In connection with a groundwater mapping project carried out on Fur, two wells were drilled in 2022 using the air-lift drilling-method. In this type of well, each sample represents sediments from a ca. 1 m interval. The wells are situated approximately 750 m apart. The results of the biostratigraphic study presented here were published by Sheldon et al. (2023).

The DGU 38.1203 well penetrates a 60 m thick succession where the uppermost 14 m consists of Holocene glacial deposits. 13 sediment samples from the interval from 60 to 14 m were processed for microfossils (foraminifera, large, pyritised diatoms, large radiolaria) and palynology. The lowermost part of the well (60 to 57 m) is assigned to the Fur Formation. The sample representing the interval 56–55 m has a microfossil assemblage typical of the Fur Formation, however, palynomorphs suggest the presence of the Knudshoved Member of the Røsnæs Clay Formation. This finding may suggest that the boundary between the Fur Formation and the overlying Røsnæs Clay Formation is located somewhere between 56 and 55 m depth. The Knudshoved Member of the Røsnæs Clay Formation is present from 54 to 50 m. Two samples from the 49 to 48 m interval are assigned to the *Wetzeliella articulata-ovalis* Zone (Heilmann-Clausen 1988), which is typical of the upper part of the L4 Bed and the lower part of the L5 Bed of the Lillebælt Clay Formation. The interval from 41 to 14 m is assigned to the Viborg Formation.

The DGU 38.1204 well penetrates a 48 m thick succession where the uppermost 12 m are assigned to undifferentiated Holocene glacial deposits. 12 sediment samples were studied for microfossils (diatoms, silicoflagellates and radiolaria in the fine fraction), and 9 of those samples were also studied for palynology. The 48 to 43 m interval yields common to abundant specimens of the dinoflagellate cyst *Apectodinium augustum,* assigning this interval to the Stolle Klint clay. However, the sample 43-44 m was assigned to the Knudeklint Member of the Fur Formation based on microfossils. The interval from 39 to 12 m is assigned to the Knudeklint Member of the Fur Formation

Typically, on Fur the early Eocene Røsnæs Formation is overlain by the earliest Oligocene Viborg Formation, with a hiatus of at least 13 Ma. This study is the first that reveals the presence of the Lillebælt Clay Formation on Fur. Furthermore, our results show the strength in combining various fossil groups in resolving the stratigraphy in such complex geologic settings. Despite a relatively short distance between the wells, they penetrate different parts of the Danish Paleogene succession.

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Palaeocommunity persistance despite environmental disruption: Carboniferous brachiopods from the North American Mid-continent

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A key question in paleoecology and macroevolution is whether assemblages of species (palaeocommunities) represent persistent entities that can endure over millions of years. Whilst it has often been presumed that any abrupt abiotic changes discernible in the geological record will lead to cascading extinction and community turnover, it has also been proposed that paleocommunities persist for long time periods and regardless of environmental disruption. If palaeocommunities can and do remain stable entities despite disruption, what processes allow for such a scenario remains an open question. Potential options include the degree of change in the physical environment, which possibly only rarely exceeds the threshold required for community collapse, or due to 'Ecological Locking', where directional selection is constrained by ecological processes. We investigate these issues by analysing the detailed fossil record of Carboniferous brachiopod communities from the Mid-continent of North America. These highly diverse communities were subjected to frequent and geologically rapid phases of marine transgression and regression associated with climate change over approximately a 20-million-year period, a scenario where repeated community destruction and renewal would be expected as suitable habitat was lost and then subsequently re-established. By characterizing both the nature and scope of changes in these palaeocommunities over time, we firstly identify that brachiopod palaeocommunities were not stable throughout this interval, both in terms of taxonomic composition and the associated abundance of those taxa. Thus, there is no evidence of obdurate ecological stasis, as new discrete assemblages, statistically dissimilar from previous and subsequent iterations, form following each environmental disruption. However, at a higher ecological scale, stability is manifest, with diversity patterns stable across time and despite episodes of environmental change. In particular, we identify a form of qualified ecological stasis for both the different environments present during this interval and for the larger region as a whole. The individual taxa that comprise each palaeocommunity may differ over time, but there is a consistent number of species that can exist in any given assemblage, such that palaeocommunities remain functionally similar. This indicates that, whilst the individual taxa that come to form palaeocommunities arrive via the idiosyncrasies of recruitment, the overall diversity of the communities is set by some higher-level ecological rules. Specifically, the rules for taxon packing are seemingly constant in distinct environments, likely due to physiological controls that limit how many taxa can be maintained in an environmental setting and/or perhaps because the amount of space needed for any individual to develop into an adult is invariant across different taxa within the same clade. Further, these ecological rules allow for stability even in the face of constant disequilibrium, which aligns with patterns identified in the recovery of marine invertebrate communities from disruptive events in modern systems. Based on these results, we advocate for consideration of different hierarchical entities and scales when interpreting the ecological dynamics of fossil assemblages, as focusing exclusively on changes in taxon identity/abundance or diversity levels can lead to very different results.

Temporal and spatial variation within a Permian polar coal-forming forest

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Permineralised (silicified) peats hosting non-compressed, three-dimensionally preserved organisms offer unique insights into plant diversity and ecosystem structure of ancient terrestrial coal-forming environments. Silicified peat (chert) entombs one such high-latitude forest mire ecosystem in the middle Permian (c. 265 Ma) Toploje Member (Bainmedart Coal Measures) within the Lambert Graben, East Antarctica. The peat layer hosts a relatively low-diversity flora dominated by glossopterid gymnosperms (Holdgate et al., 2005; Slater et al., 2015). It also contains cordaitalean gymnosperms (*Noeggerathiopsis*), herbaceous lycopsids, fern tissues, fungal matter, dispersed pollen and spores, charcoal, and evidence of animal-plant interactions including coprolites (McLoughlin & Drinnan, 1996; Slater et al., 2012; McLoughlin et al., 2015).

Five vertical profiles through the Toploje Member silicified peat, represented by 5–10 thin sections each, and distributed along 2 km of strike were studied. We carried out quantitative analyses of the peat constituents via the point-counting method and microlithotype analysis to investigate the variation in forest mire structure both stratigraphically and spatially. The peat architecture is dominated by woody subaerial axes (*Australoxylon*) and subterranean roots (*Vertebraria*: reflecting *in situ* tree growth), with sporadic bands of matted *Glossopteris* leaves (representing autumnal leaf shed) and charcoal (denoting wildfire events). Dispersed pollen and spores are relatively common through most profiles and their greater diversity compared to the macrofossils may reflect contributions from plants growing outside the immediate mire community. Fungal spores and reproductive structures, fern sporangia, lycopsid megaspores and water moulds (Oomycetes) are subsidiary components of the fossil biota. Work is currently underway to assess whether changes in peat constituents across the mire transect reflect variance in mire moisture availability, and vulnerability to wildfires.

This study has implications for interpreting middle Permian forest mire ecology, for understanding the fundamental constituents of Gondwanan Permian economic coals, and for clarifying the response of peat-forming ecosystems to palaeoenvironmental and climatic changes. Comparison of the Permian peats with extant plant communities will help to resolve the environmental setting (e.g., ombrotrophic vs rheotrophic mire) and clarify the evolution of peat-forming communities through deep time.

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Session 33

New tools in geoscience (remote sensing, digital outcrops): Open session

Porosity and permeability estimations by fluorescence microscopy: Examples from weathered basement rocks on- and offshore Norway

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Porosity and permeability are two important parameters in textural characterization of rocks. Simple, fast and inexpensive methods of quantifying these parameters are of great interest in all fields where textural analyses of rocks may be important. For crystalline rocks, porosity and permeability may be particularly important in petroleum prospecting, carbon capture and storage, geothermal energy, and nuclear waste disposal. In this study we propose a new method of estimating porosity and permeability using fluorescence microscopy. The results are compared with measured He-porosity and air permeability, and micro-CT analyses of similar samples form the same study areas. The samples were collected from drill cores from altered and weathered granitoids at Bømlo, Western Norway, in addition to Frøya and Utsira Highs offshore, the latter being a part of the currently oil producing Johan Sverdrup field.

Mosaics of thin sections were created using a petrographic microscope under fluorescent reflected light conditions, and porosity was determined in ImageJ based on the assumption that the intensity of fluorescence directly correlates with pore depth in each pixel. This method helps to avoid the typical underestimation of porosity that can occur with point counting or image thresholding by color, as the low reflectance of silicate minerals won't conceal the colored epoxy in reflected light. Permeability was calculated using the equations in Nishiyama & Yokoyama (2017) using the median pore radius measured by fluorescence intensity and the local thickness function in ImageJ, and a weighted porosity by combining the pore radius and Strahler mode of each pixel as the open porosity.

The variation in both porosity and permeability is considerable, ranging from less than 1% and under 0.01 mD in weakly and unaltered samples, to 2-20% and 1-1000 mD in samples with variable alterations, and ca. 40-60% and ca. 250-15000 mD in unconsolidated saprolite samples. For all samples, the computed results fall within the range of values measured for similar samples in laboratory experiments. This indicates that the method is valid and serves as a useful complement to the mineralogical and textural information obtained through conventional thin section petrography.

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Session 34
From the Caledonides to the Scandes

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Redefining late Cambrian/Early Ordovician subduction of the Seve Nappe Complex: tectonic implications for the Scandinavian Caledonides

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The Scandinavian Caledonides are an excellent record of Wilson-cycle tectonics. The Seve Nappe Complex (SNC) is a key component for understanding the tectonic evolution of the Caledonides. It comprises relics of the Baltican outermost margin that records Iapetus ocean opening and closure leading to continental collision. The SNC in Sweden has often been discussed according to three major (ultra-)high pressure (UHP) regions, defined here from south to north as: the west-central SNC (west-central Jämtland), the central SNC (northern Jämtland/southern Västerbotten), and the northern SNC (Norrbotten). Initial stages of the Caledonides in late Cambrian/Early Ordovician were first recognized in the northern SNC, whereas the other SNC localities were thought to only record Middle Ordovician (U)HP metamorphism. This apparent pressure-temperature-time (P-T-t) dichotomy suggested either northeast to southwest oblique collision of the Baltican margin or collision of a margin promontory in the northeast. However, recent research has begun to redefine the late Cambrian/Early Ordovician subduction history of the SNC. In the northern SNC, three (U)HP terranes demonstrate a progressive decrease in P-T conditions related to subduction that are recorded within the same time interval, from southwest to northeast: Grapesvare nappe (2.8-3.1 GPa and 660-780°C at 482-480 Ma), Råvvejávvre nappe (2.4-2.6 GPa and 580-680°C at c. 486-482 Ma), and the Mårma terrane (1.0-1.5 GPa and 590-660°C at c. 488-481 Ma). Evidence for (U)HP metamorphism apparently disappears in the SNC northeast of the latter; a record of (U)HP metamorphism is absent in upper gneiss unit of the Váivančohkka-Salmmečohkat region. Altogether, the P-T-t pattern indicates southwest-to-northeast oblique subduction of the northern SNC with decreasing continental material present within the subduction channel, leading to predominant oceanic subduction. Recent work in the west-central and central SNC supports the late Cambrian/Early Ordovician south-to-north subduction of the SNC. The Tväråklumparna gneiss (west-central SNC) and the Avardo and Marsfjället gneisses (central SNC) all record partial melting in (U)HP conditions at c. 483-480 Ma. In the Marsfjället gneiss, this partial melting event may have succeeded the formation of metamorphic microdiamonds included in garnet, suggesting continental material was deeper in the central regions of the SNC compared to the north in the late Cambrian. Exhumation (or possible stagnation) within the subduction channel appears to be broadly coeval across the SNC at c. 480-470 Ma, regardless of the prior P-T conditions. However, the west-central and central SNC both record (U)HP events at c. 463-455 Ma, which is not recorded in the northern SNC. Subsequent exhumation of the west-central SNC occurred at c. 446-435 Ma through 700-820°C, associated with partial melting, whereas central SNC exhumation occurred at c. 446-440 Ma in temperatures of ~550-690°C without partial melting, and the northern SNC was exhuming at c. 447-440 Ma through temperatures of ~350-500°C, consistent with deeper to shallower burial of the presently exposed (U)HP SNC terranes from the southwest to northeast. The incipient record of continental (Scandian) collision appears uniform across the SNC at c. 434-424 Ma. The emerging tectonic record of the SNC demonstrates that a larger volume of continental crust was being subducted across the extent of the Scandinavian Caledonides than previously thought. This requires revisiting of our understanding of the Caledonian Orogeny starting in the late Cambrian and establishing tectonic relationships with subduction processes in the Iapetus Ocean for influencing the SNC subduction-exhumation cycles and accommodating closure of the Iapetus Ocean leading to continental collision.

Significance of orogenic peridotites in understanding the evolution of Baltican margin throughout the Caledonian Wilson cycle

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Fragments of ultramafic rocks representing "enclaves" of the Earth's upper mantle within crustal units – the orogenic peridotites – bear petrological and geochemical imprint of evolutionary paths of the lithospheric mantle. Such record can supplement, often overprinted or blurred, geological information from the allochthonous crustal units in an orogenic setting. In Scandinavian Caledonides, numerous occurrences of orogenic peridotites were identified within allochthonous nappes forming the hypothetical suture between continental margin of Baltica (Seve Nappe Complex; SNC) and Iapetus ocean-derived terranes (Köli Nappe Complex). In this study we discuss the origin of orogenic peridotites within the SNC and their insight on the tectonic evolution of the Baltican margin throughout the Caledonian Wilson cycle.

The occurrences of the mantle fragments within the SNC in northern Jämtland and southern Västerbotten in Sweden are dominated by spinel facies peridotites of three main groups: 1) serpentinized peridotites, 2) recrystallized peridotites, and 3) retrogressed garnet peridotites. The serpentinized peridotites are characterized by refractory, modal (harzburgitic/dunitic; Ol+Spl±Opx) and bulk chemical (e.g. $Al_2O_3 \leq 1.0$ wt%, Mg# = 95.1-95.6) composition. Olivine is typically Fo_{91-90}. Serpentine mesh texture represented by lizardite-chrysotile (low-T polymorphs) and the presence of Amph is common. Spinel is often zoned with chromitic/Al-chromitic cores (Mg#=27.9-39.9; Cr#=68.9-83.1) and rims of chromitic composition (Mg#=15.1-27.3; Cr#=83.5-95.9) trending towards Fe-chromites. Collectively, the textural and chemical features suggest that serpentinized peridotites represent fragments of shallow, sub-oceanic lithospheric mantle.

Second group – recrystallized peridotites – shares the refractory character with the serpentinized samples. However, they bear no serpentine group minerals and are characterized by well-equilibrated texture dominated by triple-point boundaries in olivine of variable Fo content (from ~90 up to >93). The typical ultramafic assemblage of Ol+Opx and Spl (chromite to magnetite) includes also Chl, and Amph. Moreover, single samples contain zoned Amph with rims containing increased Na_2O content (1.2-0.4 wt%), indicating prograde conditions. This group is interpreted to be an effect of dehydration of serpentine-bearing peridotites during the prograde metamorphism (subduction) and recrystallization (deserpentinization) in variable oxidation conditions.

The last group – retrogressed garnet peridotites – are refractory dunites with poorly developed serpentine mesh. The samples are rich in amphibole occurring in several textural positions: as 1) zoned patches in the peridotite, 2) a constituent of pressure shadows, 3) healing of brittle deformation of garnet before its decomposition, and 4) a component of post-garnet kelyphites. The variations in Amph composition, together with textural evidence, allow the reconstruction of melt/fluid reactions. Similar, but usually "less hydrated", textures were described to be an effect of deep mantle exhumation through lithospheric mantle shear zones (Afiri et al. 2011), therefore retrogressed garnet peridotites are interpreted as an effect of a similar process in fluid-saturated conditions.

Interpretations of tectonic insights given by each of the groups of peridotites allow narrowing down the number of scenarios of the events that took place at the Baltican margin. We suggest that a "continent-like" terrane within (possibly non-Iapetian?) oceanic domain must be considered to fully explain the character of included orogenic peridotites and the tectonic evolution of the region.

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Geochronology and geochemical characterization of continental rifting in the Kebnekaise region, northern Scandinavian Caledonides

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The Scandinavian Caledonides are composed of a series of allochthons divided by major shear zones. The Middle Allochthon in particular represents the Neoproterozoic continental passive margin, containing Neoproterozoic dolerite dykes and mafic plutonic rocks, as well as Mesoproterozoic and Paleoproterozoic orthogneiss. For this work, we collected several samples of metamorphosed plutonic rocks from the Middle Allochthon in the Kebnekaise region, northern Sweden. These samples include: a migmatitic variety of the Vierručohkka amphibolite, the metamorphosed Aurek gabbro, and the Aurek amphibolite. U-Pb zircon geochronology of the migmatitic sample (banded amphibolite) yields crystallization ages of 626 ± 7 Ma and a younger age of 598 ± 3 Ma. The former represents the crystallization age of the protolith and the latter is interpreted as partial melting of the Vierručohkka amphibolite. The Aurek metagabbro and Aurek amphibolite rocks yielded zircon crystallization ages of 614 ± 2 Ma and 609 ± 2 Ma respectively, both interpreted as the crystallization ages of the igneous protoliths. The whole rock geochemistry show evidence of crustal assimilation in Th and La, and compared to continental crustal compositions, they suggest assimilation of the lower continental crust by the Aurek magmas. Whereas for the banded amphibolite, which is also enriched in rare earth elements (REE), an affinity with upper crust is proposed. The REE of the Aurek metagabbro and amphibolite provide evidence of a general depletion of REE compared to N-MORB. Comparing the geochemistry of the Aurek samples with their Laurentian counterparts from continental rifting in the Appalachians, they show similar source compositions overprinted with crustal assimilation. This new data reveal that, in the Kebnekaise region, there is evidence of prolonged mafic magmatic activity between c. 626 Ma and c. 609 Ma testified by the emplacement of the dyke swarm and mafic bodies such as the Aurek gabbro and amphibolite. Moreover, this provides new evidence of a thermal anomaly at c. 598 Ma, causing localized partial melting of the Vierručohkka amphibolite. From a geochemical point of view, the new data show evidence of a depleted mantle source and assimilation of continental crust during continental rifting associated with the opening of the Iapetus Ocean.

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Th-U-Pb dating of monazites from the Upper Köli Nappes in the Northern Scandinavian Caledonides

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The Köli Nappe Complex in the Scandinavian Caledonides of Sweden originated as terranes within the Iapetus Ocean derived from subduction-related magmatic and basin systems. The Krutfjellet Nappe in Västerbotten, Sweden, and the Gasak Nappe in Nordland, Norway, are both part of the Upper Köli Nappes. In both of these units, siliclastic, carbonate and volcanic protoliths underwent amphibolite facies metamorphism (involving in places extensive migmatisation) which was of a distinctly higher grade than the lower and Middle Koli Nappes. Foliations and early folds in the metasediments are cut by metagabbros and metagranites with an age of ~445-435 Ma (e.g. Senior and Andreiessen 1990; Pedersen *et al.* 1991). Emplacement of the intrusions was followed by regional greenschist-lower amphibolite facies metamorphism, probably related to the Scandian collision.

Four sillimanite and/or kyanite-bearing pelitic migmatite samples from the Norra Storfjället lens of the Krutfjellet Nappe and three samples of pelitic garnet mica schists and migmatites from the Sulitjelma area of the Gasak Nappe were selected for Th-U-Pb dating of monazite. Monazites were dated *in-situ* using LA-ICP-MS at the Institute of Geology of the Czech Academy of Sciences. One sample from the Krutfjellet Nappe yields a U-Pb concordia age of 427.88 ±1.31 Ma. The remainder of the samples yielded a large proportion of discordant analyses that fall on discordia lines at high angles to the concordia curve. We interpret this discordance to be due to the presence of initial Pb in the monazites, thus the ages are taken from the lower intercepts of the discordia to remove the effect of initial Pb. U-Pb lower intercept ages for 3 samples from the Krutfjellet Nappe are found to be 422.92 ±1.36 Ma, 426.27 ±1.16 Ma and 426.44 ±1.96 Ma. U-Pb lower intercept ages for the Gasak Nappe are found to be 416.74 ±1.50 Ma, 423.53 ±1.71 Ma and 427.7 ±1.5 Ma. These ages are interpreted as being related to metamorphism and/or fluid-related alteration at between 428-417 Ma in both the Krutfjellet and Gasak Nappes. In lower Köli Nappe Complex units further south in Sweden, similar ages of 431-426 Ma have been interpreted as representing the time of shearing related to nappe stacking during assembly of the Caledonian orogenic wedge (Bender *et al.* 2019) prior to its final translation and imbrication.

Our isotopic ages for the Krutfjellet Nappe are younger than EPMA U-Th-total Pb ages obtained for the same monazite grains (Carter *et al.* 2023). The monazites often have complex zoning patterns in Y, however the zoning appears to be decoupled from the ages. We suggest that the monazites from the Krutfjellet Nappe may have experienced pervasive resetting, possibly related to dissolution-reprecipitation, which led to contamination of the monazites with initial Pb and decoupling of the U-Th-Pb system from Y zoning. The actual age of migmatisation remains enigmatic.

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The high-level peneplains of southern Norway cut across rocks of different resistances to erosion

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The Palaeic landscape of southern Norway was originally defined by Reusch (1901) as the near-flat plateaus at higher elevation than the deeply incised valleys and fjords. We have used the techniques of Stratigraphic Landscape Analysis (Green et al., 2013; Lidmar-Bergström et al., 2013) to show that the Palaeic landscape consists primarily of three extensive low-relief surfaces, incised by deep valleys and fjords and with areas of alpine landscape above the highest surface. These surfaces were first identified by Bonow et al. (2003) in the area that they called the Kjølen Mountains bounded by the alpine Jotunheimen, Rondane and Dovrefjell Mountains.

The highest surface (that we have named the Halling surface) is found only in scattered remnants at altitudes of 1700 to 1900 m above sea level (asl), typified by the low-relief surface found on the Hallingskarvet Ridge. The lowest surface is most extensive on eastern Hardangervidda (the Hardanger surface), at an altitude of around 1200 m asl, but extensive remnants extend north-eastwards at altitudes down as low as 900 m asl from Hardangervidda around Gudbrandsdalen to the Kjølen area. The middle surface (the Joste surface) is found at altitudes of 1400 to 1700 m around the western margins of Hardangervidda and to its north through Skarvheimen and forms the surface supporting the ice caps around Jostedalsbre.

On Hardangervidda, the Hardanger surface coincides approximately with the outcrop of the Base Cambrian Unconformity (BCU) (Japsen et al. 2018) but is cut above remnants of Cambro-Ordovician metasediments (phyllites) where they are faulted or folded down and below the BCU where it is folded or faulted upwards to above the summit of Gaustafjellet.

All three surfaces cut across rocks of different resistances to erosion: Precambrian gneisses, phyllites and overthrust Caledonian nappes. In places an escarpment separates a higher surface eroded into rocks of lower resistance (phyllites) from a lower surface cut into rocks of higher resistance (e.g. Precambrian gneisses). These observations show that the surfaces are independent of the rocks into which they have been eroded and that they must have been formed by erosion graded to an external base level; sea level as there is no other extensive resistant surface. The surfaces are therefore peneplains. A higher surface must also have been uplifted so that the next, lower surface could have formed. All the surfaces must also have been uplifted after formation of the lowest peneplain to start incision of valleys. Isostatic response to the incision would then have lifted them to reach their present elevations.

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The Jotun-Valdres Nappe Complex

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The Jotun-Valdres Nappe Complex (JVNC) consists of Precambrian intrusive and metamorphic rocks, in part with a cover of Late Precambrian to Early Paleozoic sediments (sparagmite), the whole thrust onto the autochthonous Baltic continent during the Scandian phase of the Caledonian Orogeny. The JVNC is a tectonic composite of different units with distinct magmatic and metamorphic histories. The uppermost unit, the Upper Jotun Nappe (UJN), comprises in its northeastern parts a stratiform felsic to ultramafic complex, with rocks formed at about 1650 Ma and metamorphosed to granulite facies in several stages between 960 and 890 Ma. The southwestern part shares a similar Sveconorwegian metamorphic history but lacks the 1650 Ma complex and is dominated instead by a 965 Ma gabbro-anorthosite massif. All parts of the UJN, but especially the centre, were invaded by the Silurian (ca. 428 Ma) granitic Årdal dyke complex. The Lower Jotun Nappe (LJN) consists mainly of 1650 Ma orthogneiss, metamorphosed and deformed at about 900 Ma, and later covered by sediments (sparagmite), but it does not have Silurian intrusives. These main tectonostratigraphic packages are separated by highly deformed, but generally low-grade metamorphic rocks of variable origin. On the northwestern flank of the JVNC, the basal unit is a zone of imbrication comprising analogues of the LJN and sparagmite, and also a late Sveconorwegian volcanic-subvolcanic complex derived from outboard of Baltica. All of this overlies the Fortun Nappe, which consists mainly of schist and phyllite, but also with solitary serpentinite lenses, ultramafic conglomerates, slices of felsic crust, and, in its southern parts, Early Ordovician and Late Silurian (421 Ma) intrusives. The sequence represents a hyperextension assemblage (Andersen et al. 2012; Jakob et al. 2017), formed by stretching and break-up of the Baltic crust. All the tested crustal fragments in the assemblage have Telemarkian ages (1520-1480 Ma), and there are no slices of the JVNC. This implies that hyperextension only developed in the Telemarkian crust, rather than the Gothian domains farther north, including the JVNC (1700-1600 Ma). The JVNC is transected by the SW-trending Devonian Lærdal-Gjende Fault, which formed a half graben as much as 8 km deep in the centre of the complex, but seems to die out in the north. In the south it splices off into different segments, which eventually link up with the Hardangerfjord Shear Zone.

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Omphacite gneisses and mafic eclogites in the southern Norwegian Caledonides: Links between densification and palaeoseismicity?

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Microstructures indicative of brittle fracture under metamorphic conditions are an important indicator of deep crustal or mantle seismicity. It has been proposed that his may have been triggered by the physical response to metamorphic transformations, including hydro-fracturing due to dehydration reactions (particularly at the blueschist-eclogite transition (Bukała et al., 2020)) or by shear stresses set up by domains undergoing metamorphic densification (Yamato et al., 2022). Feedback between fracture, fluid ingress and catalysis of eclogite genesis in previously dry rocks are, arguably, also important.

In the southern part of the Western Gneiss Region (WGR) felsic gneisses and mafic eclogites have often escaped the pervasive anatexis that characterises its more northerly region, so high-pressure parageneses have frequently survived even in felsic orthogneisses, in which omphacite and high-silica phengite are sometimes preserved. In such rocks there is also microstructural evidence for syn-metamorphic brittle fracture in garnet and omphacite. Such microstructures, in garnet, have been observed in eclogite in the Nordfjord area in close proximity to coesite-bearing pelitic schists. Charge-contrast imaging of prograde-zoned garnet in the latter revealed a pervasive network of connected filament-like features that are also exhibited by an identical pattern of major and trace-element compositions. These microstructures are interpreted as healed microfractures and indicate that early garnet has been catastrophically disaggregated prior to new garnet growth under HP or UHP conditions. No protolith relics have been preserved at this locality. However, further south in Sunnfjord, eclogites are associated with granitoid HP orthogneisses that have developed from dry Proterozoic charnockites and anorthositic gabbros that pass over short distances into domains of eclogite-facies felsic rocks of up to a few km^2 in extent. Similar features to those seen at Nordfjord have been imaged in garnet in both eclogite and granitoid HP gneiss, but here omphacite also shows similar “channel”-like networks. At least two sets of healed micro-fractures here suggest multiple seismic events. No evidence for lawsonite breakdown that might favour reaction-induced hydrofracturing (Bukała et al., 2020) is known although omphacite-filled hydrofractures are common so some role for fluids is required. Estimates of density change across the eclogite transition in these examples, based upon P-T pseudosections, demonstrate abrupt increases in the amphibole- and plagioclase-out interval during continental subduction.

The observations from Sunnfjord are consistent with recent numerical modelling (Yamato et al., 2022) of brittle deformation due to densification where seismicity is favoured by a large P overstep for eclogite formation and the formation of small eclogitic (densified) domains. Large changes in shear stress at the tips of densifying regions could have favoured seismic pumping of fluids that aided eclogitisization. A likely autochthonous source of the fluids in the WGR was a large continental shield brine aquifer (Hughes et al., 2021).

The evidence exhibited in the southern WGR suggests that seismicity as a result of metamorphic transitions is likely in the vast masses of transiently-subducted granitoid crust that characterize continental collision zones.

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Decompression evolution of sillimanite gneiss in the high-pressure terrane of Western Gneiss Region (Norway)

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Sillimanite-bearing gneisses in the Romsdal region of Western Gneiss Region (South Norway) have been investigated to document the presence, formation, composition and petrological evolution of the sillimanite-bearing assemblages. Sillimanite is found in augen gneiss, as nodular gneiss, and present in well-foliated sillimanite-mica gneiss. Lenses and layers of eclogite occur within the gneiss units. The sillimanite-bearing gneisses are heterogranular and dominated by quartz, plagioclase (An_{29-41}), K-feldspar, biotite (Mg# = 0.48-0.58; Ti = 0.16-0.33 a.p.f.u.), with variable amounts of white mica (Si = 6.10-6.30). K-feldspar occur as porphyroclasts in augen gneiss, and garnet constitutes resorbed porphyroblasts. Garnet (Alm_{51-56} $Sps_{24-29}Prp_{10-20}Grs_{4-5}$; Mg#=0.22-0.29) shows rimward decreasing Mg#, with a smaller CaO-decrease and a marked MnO-increase up to Sps_{36}. The foliation is defined by crystal-preferred oriented micas, elongation of shape-preferred oriented coarse K-feldspar phenocrysts, and a modal banding of phases. Sillimanite occurs as coarse orientation-parallel matrix porphyroblasts, as finer grains, and as fibrolitic aggregates. Quartz constitutes coarser elongated grains and mono-mineral quartz rods. Pseudosection modelling estimates the peak-assemblage of garnet-sillimanite-feldspar-biotite-quartz-ilmenite-liquid to equilibrate at temperatures up to 750 °C and pressures of 0.6 GPa. Subsequent retrogression consumes garnet. Mineral replacement and melt crystallization involving sillimanite, white mica, K-feldspar and quartz. The results document a decompression and retrogression evolution of the sillimanite gneisses in accordance with the investigated eclogites and high-pressure granulites in this northwestern part of Western Gneiss Region.

From the Caledonides to the East Greenland mountains and the Scandes

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The post-Caledonian development of Greenland and Fennoscandia has been a subject of much dispute. Here we review our studies of the post-Caledonian development of Greenland, Fennoscandia and adjacent regions based on apatite fission-track analysis (AFTA) and stratigraphic landscape analysis (SLA). AFTA defines episodes of cooling (exhumation) while SLA provides a relative denudation chronology. Integrating these results with the geological record, we were able to produce a coherent history of both positive and negative vertical crustal movements.

Late Carboniferous, Middle Triassic and Middle Jurassic exhumation affected the entire study area (with some time variations) and correlate with rifting episodes during the breakup of Pangea. The uplifts and consequent erosion led to formation of peneplains, in particular a mid-Jurassic peneplain now exposed along the Atlantic margins of East Greenland and Scandinavia.

Mid-Cretaceous exhumation affected wide parts of the study area and coincided with the inversion of the Sorgenfrei-Tornquist Zone. It resulted in tilting of the mid-Jurassic peneplain along the future Atlantic margins and in formation of a peneplain across wide areas in Fennoscandia. This episode may be linked with changes in the relative motion between the European and African plates.

End-Eocene exhumation interrupted subsidence following earliest Eocene break-up in the North-East Atlantic and resulted in formation of a peneplain across all of Greenland (the Upper Planation Surface, UPS), whereas the effects in Scandinavia were minor. This episode coincided with a major plate-tectonic change in the North-East Atlantic.

Early Miocene exhumation affected only Fennoscandia and is attributed to intraplate stress transmitted across the Eurasian plate. The exhumation resulted in formation of a peneplain, of which remnants are preserved in southern Norway (east of the highest mountains, including Hardangervidda), in southern Sweden (the South Småland Peneplain) and offshore Norway as the base-Miocene unconformity.

Late Miocene exhumation affected Greenland, Svalbard and the Barents Sea but not Fennoscandia. The uplift initiated the formation of Greenland's coastal mountains by raising the UPS and to incision below it led to the development of the Lower Planation Surface, LPS, on both margins of Greenland. This episode correlates with changes in the absolute motion of the North American Plate.

Pliocene uplift – amplified by the isostatic response to incision of valleys below the peneplains – raised all margins in the region with maximum elevations reached in coastal areas close to Iceland. This suggests dynamic support from the Iceland Plume.

The spatial and temporal extent of these episodes is well defined, allowing speculation regarding their origin as above. Geodynamic modelling is required to understand the underlying processes, offering the potential reward of new insights into the workings of the planet.

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Exhumation of the Seve Nappe Complex, central Scandinavian Caledonides: Insights from $^{40}Ar/^{39}Ar$ and AFT thermochronology

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The Seve Nappe Complex is the highest metamorphic grade unit within the Swedish Caledonides, spanning over 1000 km along the strike of the orogen. In west-central Jämtland, this allochthonous unit is further divided into the Middle and Lower Seve nappes, with ultra-high-pressure (UHP) rocks found in the Middle Seve Nappe (MSN). The tectonically lower unit, the Lower Seve Nappe (LSN), experienced high-pressure (HP) metamorphic conditions. Detailed pressure-temperature-time paths constrain late Cambrian to early Ordovician deep subduction followed by exhumation to mid-crustal levels in the Silurian. We present *in-situ* laser ablation and step-heating $^{40}Ar/^{39}Ar$ geochronology of micas, combined with apatite fission track (AFT) thermochronology to constrain the timing of exhumation of these deeply subducted rocks to the Earth's surface.

Samples were collected from the Åreskutan Mt. (MSN) and the COSC-1 drill core (LSN), providing a composite ca. 3 km vertical profile. The oldest $^{40}Ar/^{39}Ar$ apparent ages are recorded by biotite in the UHP gneisses, migmatites, and mylonites from the MSN. *In-situ* laser ablation of biotite texturally associated with the HP phases yielded 453-451 Myr ages. Relatively younger apparent ages were obtained from biotite that occurs within the main foliation (440-437 Ma) and the deformed biotite records an apparent age of ca. 428 Ma. $^{40}Ar/^{39}Ar$ step heat experiments on biotite reveal complex spectra, with apparent ages in general ranging from 447-438 Ma. Within the migmatite, *in-situ* ablation of phengitic white mica defining the main foliation yielded apparent ages of ca. 443 Ma and a range of relatively younger ages of 430-422 Ma. The latter agrees with the step-heating results obtained for the phengitic white mica which yielded an apparent age gradient from ca. 427 Ma to c. 375 Ma. Biotite and white mica within the LSN rocks yield *in-situ* ages ranging from 434-424 Ma for both undeformed and deformed grains. These ages agree with those obtained from the step heat experiments (430-427 Ma). A complex age spectrum with the oldest $^{40}Ar/^{39}Ar$ apparent ages (ca. 444 Ma) was obtained on white mica from the deepest part of the borehole. AFT ages from the MSN range from 240-190 Ma, in contrast to AFT ages from the LSN 190-70 Ma (COSC-1; including data by Green et al. 2022). Multi-kinetic inverse models (using HeFTy) indicate two episodes of rapid cooling in the Late Triassic and the Late Jurassic, with the latter also revealed in the AFT age vs. elevation plot.

In summary, in the MSN, the oldest biotite $^{40}Ar/^{39}Ar$ apparent ages apparently preserve a record of Ordovician-Silurian UHP-HT subduction-exhumation events. Both biotite and white mica in rocks from the MSN and LSN provide insights into the timing of Silurian thrusting and exhumation of these nappes. The substantial time gap of ca. 170 Ma between the youngest $^{40}Ar/^{39}Ar$ ages and the AFT data suggests that final exhumation of the SNC to shallow depths was not related to the Caledonian subduction cycle that led to the formation of the UHP unit but rather final exhumation from shallow crustal levels to the surface occurred during the Triassic-Jurassic.

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Timing and possible setting of the metavolcanic Grønfjellet unit in the Eastern Trondheim Nappe Complex, central Scandinavian Caledonides

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The Grønfjellet unit is a metavolcanic complex recently discovered 75 km southeast of Trondheim. The unit is situated in the eastern part of the Trondheim Nappe Complex and was previously included into greenstone and amphibolite belonging to the Funnsjøen Group. However, more detailed field mapping has revealed a unique metavolcanic unit consisting of both agglomerates, welded tuffs and various pyroclastic sequences. The unit covers at least 20 km^2 and is associated with layers of marble and rusty phyllites and metasandstones.

Field evidence indicates that feldspar-porphyritic dolerite dykes belonging to the latest stages of the Funnsjøen Group cut the volcanic complex. This implies that the Grønfjellet unit and the Funnsjøen Group must have been in proximity during the intrusion of the dolerites, either in primary contact or tectonically juxtaposed. To the north and east, the Grønfjellet unit has uncertain field relationships to the pre-doleritic parts of the Funnsjøen Group. Both the Grønfjellet unit and the Funnsjøen Group display a strong ductile to semiductile deformation with a prominent south-west plunging ductile stretching lineation. The dolerite dykes cut an early phase of deformation in the Funnsjøen Group (Grenne & Lagerblad, 1985), but the same field relationship has not yet been documented for certain in the Grønfjellet unit.

So far, extraction of zircons from the volcanic rocks of the Grønfjellet unit has been unsuccessful. But the Funnsjøen Group is intruded by the 437.8 ± 2.3 Ma Fongen-Hyllingen intrusion (Nilsen et al. 2007), where the feldspar-porphyritic dolerite dykes can be found as inclusions, therewith predating the intrusion. Since the Grønfjellet unit is cut by the dolerite dykes, it has to be older than the Fongen-Hyllingen intrusion. This provides a minimum age for the Grønfjellet unit, the Funnsjøen Group and part of the deformation. It is estimated that the Fongen Hyllingen intrusion was emplaced at 3,5 ± 0.5 kb, meaning that the Grønfjellet unit and the Funnsjøen Group were buried to depths of ca. 11-15 km before the emplacement of the gabbro intrusion.

Preliminary geochemical data from ten fine-grained samples of volcanic origin reveal a peculiar composition: they plot as alkaline rocks in the Nb/Y vs. Zr/Ti diagram; they are enriched in LREE as well as Th, U, Nb and Ta; they plot close to the MORB–OIB array in the Nb/Yb vs Th/Yb diagram; and they do not show significant negative Nb-Ta anomalies typical for island-arc or back-arc settings. Ranging in composition from trachybasalt, through basaltic trachyandesite to trachyandesite, they are very different from the typical island arc tholeiites and back-arc basin basalts of the Funnsjøen Group metavolcanic rocks elsewhere, and are more similar to rift-related alkaline rocks from the western Trondheim Nappe Complex.The complex therewith represents a hitherto unknown, possibly rift-related volcanic phase prior to emplacement of the dolerite dykes and the Fongen-Hyllingen intrusion.

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An Iapetus origin for a layered eclogite complex in the northern Western Gneiss Region, Scandinavian Caledonides

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The Western Gneiss Region (WGR) is a Precambrian basement domain in the Scandinavian Caledonides and one of the world's largest high- and ultrahigh-pressure terranes. The south-central WGR underwent regional eclogite-facies metamorphism 415–400 Ma ago when Baltica subducted beneath Laurentia, during the Scandian orogeny. Eclogites in the WGR group into two traditional types: 1) Precambrian mafic intrusions metamorphosed *in situ* during Scandian continental subduction and 2) eclogites, garnet peridotites, and garnet pyroxenites within ultramafic complexes derived from the subcontinental mantle beneath Laurentia. We document, using field relations, petrography, whole-rock geochemistry, and SIMS zircon geochronology, a hitherto unrecognised third type of eclogite in the WGR that places new constraints on its tectonic architecture: an eclogitised fragment of oceanic crust from the Iapetus Ocean. The Kråkfjord eclogite complex is a km^2-sized body with an interior consisting of kyanite eclogite (meta-troctolite) and subordinate layers and lenses of garnet peridotite, garnet websterite, and kyanite–garnet leucotonalite. This interior is capped by Fe-Ti-rich eclogite, which locally contains subordinate pockets of migmatitic aluminous gneiss. The elemental abundances and isotopic compositions of the Fe-Ti-rich eclogites resemble those of Mid-Ocean Ridge Basalt (MORB). In contrast, the interior kyanite eclogites, peridotites, and pyroxenites have compositions similar to the gabbroic cumulates in the lower oceanic crust of slow-spreading ridges. U–Pb SIMS dating of igneous zircon cores from a leucotonalite pod in the interior of the Kråkfjord complex yield Cambro-Ordovician igneous ages of 500–440 Ma, with the ~500 Ma age interpreted as the isotopically undisturbed age. This age matches those of Iapetan oceanic rocks exposed elsewhere in the mountain belt. Metamorphic zircon from a Fe-Ti-rich eclogite in the carapace of the Kråkfjord complex dates the eclogite-facies metamorphism at 421.9 ±2.2 Ma, synchronous with the continental collision. Zircon from a leucosome in Fe-Ti-rich retro-eclogite indicates an age of 408.5 ±2 Ma for the crystallisation of partial melt following the decompression. Detrital zircon core ages from a pocket of aluminous migmatitic gneiss in the carapace indicate derivation of sediment from the Baltic crust. Collectively, the data show that the eclogite complex (1) originated at an Iapetus spreading centre near the continent Baltica, (2) subducted to eclogite conditions during Scandian continental collision, and (3) was tectonically intercalated with the Precambrian Baltica basement of the WGR.

Caledonian granitoids on the island of Smøla, central Norway

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Granitoid batholiths are an important part of the upper allochthons in the Scandinavian Caledonides. In central Norway, the Smøla-Hitra Batholith covers a substantial area, stretching approximately150 km from Grip and Smøla islands in the southwest to Halten in the northeastern part of the Froan archipelago.

Recent structural studies, along with a drilling campaign, have been conducted on Smøla island. This research is part of the BASE (Basement Fracturing and Weathering on- and offshore Norway) project, funded by the Norwegian Research Council. As a smaller component of this project, we have also investigated the granitoid rocks on Smøla and the nearby northern islands. The region was previously surveyed in the late 1960s (Fediuk & Siedlecki, 1977), and a summary of the batholith was published by Gautneb & Roberts (1989). Detailed mapping of the southwestern areas of Smøla and the adjacent islands was carried out by Gautneb (1988).

The intrusive relationships on the Smøla island are best studied along the coast where outcrops are excellent. In contrast, the flat-lying interior parts of the island offer very few and scattered outcrops, making it challenging to verify the lithological variation as depicted on the printed map of Fediuk & Siedlecki (1977). The rocks are virtually undeformed and may have a well-defined mineral orientation or weak foliation. Some shear zones and brittle faults, probably related to late- or post-Caledonian tectonics, are present.

Apart from an area with mainly gabbroic rocks in western Smøla, the predominant rock types are diorite to tonalite. Granite and granodiorite are subordinate. Over large areas, the diorites show evidence of complex magma mingling and locally mixing, forming breccia-like rocks with several generations of mafic to felsic lithologies. Several types of dykes are common and include dolerite, fine-grained to porphyritic diorite, composite dykes, granophyre dykes, and aplite/pegmatite.

Representative samples collected from the central to northern parts of Smøla were analyzed for major and trace elements including REE. The investigated samples vary in composition from mafic gabbro to diorite and leucocratic tonalite and granodiorite. The rocks are low-K calcic to calc-alkaline and magnesian in composition, like major plutonic units from Hitra and Frøya. There are also examples of high-K calc-alkaline quartz-monzonite like those reported by Gautneb & Roberts (1989) from southwest Smøla as well as from the Froan archipelago north of Frøya.

There are few modern geochronological data from the Smøla. Available results from the entire Smøla-Hitra Batholith show that the low-K calc-alkaline rocks from Hitra, Frøya and Smøla, that intruded older meta-supracrustal rocks and gneisses, are late Ordovician to possibly early Silurian in age. The alkali-calcic plutons in the Froan archipelago, as well as in southern Smøla, are probably somewhat younger and were emplaced in the early to middle Silurian. Additional geochronological and isotopic data would be required to better constrain the plutonic evolution and tectonic models for the Smøla-Hitra Batholith. Samples for Ar-Ar dating is in progress, awaiting results.

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Constraining the late- and post-Caledonian structural evolution onshore Ofotfjorden-Vestfjorden

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The Lofoten Ridge, northern Norway, forms the southern part of the Lofoten-Vesterålen archipelago and corresponds to a structurally segmented basement high characterized by Alpine-type topography. The ridge is separated from the Norwegian mainland by the SW-NE trending Vestfjorden Basin, which represents the seaward continuation of the E-W trending Ofotfjorden. We present remote sensing and field structural data combined with geochronological K-Ar and $^{40}Ar/^{39}Ar$ data from the onshore bedrock domain in the Ofotfjorden and inner Vestfjorden regions. These data are used to reconstruct the local pre-rifting and rifting history of the North Norwegian margin with particular focus on similarities and differences in structural architecture and heritage between the Lofoten Ridge and the mainland.

Bedrock lineaments extracted from a 10 m digital elevation model cluster into two major sets: (1) Set 1 consists of predominantly E-W-striking lineaments. These lineaments are particularly abundant close to the shorelines of Vestfjorden and Ofotfjorden and generally correspond to subvertical, localized sinistral and ductile to brittle shear zones and brittle fractures. Syn-deformational biotite and/or muscovite characterize Set 1 structures. These structures are interpreted to belong to a large-scale anastomosing shear zone whose core remains in the fjords. A cumulative horizontal sinistral displacement of c. 2 km is estimated across Ofotfjorden on the basis of the offset of easily mappable lithological boundaries across the fjord. $^{40}Ar/^{39}Ar$ geochronology from amphibole, muscovite and biotite from host rocks and fault surfaces give mainly Late Silurian to Late Devonian ages spreading from 424 ± 1 to 364 ± 1 Ma. (2) Set 2 consists mainly NNE-SSW- to NE-SW-striking lineaments and corresponds to fully brittle faults, which are often associated with cataclasite and fault gouge and extensional kinematics. They are very common to the N/NW of Ofotfjorden/Vestfjorden, but very rare S/SE of it. K-Ar geochronology of illite, smectite and K-feldspar from selected fault gouges constrains several pulses of predominantly extensional faulting from the Late Devonian down to the Late Cretaceous (375 ± 5 Ma to 76 ± 3 Ma).

The Set 1 lineaments define a large-scale shear zone which was active during late-Caledonian tectonics, but probably formed by the reactivation of a pre-existing large-scale crustal weakness zone stretching from Vestfjorden far into Baltican basement on Swedish territory. This spatial distribution of Set 2 structures indicates that the large-scale shear zone defined by Set 1 structures, once formed, probably acted as a decoupling structure between the crustal units located to the N/NW and those to the S/SE of the fjords. During multiple episodes of later (post-sinistral) shear, extension strain was accommodated by the shear zone itself (brittle reactivation of Set 1 structures) and by Set 2 faults, which led to further significant structural segmentation of the Lofoten Ridge and adjacent crustal blocks N/NW of the fjords.

Provenance of the Neoproterozoic–Cambrian Vestertana Group in Finnmark, northern Norway

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Detrital zircon studies can help to constrain paleogeography, tectonic reconstructions, and crustal evolution. Zircon is popularly used as a tracer of sedimentary provenance because of its robustness and occurrence in virtually all sedimentary deposits; it is datable by the U–Pb method and its Hf composition reflects the composition of the parent rock in which it crystallized. This study utilizes field observations with emphasis on paleocurrent measurements and U–Pb geochronology and Lu–Hf compositions of detrital zircons to gain information about the provenance of the Neoproterozoic–Cambrian Vestertana Group in the Tanafjord–Varangerfjord area, northern Norway.

The Vestertana Group was deposited on the border between the Neoproterozoic to early Paleozoic continental margin of western Baltica and the Timanian basin in northwestern Russia. The group consists of five formations; from oldest to youngest: Smalfjord, Nyborg, Mortensnes, Stáhpogieddi, and Breidvika. A previous study claims that most of the sediments in the Vestertana Group were derived from southerly sources on the Fennoscandian Shield. However, a zircon population with ages around 552 Ma, appearing in the uppermost member in the Stáhpogieddi Formation, was suggested to be derived from the Timanian Orogen. The Timanian Orogen is inferred to have been located northeast of the study area. An inferred shift in the main paleocurrent direction from a northerly to a southerly direction is also used as an argument for a change in the source area within the Vestertana Group. Due to poor constraints on the extent of the Timanian Orogen and few detrital zircon studies in the northwestern part of Russia and Finnmark, one can question whether a Timanian source is correct or likely.

The claimed shift in the main transport direction from a northerly to a southerly direction within the Stáhpogieddi Formation was not observed in this study. A radical change in the rate of sediment supply, which one might expect to see if the sedimentary basin went from being a passive margin into a foreland basin, as suggested by the Timanian model, was also not observed. However, several outcrops in other areas, such as the Digermul Peninsula and autochthonous parts of the Varanger Peninsula, should be investigated before concluding.

The U–Pb and Lu–Hf data obtained from 16 samples from the Vestertana Group using LA-ICP-MS, show a strong Fennoscandian affinity in addition to input from an unknown Neoproterozoic source. Potential Neoproterozoic sources are for instance the Timanian Orogen or a hypothetical active western Baltican margin. Although no major changes related to paleocurrents or sediment-supply rates within the Stáhpogieddi Formation were observed, the input of late Neoproterozoic zircons found in the Ediacaran–Cambrian Manndrapselva Member of the Stáhpogieddi Formation indicates that a new source began to supply the sedimentary basin with sediments.

Other studies show that zircons with ages between 700 and 600 Ma are found in older Ediacaran sedimentary rocks in southeastern Norway. These zircons cannot be derived from the Timanian Orogen, which implies that there must have existed another late Neoproterozoic source of zircon in Fennoscandia at the time. However, data from Cambrian–Silurian sedimentary rocks sampled in southern Norway have detrital zircon age spectra and Hf isotopic values that are different from samples from northern Norway and Russia. To determine the provenance of the late Neoproterozoic detrital zircons found in both the Vestertana Group and in other regions, more information about the potential late Neoproterozoic sources is needed. Currently, the knowledge about the Timanian Orogen and a hypothetical active western Baltican margin is limited. The late Neoproterozoic zircons can also be derived from a yet undiscovered source.

Session 35
Planetary geoscience

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In situ NIR imaging of different types of lava flow in Iceland as an analog to Venus – in the spectral range of VEM/VERITAS

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The composition of the lava on Venus and its alteration state is poorly understood. The Venus Emissivity Mapper (VEM) (Helbert et al., 2022) will observe the surface of Venus in the NIR range through five atmospheric windows covered by six spectral bands. These will allow studying the spectral characteristics of the Venusian surface, as well as the type of lava and likely alteration processes. Both the NASA VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy) mission and the ESA EnVision missions will carry a VEM-like instrument. To prepare for these missions and deepen our understanding of the emissivity spectral characterisation of various volcanic rocks, we (1) conduct field work at Venus analogue sites in oder to collect samples, (2) develop an emulator to the VEM, aka. VEMulator, which allows in situ measurements in the spectral range of the VEM instrument, (3) use the Venus chamber at the Planetary Spectroscopy Laboratory (PSL) at DLR-Berlin, to obtain emissivity spectra of the samples at Venus temperatures (Helbert et al., 2022).

VERITAS organized a field campaign in Iceland (Nunes et al., 2023). This campaign included DLR airborne radar (SAR) data collection in x-band, like VERITAS and s-band, like Magellan and EnVision. The team also collected surface roughness and permittivity as ground truthing for the airborne SAR data, and in-situ NIR data acquisition using the VEMulator 2.0. The VEMulator covers a comparable spectral range to the six mineralogy VEM spectral channels. An earlier version of this set-up has already been successfully used in a field campaign in Vulcano, south of Italy (Adeli et al., 2023a).

To achieve the above-mentioned goals, we have focused on the Fagradalsfjall volcanic complex, as an analog site to Venus (Adeli et al., 2023b). This is an area of faults and fissure swarms, with recent and frequent volcanic activity in 2021, 2022, and 2023. The lack of vegetation and atmospheric alteration of the new lava flows, makes this site a prime Venus analog to Venus. Our goals have been to image the young basaltic lava fields, to image the fresh fumaroles and their deposits on the basaltic lava field, to image the superficially oxidized layers due to the hot gases (e.g., water), to image the hot lava surface (approximately 200-480°c) of the active vent of Litli-Hrútur (eruption terminated 2 days prior to our arrival) to obtain in situ emittance of the basaltic rock at Venus temperature. All this collected data will provide detailed spectral information and a deeper understanding of the surface composition of the studied lava flows. By comparing the field and laboratory datasets, we can assess the capabilities of the VEM instrument in distinguishing lava types, compositions, and Fe-content. This work will lay a foundation for the detailed interpretation of spectra from Venus and is vital preparation for the scientific goals of the NASA VERITAS and ESA EnVision missions.

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Layered outcrops on Mars give insights into the planet's glacial history

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Mars is thought to have been a hyperarid desert for at least the last one billion years of its history. Water is locked up in the two polar ice caps, ground ice, and widespread debris covered glaciers in the mid-latitudes. Layers expressed by the polar caps are thought to record the most recent climate cycles of Mars – up to a few tens of Ma (Becerra et al., 2017). The debris covered glaciers are thought to be tens to hundreds of millions of years old, and potentially record a deeper climate record (e.g., Hepburn et al., 2019). Here, we report on the widespread occurrence of layered outcrops intimately associated with ice deposits in the mid-latitudes. For the first time we map the global extent of these deposits previously only reported in patches (Baker and Head, 2015; Carr, 2001; Morgenstern et al., 2007; Soare et al., 2013). We explore the relationship between these layered outcrops, debris covered glaciers and more recent ice deposits by exploiting images and elevation data from the High Resolution Science Imaging Experiment (HiRISE) at 25 cm/pixel (McEwen et al., 2007), Context camera (CTX) at 6 m/pixel (Malin et al., 2007) and Colour and Stereo Imaging System (CaSSIS) at 4.5 m/pixel (Thomas et al., 2017). We use topographic data from HiRISE stereo-images to study their detailed geometry. We find that these layered outcrops are extremely widespread in the martian mid-latitudes and have similar morphology in both the northern and the southern hemisphere pointing to a globally relevant process. We find these layered outcrops are conformal to topography and on low slopes. We hypothesise that they are patchy remnants of the basal layers of past ice (or ice-rich) deposits. On Earth, basal layers within glaciers can be relatively lithic-rich compared to the bulk composition of overlying ice (Shaw, 2008). The layered outcrops on Mars could comprise mixtures of lithics and ice, though the ice-lithic ratio remains uncertain. In Hellas Basin the layered outcrops are continuous with layers expressed in the hosting icy units, whereas elsewhere on Mars they are surrounded by younger icy deposits. We infer that in Hellas Basin we are seeing a snapshot of how these outcrops were formed elsewhere on Mars, but due to Hellas' unusual setting/climate, it is only here that the outcrops are preserved within their host ice. We hypothesise that these layered deposits inform us about the former extent of mid-latitude ice caps or ice sheets on Mars. Therefore, these layered outcrops could give information of Mars climate beyond that obtainable by studying the polar caps and other well-studied mid-latitude ice deposits.

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Cryogenic Raman signatures of hydromagnesite-rich samples from Lake Salda: understanding the modern geochemistry and life potential of Mars

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The search for water, organics and potential signs of life on Mars has been a major topic in planetary sciences and astrobiology. Mars 2020 of NASA and the upcoming ExoMars of ESA are two robotic missions that will specifically assess the life potential of Mars by investigating past aqueous environments of the planet and searching for biological signatures, using the latest generation of exploration rovers. The Mars 2020 Perseverance rover of NASA is currently investigating the Jezero crater, an open-basin paleolake featuring a well-preserved delta with clays and carbonates (Grant et al. 2018). The orbital detection of a carbonate-bearing unit ("marginal carbonates") comprising hydrated Mg-carbonates in the inside margin of the crater is particularly noteworthy. A hypothesis suggests that these deposits include authigenic carbonates, precipitated in the near-shore environments of the lake (Horgan et al. 2020). On Earth, lacustrine (authigenic) carbonate deposits often form in connection with microorganisms. Some carbonate minerals (e.g., Mg- and Ca-carbonates) are found to be able to preserve biological signatures by trapping them inside layered deposits (*e.g.,* stromatolites). Some of the oldest fossils on Earth, which show the signatures of microorganisms preserved on sedimentary rocks confirm the preservation ability of carbonates (Allwood et al. 2007).

Lake Salda, Turkey, is a relevant Mars analogue site for the marginal carbonates identified in the paleolake of Jezero crater. In Lake Salda, the evaporation of alkaline Mg-rich lake waters induces the precipitation of carbonate minerals by forming mostly hydrated Mg-carbonate called hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$). In particular, hydromagnesite-rich stromatolites actively grow along the shorelines of the lake (Braithwaite & Zedef 1996). Understanding the interplay between environmental, chemical, and biological processes that are involved in these rock formations is an important focus of study (Balci et al. 2020). To support ongoing and upcoming Mars missions, the carbonate samples from Salda Lake also need to be comprehensively examined by the spectroscopic instruments included in the rovers, such as Raman spectrometers at Mars-relevant temperatures.

In this study, we characterise various hydromagnesite-rich samples from the Lake Salda, such as gravels and lake sediments using various analytical techniques, including Raman spectroscopy. The identification and assignment of the mineral phases, as well as organic components enable us to resolve the geochemical conditions of the Salda lacustrine settings. Furthermore, we report on a spectral database of hydromagnesite powders, aqueous solutions of hydromagnesite and hydromagnesite-rich sediments under Mars-simulated conditions of temperature using cryogenic Raman spectroscopy. The phase transformations of water/ice and hydrated carbonates, as well as the entrapment of potential organics in these matrices are under investigation. The collection and interpretation of these spectra from the Mars analogue samples of Lake Salda can contribute to our understanding of the Mg carbonate deposits in Jezero crater and to identify any life signature if it has ever existed on Mars.

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Insights into formation of impactites in small impact structures – shocked quartz from the Tvären impact structure, Sweden

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There are eight recognized impact structures in Sweden that represent a range in sizes and formational ages, from ~1 km to over 50 km in diameter and late Ordovician in age to the youngest ones formed during the Cretaceous (Holm-Alwmark 2021). One of these, Tvären (2 km in diameter), located in the Södermanland province of southern Sweden, remains poorly studied to this day. Earlier published works include papers on its general geology (Lindström *et al.* 1994), sedimentology (Ormö *et al.* 2007), and geophysics (Törnberg & Sturkell 2005); however, there is very little published information available on shock/impact metamorphism from Tvären. To this day the only unequivocal evidence of impact ever presented from Tvären is a single microphotograph of a quartz grain with proposed planar deformation features (PDFs; 'shocked quartz'; French & Koeberl 2010) published by Lindström *et al.* (1994). However, the putative PDFs were neither measured nor indexed, so it is unclear whether they correspond to rational crystallographic planes typical for shocked quartz (e.g., Stöffler & Langenhorst, 1994).

Here we present preliminary data from a petrographic study of the Tvären-2 drill core, obtained from the NW part of Tvären Bay, in October 1991 (Lindström *et al.* 1994). Our investigation confirms that shock features (PDFs; Fig. 1) and planar fractures (PFs), occur in quartz grains on depths from 166.9 to 215.7 m in various lithologies (mudstone, limestone, and polymict lithic breccia). Quartz grains with shock features range from 20–90 µm in size and are present in both matrix and bedrock fragments. Preliminary findings suggest PDFs mostly occur in angular grains within lithoclasts, while PFs can be found in rounded solitary grains. The presence of both PDFs parallel to $\{10\bar{1}2\}$ and PFs indicates a wide pressure range – from 5 to 25 GPa of investigated shocked quartz grains (Stöffler & Langenhorst 1994).

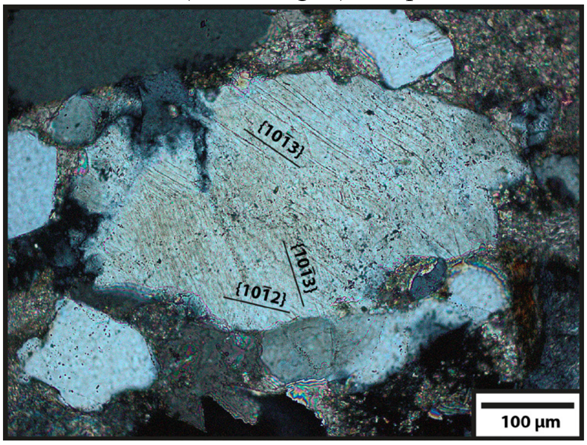

Fig. 1. Three sets of PDFs in quartz from the Tvären-2 drill core (cross polarized light). The grain has a total of eight sets of PDFs that were found during the U-stage study (three $\{10\bar{1}3\}$-oriented sets, two $\{10\bar{1}2\}$-oriented sets, one $\{10\bar{1}1\}$-oriented set, one $\{10\bar{1}4\}$-oriented set, and one unindexed set.

Our research aims to provide in-depth analysis of shock features in impactites formed under various shock pressure conditions, including the low-pressure regime, within a unique small old impact crater.

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RIMFAX ground penetrating radar observations of subsurface structures in Jezero Crater, Mars

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NASA's Perseverance Rover is exploring the Jezero Crater carrying the RIMFAX ground penetrating radar. RIMFAX has acquired a continuous subsurface radar image at 10 cm intervals along the rover's > 20 km long groundtrack across the Crater Floor and the Western Fan deposits, probing depths of ~20 m below the rover. RIMFAX provides subsurface context for better understanding the depositional environments of the major units that the rover has examined on the mission so far.

RIMFAX imaged the Crater Floor where the overall subsurface layering structure appears to generally be horizontal along rover traverses in the Máaz formation parallel to the boundary of the Séitah region. However, when the rover path becomes more perpendicular to the boundary of Séitah the layering structure appears to dip downward away from the Séitah area at angles of up to 15°. These dipping layers are observed all around Séitah and have been interpreted to be either deltaic foresets or from an igneous intrusion uplift (Hamran et al. 2022).

At the boundary between the Jezero Crater floor and the Jezero Western fan, RIMFAX detects a distinct subsurface discontinuity (Paige et al. 2023). The observed subsurface layering relationships are interpreted to demonstrate the presence of an angular unconformity at the base of the fan, reflecting erosion of the crater floor prior to the deposition of younger stratified successions of the lower fan.

RIMFAX can estimate the density of the subsurface rocks by measuring the radar velocity in the ground (Casademont et al., 2023). The velocity is measured by matching hyperbolic shapes to point scatterers in the subsurface. RIMFAX measures average densities from 3.0 to 3.3 on the Crater Floor (Casademont et al., 2023).

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Radar investigation of the subsurface of sorted stone circles on Svalbard, Norway – an analog study for mars

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We use Ground Penetrating Radar (GPR) and orbital polarimetric Synthetic Aperture Radar (SAR) to characterize the subsurface of different sorted stone circles' morphologies. Stone circles are a form of sorted patterned ground in the Arctic regions. They are characterized by their circular shape (Kessler et al., 2001) and a fine-grained center bordered by coarser-grained material (Hallet, 1998). Here, we investigate the subsurface of sorted stone circles located on Kvadehuksletta, at the northwestern tip of the Broegger Peninsula, located at the west coast of Spitsbergen (Hauber et al., 2011 and Sander et al. 2021). Radar instruments help visualize the subsurface, successfully detecting and mapping buried ice and sediments in permafrost (Brandt et. al, 2007). This work compares the size and depth of different sorted stone circles' morphologies, including the stone circle wall and its active layer. This is relevant to planetary geoscience as networks of possible sorted stone circles have been observed on the margin of an erosional channel known as Lethe Vallis in Elysium Planitia on Mars (Balme et al., 2009). Additionally, identifying and characterizing the locations of shallow (0–10 m) subsurface ice on the Moon and Mars is important for addressing high-priority science and human exploration objectives (MEPAG, 2019 and LEAG, 2016). Through assessing the capabilities of these radar systems to characterize stone circle subsurface morphology and ice, we are more prepared for future investigations on Mars.

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Svalbard permafrost landforms as analogues for Mars (SPLAM): An overview of scientific outcomes and new lines of research

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Earth-analog studies for Mars in Svalbard

On Mars, non-polar ice deposits are important records of the climate and constitute an important resource for future in-situ resource utilization (ISRU) and vital targets for astrobiological investigations. Many of these ice deposits are associated with landforms that resemble glacial and periglacial surface features on Earth. It is therefore mandatory to investigate analogous landforms on Earth in order to develop working hypotheses for the origin of those landforms on Mars. Moreover, a number of landforms on Mars have been hypothesized to have formed by the action of liquid water in the last few millions of years, and possibly even until today. Such landforms include, but are not restricted to, gullies, patterned ground, and flow lobes on slopes, which have been interpreted as evidence for debris flows, freeze-thaw cycles, and solifluction, respectively. However, under current conditions (low T, thin atmosphere), liquid water is not stable at the surface of Mars, unless special conditions are met. Thus, making reconstruction of the planet's recent climate history challenging. Furthermore, as morphologic interpretations are typically not unambiguous (the concept of equifinality), most if not all of these landforms may also have formed by alternative "dry" processes. Fieldwork on terrestrial analogues is considered essential to understand planetary landforms and their evolution, as the Earth is still our "reference" to understand geologic processes. The knowledge gained by fieldwork helps to establish multiple working hypotheses and test them. Here we will present a number of scientific outcomes from our field campaigns between 2008 up until present.

Monitoring physical changes in the Arctic landscape

The Arctic physical landscape is undergoing significant changes in the wake of global warming. This is particularly evident on Svalbard that is dominated by glaciers and are underlain by permafrost. Glaciers are receding, and permafrost is degrading. The former has a significant ecological impact, and the latter pose challenges to infrastructure and people. The changing weather patterns also increase the risk for debris flows. To be able to observe and quantify these changes we need to monitor the effects over varying temporal and spatial scales. Within the project we are monitoring several physical settings such as the degradation of ice-cored moraine (Kongsfjorden), debris flows (Hanaskogdalen) and the dynamics of patterned ground (Kvadehuksletta). To date, we have field time series that extend since 2008 and onwards for debris flows, and since 2011 and onwards for ice-cored moraines and patterned ground. Field monitoring has been accompanied by remote sensing analysis of publicly available aerial images (1966 and 1990), and two flight campaigns. In 2008, we acquired high-resolution aerial images (HRSC-AX, 20 cm/pixel) from which we derived DEMs (grid spacing 50 cm). A second flight campaign in 2020 using the Modular Airborne Camera System (MAC-Polar) repeated the coverage of our study sites and enables direct comparison of landforms and identify possible changes. The work will be followed by a third flight campaign in 2024 which will enable a higher temporal resolution of surface changes. Images and DEMs serve as a basis for our past and future field investigations. Here we present some preliminary results from these investigations.

Formation and origin of meteorites – A case study of the "Lieksa 4" iron meteorite and Haverö ureilite

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Introduction

Meteorites are some of the oldest materials known to us, with the oldest ones originating from ~4.56 Ga ago. Though rare, iron meteorites are derived from at least 50 different parent bodies, but the number might be much higher (e.g., Wasson 1990). Iron meteorites consist mainly of iron-nickel alloy, and they are believed to represent the core materials of differentiated asteroids shattered by impacts. Ureilites are carbon-rich ultramafic rocks that represent the mantle of a partially melted asteroid (e.g., Goodrich 1992, Mittlefehldt et al. 1998, Goodrich et al. 2004). The study of meteorites can provide us information about the processes that took place in different stages of the formation and evolution of the Solar System, including planet formation and differentiation, and collisional events between interplanetary objects. In my doctoral research project, I will do a detailed study of the iron meteorite "Lieksa 4" (Kotomaa 2022, Kotomaa et al. 2023) and the Haverö ureilite (e.g., Neuvonen et al. 1972, Vdovykin 1976) with the hopes that this research will offer us new insights into the study of these processes.

Future work

The purpose of the project is to study the crystallization courses, thermal histories, parent bodies and origin of iron meteorites and ureilites via case studies of the "Lieksa 4" iron and Haverö ureilite using different geochemical methods including μ-XRF, EPMA, FE-SEM, EBSD, optical microscopy and cosmogenic radionuclide dating. Though not officially named yet, the "Lieksa 4" iron is most likely an ungrouped iron meteorite consisting of ≥ 3wt% phosphorus, which makes it a unique find. Furthermore, the Haverö ureilite has never been fully studied with modern scientific methods apart from its carbon phase (e.g., Goresy et al. 2004, Ferroir et al. 2010). The objective of the doctoral research project is to collect and analyze more data of the "Lieksa 4" and Haverö meteorites to understand better the origin and history of meteoritic material in the Solar System.

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Water retention mechanisms on the near surfaces of Mars: gravimetric and cryogenic vibrational spectroscopy approaches

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The complex aqueous alteration on ancient Mars is associated with the presence of phyllosilicate clay minerals, iron hydroxides, sulfates, salts, and other types of hydrated minerals on the Martian surface today (Carter, Loizeau et al. 2015). Fe(III)-rich smectite clay, known as nontronite, and Cl-type salts have been detected all over the planet Mars by orbit analyses in varied weight percentages (wt.%). For instance, nontronite was detected at approximately 35 wt.% at Gale Crater (Gavin and Chevrier 2010, Bishop, Yeşilbaş et al. 2021). Nontronite is a swellable aluminosilicate-layered clay mineral. Its ability of swelling and the amount of absorbed water are controlled by factors such as the interlayer cations (*e.g.*, Na^+, Ca^{2+}), type of co-existing brines, humidity, and temperature. The interactions of nontronite with hygroscopic salts (*e.g.*, chlorides, perchlorides) on the near surfaces of Mars could lead to the formation and retention of liquid water through deliquescence and the formation of thin water-ice film on clay minerals following the Martian diurnal cycles. These salty solutions could potentially be retained within the interlayers of nontronite even well below 0 °C (Gavin and Chevrier 2010, Yeşilbaş and Boily 2016). Especially, it is believed that the formation of these brines in sulphate and Cl-salt mixtures on the near surfaces of Mars may play a significant role in Recurring Slope Lineae (RSL) geological structure formation during Martian early springs and summers (Bishop, Yeşilbaş et al. 2021).

This project reveals the roles of nontronite to form and retain liquid salty water from -100 to 20 °C, mimicking the conditions on the Martian subsurface. To achieve this, we investigated (i) the water sorption and deliquescence in our Martian analogues of nontronite-salt mixtures (*e.g.*, NaCl, $CaCl_2$, and $CaSO_4$) using the Dynamic Vapour Sorption (DVS) technique and (ii) the ability of nontronite to retain liquid salty water at various temperatures between -100 and 20 °C by probing the H_2O vibrational modes using Raman spectroscopy. Our preliminary findings suggest that the presence of hygroscopic salts enhances the water sorption of nontronite, even at low water vapour pressures. Our Raman results revealed that nontronite in $CaCl_2$ preserved water better than other nontronite-salt mixtures (*e.g.*, NaCl, $MgCl_2$). We shall further operate molecular dynamics (MD) simulations to investigate the interactions of liquid salty water mixtures in interlayers of nontronite at the molecular level and investigate their further expansion capabilities. This research provides fundamental information to understand the aqueous (geo)chemical history of Mars and could help to search for potential water resources on the near surfaces of Mars, where it could be of interest for the upcoming ExoMars rover mission.

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Evolution of fluvial, and possible lacustrine or marine activity in Nilosyrtis, Mars: A geomorphological and geochemical analysis

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Introduction

The quantity and coverage of high-resolution remote sensing datasets of the Martian surface have significantly increased during the last couple of decades. Today, Mars' surface is defined as a cold hyper-arid desert, but geomorphological and geochemical observations have shown that in the past, vast amounts of liquid water were stable at the planet's surface (Di Achille et al. 2006, Erkeling et al. 2012, Hauber et al. 2009). The spatiotemporal evolution of hydrological events, like the formation of lakes and river systems is however not well understood (Erkeling et al. 2012). There have been many studies to classify, map and examine the distribution of standing bodies of water in craters i.e. paleolakes on Mars (Cabrol & Grin 1999, Grindrod et al. 2018). Spectral imaging of the sediments have confirmed chemical altering of the surface material in the form of clays, sulfates and salt crystallizations. These secondary minerals are the result of hydrous chemical weathering and evaporation (Forget et.al. 2008, Grindrod et.al. 2018). Detailed mapping has been done for several of the cataloged sites of possible paleolakes and deltas in the planetary science community (Cabrol & Grin 1999, Cabrol & Grin, 2001). This is an ongoing effort and there are still many sites and regions that have not been studied. Nilosyrtis Mensae represent such an area, which is situated at Mars' dichotomic boundary between 30° and 40°N.

Aim of project

A geomorphological map of a selected crater basin in Nilosyrtis Mensae aims to decipher key features such as sedimentary fans and channelized features. Using ArcGIS Pro and mapping methods used in planetary cartography (Hargitai, 2019), high resolution satellite data from Mars Reconnaissance Orbiter (CTX, HiRISE) and other relevant datasets will be used to investigate and analyze the crater basin. The project seeks to uncover the spatiotemporal development of observed features, which will give important insights into the hydrogeological history of the basin. The project will also contribute to the understanding of past geological and climatological history. Additionally, a geochemical investigation of the same crater basin will be carried out to further strengthen the project's hypothesis of observed landforms in regard of their genesis, using hyperspectral CRISM-data.

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Slope failures and surface degradation along the Nilosyrtis Rupes, Mars: Putative slab avalanches and sublimated terrain

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New data acquired from Mars orbiters and landers have led to major advances in planetary science during the last two decades, allowing for more detailed interpretations of the geological and climatic history of Mars. With the help of gamma spectroscopy, high-resolution satellite images of polygon-patterned, sorted, and sublimated ground, as well as field samples of near-surface ice, we know that much of Mars' water reservoir is bound as water-ice in a thick latitude-dependent mantle layer (LDM) (e.g., Mustard et al., 2001). At latitudes poleward of 30°-45°, this ice-rich LDM covers the older terrain and is in turn overlain by a 10–20 cm thick layer of lag deposits, effectively protecting the underlying ice from fully sublimating under the low atmospheric pressure (Head et al., 2003; Kreslavsky and Head, 2002). Deposition of atmospheric ice and dust during periods of high obliquity has alternated with erosion and sublimation during periods of moderate or low obliquity during the last billion years or so. By studying the LDM and its degradation, we can gain insight into how seasonal variations and Milankovitch cycles could affect the possibility and extent of atmospheric precipitation and the stability of near-surface water-ice on Mars (e.g., Laskar et al., 2002).

The aim of this study is to gain further insight into the LDM properties and the spatial distribution of sublimation-induced erosion as well as the presence of mass movements that might have a mechanism similar to slab avalanches on Earth. The latter may indicate internal layering in the upper, dust and ice-rich sediments (Schon et al., 2009). HiRISE and CTX data of small-scale features of the LDM-covered Nilosyrtis Rupes shows an aspect dependency of sublimated terrain and possible slab avalanches in north and northeast slope directions, which is consistent with previous mapping of glacial structures in the area (Saar, 2022). In this study, outcrops of possible sedimentary layering and large fracture lines were observed. The fracture lines predominantly lie parallel to the Nilosyrtis Rupes in a northwest and southeast direction. The orientation of these fractures favors slope instability along the ridge and cuts through both eroded and smooth terrain. Triggering factors for these relatively new fracture lines are discussed based on two hypotheses: volume collapse caused by long-term sublimation during the current moderate obliquity angle, or geologically recent seismic events. This is the first time such failures have been studied in detail on Mars.

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Potential glacial landforms in Nilosyrtis Mensae, Mars: A qualitative geomorphological mapping and interpretation of an impact crater

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The Martian mid-latitudes north of the dichotomic boundary present a captivating array of glacial and periglacial features, with striking geomorphological resemblance of features observed on Earth. Glaciers on Mars are often found in and around impact craters, where the unique topography and crater shape can trap and preserve ice and associated deposits. In the context of the prevailing hyper-arid climatic conditions on recent Mars, glaciers were considered predominantly as cold-based; however, recent research has hinted towards the existence of warm-based glaciers within limited temporal time spans (Butcher et al. 2021; Gallagher et al., 2021; Woodley et al., 2022).

This study focuses on the geomorphological mapping of an unnamed impact crater situated in the Nilosyrtis Mensae region on Mars, aiming to discern potential glacial landforms and investigate the plausibility of a warm-based glacier's historical presence within the study area. The investigation employs a comprehensive analysis of CTX- and HiRISE-images to identify and map various landforms within the target region. Among the twelve identified landforms, seven exhibit characteristics suggestive of glacial or periglacial origins, encompassing glacial-like formations (GLF), concentric crater fill (CCF), and thermal contraction polygons.

Furthermore, our observations of eroded crater walls and the degradation of the crater rim raise intriguing possibilities of the presence of basal sliding and glacial abrasion. These observations may suggest the existence of warm-based glaciers in the study area at some period in the past, challenging conventional assumptions about Martian glacial behavior. However, the mechanisms underlying the formation of a warm-based glacier in the specific region remain enigmatic, warranting further in-depth research to explain this phenomenon. This study thus underscores the need for continued investigation to unravel the complexities of Martian glacial processes and their implications for our understanding of the Mars' geological history.

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Spectroscopic investigations of gypsum-salt interactions across Mars relevant temperatures: implications for modern Mars geochemistry

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Calcium sulphate hydrates, including gypsum ($CaSO_4 \cdot 2H_2O$) and bassanite ($CaSO_4 \cdot 0.5H_2O$), as well as their dehydrated form, anhydrite ($CaSO_4$), are commonly found together in many terrestrial settings, especially in marine evaporative deposits of the Earth. These Ca-sulphate minerals have also been detected at several locations on Mars, including gypsum dunes in the North Poles of Mars by OMEGA/Mars Express in Olympia Undae(Langevin, Poulet et al. 2005), gypsum-bassanite-anhydrite assemblages in the Gale Crater by the Chemistry and Mineralogy Instrument (CheMin) X-Ray Diffraction (XRD) instrument(Vaniman, Martínez et al. 2018), as well as bassanite detected in the Mawrth Vallis(Bishop, Lane et al. 2014). The dehydration of gypsum into its dehydrated phases of bassanite and anhydrite is highly responsive to environmental factors such as changes in relative humidity, temperature, and pH. For instance, gypsum can lose its structural water (i) when heated above ~95–100 °C or (i) mixed with salts at ~83 °C, which both enable the transformation of gypsum to bassanite and then to anhydrite(Bishop, Lane et al. 2014). Formation pathways between these Ca-sulphate phases are still complicated, and there are very few studies focused on the gypsum-Cl salt interactions at relevant Mars temperatures. Additionally, the CheMin instrument on the Curiosity rover faced challenges in distinguishing gypsum, bassanite, and anhydrite depending on the instrument's resolution limit because the crystal structure of bassanite and soluble anhydrite exhibits strong similarities. A study from (Vaniman, Martínez et al. 2018) suggested that bassanite and the other dehydrated Ca- sulphate mixtures' detection may depend on the dehydration of gypsum in the warm sample chamber of CheMin during the XRD measurements over Martian soils.

In this study, we address the need for more laboratory experiments to evaluate spectral datasets collected from orbit. This study focuses on the gypsum and Cl-salt interactions across an extended temperature range (-90 to 400 °C) using various spectral techniques (VNIR, mid-IR, Raman, XRD) and thermal analyses (e.g., Temperature Programmed Desorption (TPD)-FTIR, Thermal Gravimetric Analyses (TGA)). Our results reveal that water/rock ratio, applied heating/cooling rates, and temperature influence the formation of different calcium sulphate phases, and the detection of these phases depends on the technique used. As a noteworthy change, our XRD analyses revealed the formation of gypsum-bassanite from gypsum/$CaCl_2$ mixtures at elevated temperatures, which was not observed from pure gypsum or gypsum/NaCl mixtures. While the transition temperature in our experiments was too high to compare gypsum transformation to bassanite with the CheMin instrument, a slower heating rate and higher salt concentrations may facilitate this transformation at lower temperatures(Bishop, Yeşilbaş et al. 2021). VNIR reflectance spectra of gypsum measured under Mars-like conditions revealed sharpened structural H_2O bands at nearly the same wavelengths as room-temperature spectra(Yeşilbaş, Vu et al. 2022). This confirms the orbital detection of gypsum on Mars. Accurate characterization of gypsum and the formation pathways of its dehydrated phases will help to constrain the aqueous and geochemical history of Mars and assess potential water resources for future human missions to Mars.

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Scarce shock metamorphic indicators in mesosiderites and implications for timing of deep burial

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Introduction

Mesosiderites are some of the more puzzling meteorite groups—they are impact breccias composed of one part core-derived metal and one part crustal lithologies, such as basalt and pyroxenite, yet include few or no mantle materials. Many scenarios have been suggested for their formation (Hewins 1983 and references therein), most containing a collisional element—however, despite being impact breccias, mesosiderites show very limited signs of shock metamorphism (Haack et al. 1996). Low shock levels has been attributed to early burial on the parent body, thus protecting the material from impact overprinting (Haack et al. 1996).

Aim and results

To investigate whether shock features in minerals are missing from the whole meteorite group, we studied over 40 different mesosiderites with a focus on possible shock features. Our initial findings show that heterogeneous melt textures are common, while regular shock metamorphic indicators—such as planar fractures, planar deformation features, mosaicism, and high-pressure polymorphs—are generally not present. Among the melt textures we have observed are quenched chromite-silicate assemblages, quenched troilite-silicate assemblages, and quenched silicate melt pockets. The overall textures of the different melts seem to indicate that they have formed in-place, rather than having been incorporated in the breccias as clasts. Annealed troilite/metal/chromite veinlets are also common, indicating earlier silicate darkening by shock. Graphic troilite-pyroxene textures in the cores of olivine pseudomorphs may also indicate shock melting between olivine and troilite—this interpretation is supported by the finding of fine-grained (quenched) varieties of these textures in several mesosiderites.

Discussion and conclusions

High shock pressures and high overall post-shock temperatures that allow the formation of the melts should also have induced the development of solid-state shock features in minerals, the fact that the latter are largely absent is puzzling. We argue that a combination of two factors may be at play: (1) Mesosiderites experienced thermal annealing for a very long period of time, erasing most shock indicators—similar to what was proposed for equilibrated ordinary chondrites by Rubin (2004)—and (2) it is possible that shock impedance plays a role in moderating effective shock pressures in silicates, considering the mixture of materials with vastly different densities in mesosiderites (e.g., Wittmann et al. 2021). Assuming this is correct, we argue that it is possible that mesosiderites were buried later than previously thought.

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Session 36
Scientific drilling in a Nordic perspective: Achievements and plans

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Exploring the transition from continental breakup to a passive margin during the opening of the South Atlantic

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The Early Cretaceous opening of the South Atlantic (SA) Ocean resulted from lithospheric extension and the breakup of the Pangaea supercontinent, leading to a major tectonic reconfiguration that had a significant impact on Earth's oceanographic and climate evolution. This rifting was accompanied by extensive intrusive magmatism and extrusive flood basalts, identified as seaward dipping reflectors (SDRs) and lava flows, forming the South Atlantic (SA) Large Igneous Province (LIP). Nonetheless, the nature of the processes that led to continental breakup remains controversial, and the environmental impact of these events is not yet fully understood. Only a handful of sites have cored SA Cretaceous and volcanic rocks, and none have drilled the Argentine Continental Volcanic Margin (ACVM).

In this context, we have mapped out the extensive distribution of the volcanic complexes on the ACVM based on a regional grid of industry and academic seismic reflection data. As a result of the interpretation of the new seismic data, we propose to sample the volcanic complex through scientific drilling. The drilling will sample the SDRs at two sites to determine their age and composition, aiming to better understand the chronology of South Atlantic opening, sources, and magmatic processes involved during breakup. This will help test the active vs. passive rifting hypotheses. Additionally, we will further investigate evidence for magma/crust interaction and the impact volcanism had on climate through delivery of gases to the ocean and atmosphere.

Drilling history of Greenland

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The present review is a follow-up on recent papers on the mineral and petroleum exploration history of Greenland (Christiansen 2021, 2022). It provides a first overview of all drilling activities – for mineral and petroleum exploration, and for science − in Greenland through history with the oldest preserved core from 1948 (Christiansen et al., manuscript). Results from drilling and access to preserved material are important for future research and resource exploration. Almost all drilling projects have been documented with details on companies/operators, targets, commodities, deposits, regions, year, depth ranges, numbers, and cumulative depths together with key references.

For mineral exploration drilling, the key numbers are: 1000 km, 264 projects, and ~7000 holes. For petroleum exploration drilling, the key numbers are 58 km, 10 projects, and 39 holes. For onshore scientific drilling, the key numbers are 12.5 km, 22 projects, and 105 holes. For offshore scientific drilling, the key numbers were 10 km, 6 projects, and 35 holes.

The level of mineral drilling activities has varied significantly over time. The main activities have been in relation to specific mines and deposits to outline and document resources. Approximately 50 companies have reached a drilling phase in their exploration, and these are listed together with a ranked list of drilling on specific deposits. Most drilling was carried out by Canadian, followed by Danish/Greenlandic, Australian, and UK-based companies. The petroleum drilling was the outcome of specific licensing rounds, in some short periods with a high activity level, now completely stopped. The scientific drilling has changed due to various strategies and agendas from academia, authorities and other sponsors.

Compared with other countries like Norway, Sweden, UK, and Denmark, the number of drill holes is limited. Greenland has experienced long periods with low activity without or only with a few mines making it difficult to establish and maintain a permanent service industry. The cores and results from previous drilling have a high value and should be preserved for future research, exploration, and other future activities. Compared to other countries Greenland has a big task to develop and maintain a drill core database and make core material available for new users.

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Koillismaa Deep Hole: a window into the Archean-Proterozoic Fennoscandian Shield

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Context

Deep (>1 km) drillholes are indispensable for gaining insights into the Earth's subsurface and associated resource potential but their availability remains notably scarce within the Fennoscandian Shield. Particularly, these deep drillholes can provide substantial complementary assets when geological and geophysical research increasingly explores the deeper parts of the Earth's crust.

Exploration history

The Koillismaa area in central Finland has been a subject of scientific and economic research since the 1970s, primarily driven by the presence of the 2.45 Ga Koillismaa and Näränkävaara mafic-ultramafic layered intrusions and their associated Cu-Ni-PGE, V-Ti-Fe mineralizations. A remaining open question revolved around the origin of the 60-kilometer-long Bouguer gravity anomaly connecting these intrusive complexes. Potential field modeling has indicated that the anomaly's source lies at depths between 1 to 3 km, but direct evidence was lacking until recently. To address this question, GTK initiated the Koillismaa Deep Hole project in 2020, originally aiming for a 3 km deep borehole that could sample this anomaly. However, drilling encountered significant challenges caused by highly fractured rocks. Consequently, the borehole only reached 1724.7 m after four months of drilling. A side-track hole attempt faced similar issues and drilling was interrupted at 1594.9 m depth.

Major findings

The uppermost 658 m of the drillhole penetrated Archean (2.9–2.8 Ga) tonalite–trondhjemite–granodiorite (TTG) gneisses. The central section (658–1410 m) consists of homogeneous granites and quartz diorites dated to ~2.44 Ga. Below 1410 m these granites are alternating with mafic-ultramafic rocks. Diabase dikes of variable width and calc-alkaline affinity crosscut all other rock types. Petrophysical tests and geochemistry analysis proved that the geophysical anomaly is attributed to the presence of mafic-ultramafic rocks related to the prominent outcropping intrusions of the Tornio-Näränkävaara belt. Additionally, the granites exhibit an A-type geochemical signature and possess compositional characteristics that strongly suggest they are the result of AFC processes involving the mafic melts and the Archean crust. The relatively large volume of coeval 2.44 Ga granitoids further emphasizes the bimodal character of the early rifting events within the Archean crust in the Koillismaa area. Proterozoic granitoids are not observable from outcrops in the vicinity of the drilling site, although known from other parts of the region. Pre-drilling seismic survey and AMT soundings also indicated the presence of reflectivity and conductivity anomalies that can be associated with the mafic-ultramafic intrusions. New seismic data acquired in 2022 provided further 3D constraints on the shape of the intrusion, which was also able to image the cross-cutting dikes. Furthermore, the drillhole is intercepted by multiple strike-slip faults and zones of prophylitic alteration resulting in high porosity and permeability in the granitic rocks, opening new perspectives for deep geothermal energy exploration. Some of these features were imaged by the walk-away multi-azimuth VSP survey acquired with the Distributed Acoustic Sensing (DAS) technology.

Future research

The Koillismaa Deep Hole has already yielded valuable insights into the formation and evolution of the Archean-Proterozoic Fennoscandian crust. Currently, the drillhole is evolving into an exceptional testbed for various geophysical and geological exploration techniques employed in numerous projects conducted by GTK and its partners. Complete 50 mm diameter cores are available for the entire length of the drillhole. Presently, the drillhole is open to a depth of 1150 m and thus can be accessed for future scientific investigations.

The chemostratigraphy of the Paleocene–Eocene infill of the Modgunn hydrothermal vent complex on the Norwegian continental margin

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The Modgunn hydrothermal vent complex (HTVC) is one of hundreds of explosion craters that pepper the Vøring and Møre basins on the Norwegian continental margin. These HTVCs are rooted in shallow sill intrusions from the North Atlantic Igneous Province (NAIP) and are evidence of the explosive release of volatiles created by both contact metamorphism of country rock and the degassing of magma. Many of these craters appear to terminate close to the Paleocene–Eocene boundary in seismic sections, which led to the hypothesis that thermogenic degassing may have instigated and/or prolonged the Paleocene–Eocene Thermal Maximum (PETM) at ~56 Ma (Svensen et al. 2004). The International Ocean Discovery Program (IODP) Expedition 396 visited the Norwegian continental margin in 2021 to drill key NAIP localities. The Modgunn HTVC is on the edge of the Vøring Plateau with very little sedimentary cover, allowing for multiple holes to be drilled in a transect across the vent (Sites U1567-U1568). Initial isotopic and biostratigraphic findings placed the vent infill to just before and during the PETM, corroborating the hypothesis of a link between thermogenic degassing and the intense global warming (Berndt et al. 2023). The Modgunn locality is a perfect locality for geochemical studies across the Paleocene–Eocene boundary, as the rapid infill of the vent crater allows for high-resolution study of sediments in close proximity to NAIP activity.

Here we present a detailed chemostratigraphy of the Modgunn vent infill, expanding on the existing data set to identify the onset of the PETM in four of the five holes. Geochemical analyses of volcanic ash layers suggests several distinct populations from proximal to distal source within the NAIP. The occurrence of glendonite crystals in the Modgunn vent infill strata, a pseudomorph of the mineral ikaite, suggests cold bottom waters in the Nordic Seas, suggesting extremely stratified conditions in these restricted seas. Exotic pore water chemistries within the vent infill indicate that ikaite formation may have been promoted by volcanic ash-rich strata. Magmatic proxies such as mercury (Hg) contents indicate that vent activity in very close proximity to the Modgunn HTVC continued during the PETM, further linking the emplacement of the NAIP to the hyperthermal conditions.

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Volcanic Forcing and Paleogene Climate Change (PVOLC): An international continental drilling program (ICDP) project in Denmark

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The main emplacement of the North Atlantic Igneous Province (NAIP) occurred during a period of sustained climate change in the Paleogene, punctuated by major global warming events such as the Paleocene-Eocene Thermal Maximum (PETM). This temporal correlation has led to the hypothesis that NAIP activity played a significant role in causing environmental disturbances. However, our current understanding of the timing and fluxes of magma emplacement are not sufficiently constrained to be able to rigorously test this hypothesis on the gradual Paleogene warming and/or the transient hyperthermal events such as the PETM. In order to properly evaluate any causal relationship, and to couple a causal link to a mechanistic understanding, a detailed high-resolution record that contains signals of both volcanic and climatic events is required.

The aims of the international continental drilling program (ICDP) PVOLC project are to complete two onshore boreholes in northwest Denmark that target a unique marine sedimentary archive containing >200 ash layers that covers almost all of the Paleocene and Eocene. Most of this sequence is exceptionally well preserved, but surface outcrops are deformed and discontinuous due to the effects of glacial tectonism. Hence, the need for drilling deeper into an undeformed succession. The acquisition of these core can address two fundamental research goals:

1) Understand what role the NAIP plays in driving climate, biotic, and tectonic changes in the Paleogene

2) Distinguish between different magmatic processes, such as explosive eruptions and contact metamorphic degassing, and assess whether there are contrasting effects in terms of environmental disturbances

The successful completion of the PVOLC project has the potential to greatly improve the relative timing of volcanism, biotic and environmental change, helping to unravel the direct and indirect effects that volcanic forcing has on the environment. The drilling sites are ideal because they contain numerous records of volcanic and environmental proxies and has been logistically proven in previous successful drilling campaigns, providing a high probability for success for a relatively modest budget. The target section contains evidence of global warming events on timescales from thousands to millions of years, providing the opportunity to establish the causes of such warming on a variety of timescales. Coupled with the international ocean discovery program (IODP) Expedition 396 to the mid-Norwegian continental margin and the upcoming ICDP Svalclime proposal to drill Paleogene strata in Svalbard, these localities will give extensive coverage of the Nordic Seas during this key time interval. This knowledge will then improve our understanding of other periods in Earth history where volcanic forcing of the climate has been suggested, and potential feedbacks for present day global warming.

Collisional Orogeny in the Scandinavian Caledonides (COSC): From start to finish

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The Swedish Scientific Drilling Program was initiated in 2007 via a feasibility study grant form the Swedish Research Council (VR). The grant had two aims, first to investigate Swedish interest to join the International Continental Scientific Drilling Program (ICDP) and, secondly, develop a strategy for initializing scientific drilling projects in Sweden and abroad. As work progressed within SSDP it became clear that control of a national drilling rig capable of coring to 2.5 km would be beneficial for flexibly executing drilling objectives. In 2009 VR approved an application from SSDP for the procurement of such an infrastructure, known now as "Riksriggen". In parallel, approval was granted for Sweden to join ICDP and a number of applications were submitted for ICDP planning workshops. In 2010 the COSC ICDP planning workshop was held in Åre with the aim to define objectives for drilling two 2.5 km deep boreholes in the Åre-Järpen-Mörsil area (Gee et al. 2010, Lorenz et al. 2011). Further applications to ICDP (full proposals), the Swedish Research Council and other funding agencies resulted in the COSC-1 borehole being drilled to 2.5 km near Åre in 2014 (Lorenz et al. 2015) and the COSC-2 borehole to 2.28 km near Mörsil in 2020 (Lorenz et al. 2022). COSC-1 was drilled into the high grade Seve nappe with the top c. 1700 m consisting mostly of sub-horizontal and shallowly dipping intermittent layers of felsic calc-silicates/gneisses and amphibolite. First signs of increasing strain appear shortly below 1700 m in the form of narrow deformation bands and thin mylonites. Below c. 2100 m, mylonites dominate and garnets become common. A transition from gneiss into lower-grade metasedimentary rocks occurs between 2345 m and 2360 m. The lower part of the drill core is dominated by quartzites and metasandstones of unclear tectonostratigraphic position that are mylonitized to varying degree. The lowermost 800 m can be interpreted as a thick shear zone. COSC-2 started in Ordovician turbidites and penetrated a c. 80 m thick Alum shale at about 800 m, interpreted as the main detachment. Onwards to about 1200 m, rocks consist mainly of basal conglomerates and mixed siliciclastics covered by Cambrian coarse-grained sediment gravity flows grading into finer-grained turbidites. Magnetite rich Precambrian granitic rocks with dolerite intrusions were expected to be encountered below 1200 m. Instead, Precambrian porphyries are found, intruded by dolerites. These dolerite intrusions are interpreted to be responsible for the pronounced reflectivity observed in the area down to 15 km. One remaining geophysical enigma is the depth to the source rocks that generate the pronounced magnetic high that characterizes this part of the Caledonides. The COSC operational phase ended with the COSC-2 sampling party in summer 2022, about 15 years after the project was sketched out, and with much of the research still to be conducted.

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Developing EGS in crystalline rock: lessons learned from two 6 km deep holes in Otaniemi, southern Finland

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St1 Deep Heat project drilled two deep boreholes to a depth of 6.1–6.4 km. The aim was to pilot EGS (enhanced geothermal system) in Finland and produce thermal power for the district heating network. The drilling encountered challenges but reached the desired depth where the temperature is over 100 °C. In EGS, the temperature of the fluid is raised by circulating the fluid between the injection and the production well. In Otaniemi, natural hydraulic conductivity at the depth of 6 km is low and had to be enhanced to reach sufficient conductivity. For this, two hydraulic stimulation campaigns were conducted, OTN-3 and OTN-2 in 2018 and 2020, respectively. The stimulations caused seismic activity around the wells with the largest event occurring during the OTN-3 stimulation, having a local magnitude of 1.9. With careful monitoring of seismicity using a traffic light system, larger events were successfully avoided. Despite the stimulation campaigns, sufficient hydraulic conductivity was not reached for commercial production, and the Deep Heat project was cancelled. At present, the scientific use of the deep drill holes is developed by an international team aiming to continue seismic, hydrogeological, microbiological and geothermal studies in the *DEEP EGS* project of the International Continental Scientific Drilling Program (ICDP).

A unique late Cenozoic archive of Greenland climate evolution recovered by IODP Exp 400

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When was the onset of glacial expansion in northern Greenland? And how has the Greenland Ice Sheet responded to past climate warmings? Motivated by these key questions IODP Expedition 400 drilled six sites along a transect covering the deep basin of Baffin Bay and the glaciated margin of north west Greenland. To obtain data capturing the late Cenozoic ice sheet history as well as gaining high-resolution paleo-oceanographic records, the campaign targeted four different settings of the continental margin succession: (1) A lower slope sediment drift - channel system; (2) Aggrading shelf units of the Melville Bugt trough-mouth fan; (3) Mounded contourite deposits buried by early glacigenic progradation; (4) Strata infill of an inner shelf rift basin. Sites U1603-U1608 yielded a total of 2,299 m of sediment core from a composite stratigraphic section >3 km thick, covering the last 25 million years, i.e. from Oligocene to Holocene. From four sites we obtained a comprehensive logging suite that ties the core data to the seismic-scale development of the northwest Greenland margin. This presentation provides an overview of the preliminary results, and the scientific objectives for understanding late Cenozoic climate evolution in northwest Greenland.

New ICDP project proposal: Post-drilling assessment and experiments in the St1 Deep Heat Reservoir, Finland (DEEP EGS)

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The ongoing climate change and energy crisis have confronted societies with urgent challenges of finding energy resources, which should be renewable and sustainable. There is a quest for low-enthalpy energy especially for space heating in typical continental areas, including Precambrian shields. Enhanced Geothermal Systems (EGS) provide an option to utilize low-enthalpy geothermal energy practically everywhere. Low geothermal gradients and large lithospheric stresses complicate application of EGS at depths of several km. There are considerable challenges and knowledge gaps related to hydraulic stimulation, induced seismicity, and hydraulic properties of fractured heterogeneous media. Shedding light on these factors will aid developing a more efficient and economically viable EGS technology and improve its societal acceptance. Numerous EGS projects have encountered problems in achieving sufficient and sustainable flow rates for economic operation of EGS as well as controlling induced seismicity.

The world's deepest Enhanced Geothermal System (EGS) project was carried out by the company St1 in Espoo, Finland, 2014 - 2022. The project comprised drilling two deep wells to >6 km depths, and carrying out hydraulic stimulation and monitoring of induced seismicity with downhole seismic arrays and satellite stations. The St1 drill site in Otaniemi, Espoo, is a world-class site, where superdeep wells are accessible in an urban area. Seismological, structural, hydraulic, geothermal and microbiological research has been already done providing in-depth background knowledge (Kwiatek et al., 2019; Purkamo et al., 2020; Heikkinen et al., 2021; Kukkonen et al., 2023). The St1 deep holes provide a unique possibility to establish a deep borehole observatory and geothermal laboratory offering unprecedented possibilities for research in induced seismicity, geothermics, hydraulic properties, deep fluids and gas as well as deep biosphere, helping to understand the behavior of crystalline bedrock at extreme depth.

Our aim is to apply the boreholes and data sets for a thorough analysis of the crystalline bedrock conditions at 5 – 6 km depth, solving problems related to developing EGS in crystalline rock as well as basic research questions. We expect that the project will provide novel and indispensable data for planning new EGS projects.

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IODP Proposal 976: Understanding the temporal evolution of asymmetric plume-ridge interactions in the Northeast Atlantic

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Scientific drilling has been key to understand fundamental geodynamic concepts. Various geophysical projects in the NE Atlantic during the 1970's indicated that spreading centers near Jan Mayen coexisted with the now extinct Ægir Ridge prior to the initiation of the Kolbeinsey Ridge at 26 Ma. Previous drilling projects in the NE-Atlantic since the 1970's did not address rift reorganization and propagation processes associated with breakup of oceanic crust within the Iceland Plateau (IP), west of Jan Mayen. The crust below the IP is the least understood within the North Atlantic, yet potentially holds clues to constrain fundamental aspects of plume dynamics, rift propagation and formation of microcontinents. The Iceland Plume and North Atlantic spreading ridges have interacted since continental breakup (~55 Ma). Spreading along the Reykjanes Ridge south of Iceland has been continuous, and geochemically enriched mantle from breakup to the present has been feeding into the northern part of the Reykjanes Ridge. By contrast, the model for the formation of the Iceland Plateau that this proposal is set to test, is one of northward rift propagation into the East Greenland continental margin since ~50 Ma. Thus, overlapping with a northward retreat of spreading along the Aegir Ridge east of the plateau, until eventually rift propagation was replaced by formation of the Kolbeinsey Ridge within the western-most part of the plateau (~23 Ma), and spreading along the Aegir Ridge ceased. Assuming an axis-symmetric plume structure, this ostensible link between the plume and rift-propagation suggests that a comparable plume enrichment within the crust of the Iceland Plateau is present. However, indications are that neither at present, nor in the past, is such symmetry to be found. Instead, a distinct shift from enriched compositions in the south to depleted compositions north of Iceland exists today. A transect of seven boreholes will test our tectonic model of rift propagation and will at the same time map the temporal evolution of the mantle from which the Iceland Plateau formed in order to test if, and for how long this asymmetry extends back in time. This evolution, combined with existing geophysical constraints on crustal thickness, modeling of the lithological composition of plume mantle and its potential temperature (Tp) will support geodynamic modelling of plume nature and its deep origin. One important objective is to examine the hypothesis that mantle plumes may be rooted in Large Low Shear Velocity Provinces (LLSVPs) at the core-mantle boundary, and that distinct geochemical reservoirs in these provinces and adjacent mantle can be preserved through vertical, laminar flow during plume ascent, and result in a strong compositional zonation within the lithosphere. Or alternatively, if melting processes acting on well-mixed mantle can disentangle different mantle components and generate a similar zonation. Secondary objectives are the transition into the ice-house world during the Oligocene and variability in sea-surface temperature and ice-cover during the Plio-Pleistocene, studies that the Icelandic Plateau is well positioned for. Furthermore, the IPR-IODP-976 proposal addresses the evolutionary period and geological speaking missing link between the recent IODP-drilling projects Expedition 395 on the Reykjanes Ridge (0-30Ma) and the Expedition 396 on the Vøring Margin (breakup ~56 Ma) facilitating a complete record of the solid-earth and paleo-environmental changes of the NE Atlantic from breakup to present-day. This type of proposal will be difficult to implement without a drilling platform like the US provided JOIDES Resolution platform, which will end its operations by August 2024.

Research Data Management in Scientific Drilling: form the acquisition of consistent data at the drill site to FAIR data dissemination

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Proper Research Data Management (RDM) is a key requirement for making major scientific projects work smoothly and effectively. In general, the scientific drilling community was an early adopter of RDM and making data open and citable, but with varying success. During recent years, the demands on RDM have been increasing further through, e.g., the adoption and enforcement of the FAIR data principles (Findable, Accessible, Interoperable, Reusable) by major science programmes, funding organisations and scientific journals. This positive development significantly fosters the (re-)usability of data and sample material, resulting in a higher scientific output for the invested funding. Luckily, FAIR research data management has not to be cumbersome with the appropriate tools.

The mobile Drilling Information System (mDIS): consistent data at the drill site and in the core repository

The mDIS is a data management system designed for the acquisition of data and scientific documentation at the drill site. It can be easily adapted to the individual projects' needs and is able to handle all common tasks and workflows at a drill site. Its core task is to document the sample material from the borehole in a hierarchical structure ("borehole – core – section – sample") and assign globally unique and resolvable identifiers to all items (IGSNs, see below). The mDIS development was initiated and has been significantly funded by the International Continental Scientific Drilling Program (ICDP, www.icdp-online.org), of which the majority of the Nordic Countries are members. The system is also used for curation at major core repositories.

The International Generic Sample Number (IGSN): a unique identifier for physical samples

The International Generic (formerly "Geo") Sample Number is a globally unique, persistent and resolvable identifier for physical samples (www.igsn.org). Beyond a basic, for all disciplines common data schema, extended schemata are available for various disciplines, such as for (scientific) drilling. IGSNs are created automatically by mDIS. Every little piece from a drill core that has an IGSN assigned can be resolved easily via the Handle System, and data including the full sample hierarchy up to the borehole level retrieved. IGSN is "FAIR samples" and provides an easy way to unambiguously cite samples and resolve associated data.

The European Plate Observing System (EPOS): FAIR solid Earth sciences data

EPOS is the pan-European distributed e-infrastructure for solid Earth sciences (www.epos-eric.eu). Its main purpose is making FAIR solid Earth sciences data available to the scientific community, either through its data portal or by directly interfacing the data services. To achieve pan-European FAIR data provision, metadata and data have to be harmonized both within scientific communities and across borders, and the metadata/data transfer has to follow open standards. For "boreholes", such standards were defined in and data services set up by the "Geological Information and Modelling" thematic community (TCS GIM). Scientific drilling data are part of EPOS FAIR data provision. While for practical reasons only discovery data are provided for pre-mDIS boreholes, which include links to the respective data repositories (e.g. https://www.geodata.rocks/BoreholeView/SD-DSDP_12-114), fully Linked Data services are supported by the information derived from mDIS, providing rich information directly to the user (e.g. https://www.geodata.rocks/Boreholes/SD-5054_2_A).

In summary, the combination of mDIS, IGSN and EPOS provides an appropriate and user-friendly solution for consistent data acquisition and curation, FAIR handling of drill core/sample material and FAIR (scientific) drilling data provision, with the COSC-2 (Collisional Orogeny in the Scandinavian Caledonides) ICDP project being the first example to utilise all of its components.

The high-resolution paleoclimatic record of the western margin of Svalbard (Proposal IODP 985-Full2, IODP Expedition 403)

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High-resolution depositional archives were identified in the contourite drifts developed on the mid-upper slope of the western continental margin of Svalbard (Bellsund and Isfjorden drifts, Vestnesa and Svyatogor ridges) under the persistent effect of the West Spitsbergen Current (WSC). The sediment drifts contain very similar stratigraphic sequences characterised by depositional marker beds (Heinrich-like and meltwater related deposits) outlining a synchronous, almost simultaneous response of the Svalbard-Barents Sea paleo-ice sheet to changing climatic conditions. These observations strengthened the idea that the WSC, transporting warm Atlantic Waters to the Arctic, was one of the major drivers of the Arctic climate variability and cryosphere evolution in the area.

The above considerations inspired the writing of Proposal IODP 985-Full2 that was motivated by the necessity of retrieving continuous, high-resolution, and datable depositional sequences containing the record of the palaeoceanographic characteristics and cryosphere evolution during the past climatic transitions that followed the opening of the Fram Strait in the Arctic. Such data are greatly needed to better constrain global climate connections, forcing mechanisms and climate models.

The general objective of 985-Full2 is the reconstruction of the variability of the WSC and its influence on climate changes particularly during key climate transitions (i.e. the late Miocene–Pliocene transition, late Pliocene–Pleistocene Transition, Mid-Pleistocene Transition, Mid-Brunhes Transition, and sub-orbital Heinrich-like events), its impact on the Arctic glaciations, ice shelves development and stability, and sea ice distribution over last 5.3 Ma.

The proposal submitted in April 2020 was approved in May 2022 and scheduled as IODP Exp. 403 (June 4th to August 2nd, 2024).

Inter-lava sedimentation and siliciclastic reservoir potential, mid-Norway: IODP site U1566

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International Ocean Discovery Program (IODP) Expedition 396 drilled 21 holes at 10 sites spanning the mid-Norwegian volcanic rifted margin in 2021. In the northwestern part of the Møre Margin Site U1566 penetrated the western flank of the Kolga High, close to the continent-ocean boundary. Hole U1566A penetrated a ~120 m Seaward Dipping Reflector (SDR) sequence beneath a thin Quaternary sediment cover. Coring revealed a basaltic lava flow dominated sequence with inter-layered volcaniclastic and siliciclastic sediments, the latter containing granitic clasts eroded from the nearby high. The base of the volcanic sequence was recovered in the cores and marks a sharp transition from sub-aerial lava flows into deeply altered and weathered granite. Approximately 27 m of granite was recovered which includes multiple granite-derived sandstone stringers of variable orientation, a feature attributed to infill of a deep sub-aerial weathering profile in the granite.

A comprehensive suite of shipboard petrophysical and wireline data were collected in order to characterize the SDR sequence including whole-Round Multi-sensor Logger measurements, P-wave caliper and point magnetic measurements on working-half core sections, plus 102 discrete sample measurements for porosity and density. In addition, ambient permeabilities were measured on 30 minicore samples along with petrography and SEM imaging. Wireline data including gamma, density, P- and S-wave velocity, resistivity, magnetic susceptibility, and image log data (micro-resistivity and acoustic) were collected over the main volcano-sedimentary sequence along with VSP.

Facies analyses of the volcanic sequence reveals a mixture of pahoehoe, transitional and aa lava flow lobes rarely exceeding ~3 m in thickness. Despite porosity exceeding 40 % for some lava flow margin samples, matrix permeability rarely exceeds a few 10's of millidarcies and is linked to alteration and pore clogging by secondary minerals. These findings highlight the requirement for fracture contributions to fluid flow in order to achieve useable reservoir potential in the post-erosion preserved lava flow sequence at this and similar sites. Fifteen sedimentary interbeds were recovered ranging from c. 1 cm up to 2.6 m in thickness with an average thickness of c. 66 cm. Nine of the interbeds are dominated by siliciclastic sediments derived from the Kolga granite with an average thickness of c. 83 cm. Mini-core samples of siliciclastic inter-layers spanning the volcanic and granitic sequence reveal average porosities of c. 30 % with permeabilities up to 430 millidarcies highlighting potentially good reservoir potential within the area.

Results from site U1566 reveal unique insights into the formation of SDRs on the mid-Norway margin revealing that the Kolga High is capped by a granite which was rapidly eroded and exposed sub-aerially during pre-, syn- and post-SDR development. In addition, the site provides the first evidence for coarse grained siliciclastic sedimentation during SDR eruptions as continental breakup progressed. This highlights the possibilities for inter-lava reservoir potential mid-Norway. The results also highlight the requirement for new drilling to bring understanding of this complex area forward.

Characterization of the Cameroon volcanic line: insight from 2D and 3D seismic reflection data in the Douala and Rio Muni basins

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The morphometric and stratigraphic study in the Douala (Cameroon) and Rio Muni (Equatorial Guinea) basins, using seismic reflection data, has enabled the identification of volcanoes and volcanic mounds in the area, and then the characterization of their internal and external structures. This has led to a better understanding and constraint of the style of volcanic eruptions in the region. The various seamounts encountered in the area have been identified as shield volcanoes, which exhibit different characteristics. Some have slightly inclined flanks and rounded summits, while others have conical summits with moderately steep-sided flanks.

The seismic volcanostratigraphy and seismic geomorphology methodologies were used to describe the seismic facies units of the shield volcanoes. Chaotic and disrupted reflections can be observed within the structure of the volcanoes, whereas parallel to sub-parallel reflections are evident on the flanks. Moreover, the Analysis of the seismic data has also allowed the identification of major structural elements, such as faults (including compaction, slope failure, horst and grabens), valleys, canyons, channels, and vents. These features provide evidence of an active shear zone and the mobilization of the oceanic crust in the study area.

The examination of various parameters has indicated a positive relationship between the summit height, the flank slope, and the base diameter. Nevertheless, there is a negative correlation observed between the flank slope, the basal diameter, and the volume of the volcanoes.

The International Continental Scientific Drilling Program (ICDP) – status and prospects for Nordic drilling projects

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The International Continental Scientific Drilling Program (ICDP – https://www.icdp-online.org/home/), founded in 1996, currently includes 22 member nations, including Iceland, Finland, Norway, and Sweden. UNESCO serves as a Corporate Affiliate. GeoForschungsZentrum (GFZ) in Potsdam is acting as ICDP's Executive Agency and is also hosting an Operational Support Group for project planning and technical assistance. ICDP supports drilling projects addressing significant scientific and societal concerns, such as environmental changes, geohazards, Earth resources, and the origin and evolution of life through Earth's history. Collaboration with organizations like IODP is a priority. ICDP has supported over 80 planning workshops and 55 drilling projects. Several projects have been completed or are planned in the Nordic countries. Some examples of are briefly summarized here.

COSC-2 (Collisional Orogeny in the Scandinavian Caledonides), following COSC-1, was successfully completed in 2020 at the Caledonian front near Åre in central Scandinavia. Cores are now available through key sections of the Caledonian Nappe stack and the underlying Fennoscandian Shield.

Krafla Magma Testbed project, approved by ICDP in 2021, builds on the experience from previous drilling in Iceland. The project aims to drill into the magma front and sample the rock-magma interface at the Krafla volcano and has important implications for the use of geothermal heat as well as volcano monitoring.

DAFNE (Drilling Active Faults in Northern Europe) has ICDP support for a drilling project aiming to intersect a postglacial fault near Kiruna. Prominent post-glacial faults are widely distributed in northern Fennoscandia, and given their relatively recent movement history, a better understanding of these fault systems has great scientific and societal relevance.

PVOLC (Volcanic Forcing and Paleogene Climate Change) was approved by ICDP in 2020. Two planned boreholes in northwest Denmark will obtain a complete section through Paleocene-Eocene marine strata, including abundant ash layers. The drill cores will provide data that will give new insights into the relationships between the North Atlantic Igneous Province and the global Paleocene-Eocene Thermal Maximum (PETM).

GOE-DEEP (Gabon and Oxygenation of Earth - Drilling Early Earth Project) aims at creating a drill core archive of the best-preserved Paleoproterozoic sedimentary rock successions for the 2.2-2.0 Ga time interval. Its goal is to enable researchers to confidently reconstruct original environmental conditions that led to the emergence of the modern aerobic Earth system during and following on from the Great Oxidation Event, previously studied in the highly successful FAR-DEEP project.

ICDP, after more than 25 years, has proven highly successful, fostering international collaboration, involving students and early-career scientists, and yielding groundbreaking discoveries. All cores and samples are preserved for future research. Financial support from ICDP varies, often securing only initial funding. Obtaining the remaining part of the budget has in many cases turned out to be challenging, also in the Nordic community. Therefore, it is crucial to identify ways to highlight the great benefits of both onshore and offshore drilling projects and develop strategies and collaborative platforms to attract and secure funding from research councils, universities, and other relevant organisations.

Using the ICDP platform, the Nordic earth science community has an excellent opportunity to develop drilling projects of potentially great scientific and applied importance.

Characterization of the Vøring Transform Margin by IODP Exp. 396 Drilling and high-resolution 3D Seismic on the Mimir High

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Transform continental margins form by strike-slip motion between two continental lithospheric plates during the initial opening of new oceanic basins and develop progressively into passive transform margins as the spreading axis moves oceanward. The c. 250 km long Vøring Transform Margin (VTM) was formed along the southern Vøring Plateau as a result of the Paleogene continental breakup and seafloor spreading in the early Eocene. In the central part, the c. 50 km long Mimir High was formed, with uplifted and eroded upper Cretaceous and Paleogene sedimentary sequences that are presently buried below thin post-breakup sedimentary deposits. In 2020, we acquired nine high-resolution 2D seismic profiles (total length c. 150 km) using a 300 m streamer with 3.1 m group interval and one P-Cable 3D cube (8.0x1.2 km large cube with 6.1x6.1 m grid size) using the R/V Helmer Hansen. The data were processed shipboard and subsequently used as site survey data for planning IODP Expedition 396 drilling of Sites U1569 and U1570. In the late summer of 2021, Hole U1569A penetrated 405 m of Paleogene and Neogene sediments, with a total recovery of 135 m (Planke et al., 2021). Four 200 m-deep offset holes were subsequently drilled along a corridor at Site U1570, penetrating 763 m and recovering 270 m of dominantly Paleocene and Eocene sediments. All holes were drilled using the RCB system and wireline logs were collected in Holes U1569A and U1570D. Preliminary results show that the sedimentary succession on the Mimir High includes an expanded Paleocene-Eocene Thermal Maximum (PETM) and Paleogene section which allow detailed studies of the Paleocene to Eocene paleoenvironment. Ten lithostratigraphic sediment units from the middle Paleocene to the Quaternary are separated by unconformities constraining the vertical movement of the area. Ash layers, igneous units, and thermal alteration of organic matter are observed around the PETM succession suggesting nearby volcanism and deposition in coastal environments during most of the Paleocene and Eocene. In summary, the new core and seismic data provide detailed insight into the Paleogene structural and environmental evolution of the VTM and the Mimir High.

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Drilling a low temperature convective system, Glyvrar, Faroe Islands

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The Faroe Islands are a volcanic archipelago in the Nord Atlantic Ocean, located in the triangular area between Iceland, Scotland, and Norway.

Fifteen years ago, the government of the Faroe Islands introduced shallow geothermal heat pump systems for heating private houses around the islands as a greener energy solution instead of oil burners. It took almost 10 years before the people of the Faroe Islands undertook this solution but at present there are more than 1500 buildings being heated with shallow geothermal energy.

The drilling of these shallow geothermal energy systems gave The Faroese Geological Survey (Jarðfeingi) the opportunity to access large amount of information regarding the underground. Information that had not been accessible before. The information was and still is being collected by measuring the depth of the groundwater table and the temperature and the conductivity of the groundwater each five meter down the borehole. With time more advanced logging equipment was acquired such as Optical Televiewer, Caliper log, Gamma ray log, SP log and a Flow log. These new tools have added to the database and have given the possibility of a better geological understanding of the underground.

Based on the collected data a geothermal gradient map was constructed and areas with geothermal gradients up to 140ºC/km were discovered. The average geothermal gradient of the Faroe Islands in general around 30ºC/km.

In 2021 a hypothesis regarding convection of groundwater in fracture zones was put forward in a test project. An area with a geothermal gradient of approximately 60-70ºC/km was chosen close to a school. In addition to the high geothermal gradient the aim is to drill an artesian warm water well. If the test is successful and artesian water found, the energy from the water could be used for heating the school thought an open-loop shallow geothermal system.

Geological mapping of the area commenced with a specific focus on fractures where convection of groundwater was expected to occur. Three large fracture zones were mapped in the area - using 3D topographic maps in Petrel – and all turned out to dip between 30-38º in a northwest to northern direction. The central fracture zone was interpreted in depth closest to the school. Thereafter three wells were planned in the area: one 100 m deep control well north of the school and two 400 m deep wells 25 and 75 m south of the school, respectively. The plan was to reach the fracture zone at approximately 350 and 250 m depth, respectively.

The wells were drilled between the 12th and the 20th of December 2022. Both wells south of the school were artesian but due to water pressure it was only possible to drill the southernmost well, the well farthest away from the school, 275 m deep. The amount and heat of the water running out of the wells was 0.7 m^2/h of 19.5ºC and 4.5 m^2/h of 24.5ºC warm water, respectively, while the groundwater level in the 100 m deep control well was placed at 7.5 m below surface.

The wells were logged with all available logging tools and on the Optical Televiewer fractures were seen at 228, 356 and 371 in the well closest to the school and at 203 and 245 m depth in the well farthest away from the school. A pump test tells us that the borehole farthest away from the school can manage to provide more than 7 m^2/h of 24.5ºC warm water to the system, without affecting the two other boreholes.

So far, only closed loop geothermal heat pump systems are installed in the Faroe Islands. But as 25% of the shallow geothermal wells in the Faroe Islands are artesian well, this is a waste of water and energy. Therefore, the next step of this project is to get funding to install the first open loop geothermal heat pump system in the Faroe Islands. An open loop geothermal heat pump systems is expected to provide 10 times more energy pr. borehole depending on the water amount and temperature.

After the heat is taken out of the water the hope is that the municipality will use the water as drinking water for the inhabitants in Glyvrar or it will be transported to the salmon factory located 400 m north of the school. The energy of the water is at least four times of what the school needs and the second phase is to connect other surrounding buildings to the same open loop system.

Understanding volcanic rifted margins and paleoenvironment by scientific drilling in the NE Atlantic

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Large igneous provinces (LIPs) are frequently associated with the breakup of continents, leading to the formation of magma-rich rifted continental margins, or so-called volcanic rifted margins. The concept of volcanic rifted margins has primarily developed from studies of the NE Atlantic margins during the past fifty years by integrated interpretation of seismic reflection, wide-angle, and scientific borehole data. Initially, the presence of breakup basalt was proven by coring shallowly buried basement on the Vøring and Rockall plateaus during DSDP Legs 38 and 81 in the 1970's. Subsequently, ODP Legs 104, 152 and 163 in the 1980's and 1990's documented the presence of kilometer-thick subaerially emplaced basalt flows on the Vøring Plateau and offshore SE Greenland by drilling the feather edge of seaward-dipping reflectors (SDRs). These research results from the NE Atlantic have had global implications, as 2D industry and academic seismic surveys now reveal that similar SDRs are present globally. However, most breakup volcanic sequences are buried below kilometer-thick post-breakup sedimentary deposits, making them inaccessible for open-hole scientific drilling. The NE Atlantic therefore remains the premier choice for research and drilling of magma-rich margins, leading to the submission of several IODP drilling proposals in the Norwegian-Greenland Sea. These proposals have benefited from a large database of industry 2D and 3D seismic data and the development of new interpretational methods, such as seismic volcanostratigraphy and igneous seismic geomorphology. Since 2000, we have also developed and used new technologies for acquisition of high-resolution 3D seismic data, the P-Cable system, which is particularly well-suited for core-log-seismic integration. In the late summer of 2021 IODP Expedition 396 ("Mid-Norwegian Margin Magmatism and Paleoclimate Implications") successfully drilled 21 boreholes on the Vøring Margin, with more than 2 km of core recovery (Planke et al., 2023). Some of the highlights of Expedition 396 include the recovery of sub-basalt granite (c. 15 m) on the Kolga High at the boundary from the Møre to the Vøring Basin, intra-basalt sandstones at the Kolga High, expanded sequences of Paleocene-Eocene Thermal Maximum (PETM) deposits (c. 240 m) along the Vøring Transform Margin, pillow basalts and hyaloclastites at the Eldhø outer high, and basalt lava flows emplaced in subaerial and swampy environments on the Skoll High (c. 150 m). The drilling data furthermore ties shallow-water venting of large volumes of greenhouse gases to the PETM (Berndt et al., 2023). These results will be combined with geodynamic modeling to reconstruct the evolution of the margin, the origin of the break-up volcanic successions and their role in the rapidly changing environment throughout the Paleogene. Our research confirm that scientific drilling is an essential tool for developing fundamental new understanding of deep-time links between solid earth processes and paleo-environments, and that the NE Atlantic holds an invaluable geologic archive for future drilling expeditions and research.

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From the deep ocean to deep data: leveraging advanced µCT and AI techniques in foraminifera morphological data processing

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Ocean drilling has generated a vast library of geological and environmental data derived from sediment cores. Microfossils preserved in marine sediment, particularly calcareous foraminifera, have become a foundational tool for paleoceanographic and climate reconstructions, including analysis of ecological distribution (e.g., species abundance and diversity), geochemical signatures (e.g., stable isotopes and trace elements), and shell morphology (e.g., thickness, weight, circularity). Conventional microcomputed tomography (µCT) serves as a common, high-resolution approach to studying shell morphology. However, its utility is hindered by prolonged scanning times, limiting the feasibility of generating extensive time series of morphological variability. Recently, there has been a shift towards employing synchrotron-based methods for µCT scanning, which facilitates a higher frequency of scans compared to conventional µCT methodologies. However, the increased quantity of µCT data gives rise to a data processing challenge that is labor-intensive and time-inefficient. Fortunately, artificial intelligence (AI) offers a potential methodological solution in its capacity to streamline data processing workflow. In this study, we showcase the use of the commercially available software Dragonfly for processing µCT scans of foraminifera from a sediment core in the Baltic Sea-Kattegat region (IODP Expedition 347, Site M0060). We scanned ~450 specimens of the benthic foraminiferal species Elphidium clavatum, covering the time period 17.6-13 ka BP, using the Anatomix beamline at the SOLEIL synchrotron facility in Paris, France to generate over 20 terabytes of three-dimensional morphological data. This project aims to parse the benefits and limitations of AI-integrated methodologies in managing voluminous µCT datasets, contributing valuable insights towards optimizing data processing in microfossil morphological studies.

Deep-time climate archives in Svalbard: opportunities for scientific drilling

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The high Arctic archipelago of Svalbard is globally unique in that it facilitates scientific coring across multiple stratigraphic intervals within a relatively small area. The polar location of Svalbard for some of the Mesozoic and the entire Cenozoic makes sites in Svalbard highly complementary to the more easily accessible mid-latitude sites, allowing investigation of the polar amplification effect over geological time. Coal, petroleum and research wells provide insights into the stratigraphy and linkage to the well exposed outcrops. Nonetheless, only the two 100 m deep boreholes drilled in Deltadalen in 2014 specifically targeted one of the deep-time paleoclimatic events of global significance, namely the end Permian mass extinction.

Other globally important climatic and paleoenvironmental events are recorded in Svalbard's rock record. However, since these are out of the scope of the coal and petroleum industry, the available core material is limited. Therefore, we have initiated the SvalClime project (Senger et al., 2023) and developed a scientific plan to address three main objectives through scientific drilling onshore Svalbard:

a) Investigate the coevolution of life and repeated greenhouse- icehouse-greenhouse climate transitions, likely forced by orbital variations, by coring Neoproterozoic and Late Paleozoic glacial and interglacial intervals in the Cryogenian ("Snowball/Slushball Earth") and Upper Carboniferous to Lower Permian (Late Paleozoic Ice Age) sedimentary successions.

b) Assess the impact of Large Igneous Province emplacement on rapid climate change and mass extinctions, including the end-Permian Mass Extinction, the end-Triassic Mass Extinction, the Jenkyns Event (Toarcian Oceanic Anoxic Event), the Jurassic Volgian Carbon Isotopic Excursion, the Cretaceous Weissert Event and Oceanic Anoxic Event 1a.

c) Examine the Early Eocene hothouse and subsequent transition to a coolhouse world of the Oligocene by coring Paleogene sediments, including records of the Paleocene-Eocene Thermal Maximum, the Eocene Thermal Maximum 2, and the Eocene-Oligocene Transition.

The SvalClime science team created plans for a three-year drilling program using two platforms: 1) a light-weight coring system for holes of ~100 m length (4–6 sites), and 2) a larger platform that can drill deep holes of up to ~2 km (1–2 sites). The results from the proposed scientific drilling will be integrated with existing industry and scientific boreholes to establish an almost continuous succession of geological environmental data spanning the Phanerozoic. In this contribution we outline the background and motivation of the SvalClime ICDP proposal, focusing on describing the main hypotheses and presenting the potential drill sites.

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Rhomb porphyry lavas from the Oslo Rift revisited: New insights from construction-related boreholes and cores

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The Oslo Rift formed about 300 million years ago and is characterized by emplacement of subaerial lavas and an extensive sub-volcanic system of sills, dykes, and plutons. The lavas range in composition from ultramafic melilitites and basalts, to evolved trachytes and rhyolites. The earliest stages of volcanism were dominated by plateau basalts (the B1 series) followed by trachytes (including rhomb porphyries), and later stage caldera-related basalts, rhyolites and ignimbrites. Historically, research on the lavas has gone through many phases and several key lava regions are well mapped based on outcrops. In the case of the rhomb porphyry lavas in Krokskogen, which is one of the most well-known rock types in Norway outside the geoscience community, almost no geochemical and petrological data are available, and the volcanology is still poorly researched. Moreover, weathering and a dense vegetation cover has made detailed field observations challenging.

Here we use construction-related boreholes to obtain new knowledge about the development of the rhomb-porphyry volcanism in the Krokskogen area. This study relies on the extensive geotechnical exploration undertaken during the past decade as part of planning for a railroad tunnel and the new E16 road between Sandvika and Sundvollen. Numerous boreholes, including fully cored boreholes up to 450 m deep, were drilled and logged by geotechnical companies along the railroad and road transects.

We present wireline logs, geochemical, and volcanological results from one of the boreholes. The hole is 407 meter deep and the upper 350 meters contain interbedded sandstones and lava flows. The basal lava flow, the B1 basalt, is 21 meters thick and is overlain by 1.2 m of conglomerate and sandstone, followed by four types of rhomb porphyry (RP). These are named RP1 to RP4 and have been mapped as distinct flows regionally based on colour and phenocryst shape and size. Our study shows that the flows are also geochemically distinct. We have identified a total of 38 individual flow units in RP1-4, with average thicknesses of 8.8, 5.2, 2.5, and 6.0 m respectively. Several of the flow units in RP1 and RP4 have eroded tops. Moreover, alluvial-type deposits are common between the flow units in addition to sandstone beds that show dynamic interactions with the lavas. In RP2-4 welded breccias with altered volcanic glass and deformed vesicles are common in the upper parts of individual flow units, interpreted as fallout deposits close to the fissure volcano.

We conclude that the construction-related boreholes represent a unique opportunity to further understand the development of volcanism in the Oslo Rift. Fully cored boreholes make high resolution studies possible, including studies of lava units and interlayered sediments or flow tops, which are rarely preserved in outcrops. Collaboration with key agencies will lead to better knowledge transfer related to important construction-related themes such as volcanic evolution and heterogeneities, and water leakage.

Petrology of magmatic rocks drilled on the Mid-Norwegian margin

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The volcanic rifted margin of Mid-Norway is well constrained by seismic reflection data and bore hole data. About 50 years ago it was first proved that seismically imaged seaward-dipping reflectors were composed of subaerial basalt flows (Hinz, 1981). More recently focus has been on testing the hypothesis that Northeast Atlantic magmatism caused abrupt environmental disturbances known as the Paleocene-Eocene Thermal Maximum about 56 Myr ago (Planke et al., 2023; Berndt et al., 2023), and on constraining mantle melting models resulting in excess magmatism (Berndt et al., 2019). Ten drill cores have intersected the magmatic rocks of the Mid-Norwegian margin, including Deep Sea Drilling Program Leg 38 (1974), Ocean Drilling Program Leg 104 (1985), International Ocean Discovery Program Leg 396 (2021), and industry core. We have compiled all available geochemical data for the magmatic rocks of these drill cores, including our unpublished data. Basaltic compositions are dominant, but the drill cores also include silicic rocks such as dacite. Trace element compositions show that some of the basalts are strongly contaminated by continental crust, and the dacite even reflect direct crustal melting (Morris et al, 2023). The uncontaminated basalts display a range of trace element compositions reflecting signatures from depleted to enriched mantle source components. Calculated mantle potential temperatures are elevated relative to ambient mantle (Hartley et al., 2023). Estimated depths of mantle melting are relatively deep for basalts in the most landward drilling sites and relatively shallower for basalts drilled further seaward. In general the compositions of the uncontaminated basalts and their estimated mantle melting conditions appear to have been similar to Iceland today, and modulated by lithospheric thinning and segmentation of the rifted margin.

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History of Drilling on Greenland

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Subsurface core drilling provides important data on geological materials that cannot be sampled on the surface. This includes fresh rock samples unaffected by surface processes, buried marine sediments or deep ice cores. The history of core drilling in Greenland is more recent than either Canada or the Nordic countries with their long histories of mineral exploration and exploitation. Drilling on Greenland can be subdivided based on purpose into three categories, mineral exploration, petroleum exploration and scientific research. Most onshore drilling is for mineral exploration whereas most of the offshore drilling has been for hydrocarbons. Only a small proportion of drilling has been for purely scientific purposes.

Information on the history of drilling has been compiled into a single source for the first time (Christiansen et al. 2023). It is important this information is available to the extractive resource industry, academic researchers and the society of Greenland while first-hand knowledge of many drill campaigns in still available. Information is accessible through the Greenland Portal www.greenmin.gl; a web accessible portal that is the result of collaboration between the National Geological Survey of Denmark and Greenland (GEUS) and the Mining and Mineral Resources Authority of Greenland (MMR).

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The tectonomagmatic development of the Vøring Marginal High, Norwegian Sea: Core-log-seismic integration of the IODP Expedition 396 Boreholes U1571 and 1572

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During the Paleogene, the northeastern Atlantic Ocean witnessed a significant episode of magmatic activity, resulting in the production of an immense 6-10 million cubic kilometers of magma. This magmatic activity was associated with the occurrence of the Paleocene-Eocene Thermal Maximum (PETM) around 56 million years ago, attributed primarily to the release of thermogenic gases. The outer margins of the northeastern Atlantic subsequently underwent the final stages of tectonic rifting, resulting in regional uplift and erosion. One of the most prominent geological features in this region is the Vøring Marginal High, characterized by substantial seaward-dipping reflectors near the COB (Continental-Ocean Boundary) and the presence of diverse volcanic facies in its eastern sector. Here, the Skoll High exhibits a thin basaltic cover and below a few hundred meters of Cenozoic sediments allowing the study of breakup-related tectonomagmatic processes through shallow drilling and high-resolution seismic acquisition. In this study, we evaluate drilling data from IODP Expedition 396, focusing on sites U1571 and U1572 on the Skoll High. We apply an integrative approach by combining core and log data with high-resolution bio- and lithostratigraphy and a range of seismic reflection data, encompassing both conventional 2D and 3D seismic datasets as well as high-resolution 2D and 3D seismic data acquired during the CAGE22-5 research cruise. We identify four distinct Cenozoic sedimentary horizons, which include the Top Basalt and Base Basalt, along with two sub-basalt horizons. Furthermore, we have conducted a comprehensive volcanic facies analysis, utilizing the principles of igneous seismic geomorphology. The Top Basalt horizon provides remarkable insights into the characteristics of the ancient volcanic surface. While the top of the basalt pile in the southeastern part of the Skoll High is faulted and eroded the Top Basalt attribute map reveals a pitted top basalt surface and with lobate structures and linear ridges towards the west. The pits are interpreted as rootless cones, which comprise volcanic craters resulting from the explosive reaction between lava flows, which flow over water-saturated sediments. The dimensions of the rootless cones are comparable with cones present in the Myvatn area of NE Iceland. The mapping of sub-basalt horizons indicates potential pre-breakup episodes of extrusive volcanism, which were previously undocumented for the Vøring Margin. High-resolution biostratigraphy data show that sediments recovered directly above the basalts contain *Azolla* spp. and associated dinocyst marker species. This discovery possibly widens the timeframe for the cessation of extensive magmatic activity in the region to the *Azolla* event, which occurred from 49 to 48 million years ago (mid-Chron 22n to mid-Chron 21r). The results of this comprehensive study shed light on the complex paleoenvironment of the Vøring Marginal High during the pre- and syn-breakup phases in the Paleogene. The findings suggest the presence of rapid uplift/subsidence events and a more prolonged period of volcanic activity in this region of the NE Atlantic than previously documented.

Drilling the Permian-Triassic boundary in Svalbard: from the design of the project to scientific outcome, what to keep and what to change?

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The High-Arctic areas of Canada, Greenland, and Svalbard offer a stunning glimpse into the northern boundaries of Pangaea during the Permian-Triassic time. Over the years, numerous generations of field geologists have diligently examined these geological formations, overcoming challenging access and varying outcrop conditions. Yet, the resolution of the collected data and the associated analyses are strongly dependent on the degree of weathering of these outcrops. To circumvented this issue and to recover pristine, unweathered material across this crucial interval of the Earth's history, it was decided back in 2013 (against the opinion of many), to try to drill through the Lower Triassic mudstones of the Vardebukta Formation and the chert-rich strata of the Kapp Starostin Formation in Deltadalen Central Spitsbergen, as this area was relatively unaffected by Cenozoic tectonic activity.

With a budget of 0.6 Mio Nok, the plan was to use Store Norske Kullkumpani portable drilling rig, which can be transported by helicopter. In 5 days, working in 12 h-shifts, the team recovered two twin-90 m cores, with close to 100 % recovery rates. These cores were complemented by material collected in a river section ca. 1 km north-east of the drill site.

The analyses-results of the recovered material have very much improved the understanding of what happened before, during, and after the End-Permian Mass Extinction, and published in three international scientific journals (Schobben et al., 2020; Zuchuat et al., 2020; Rodríguez-Tovar et al., 2021), while several additional publications using the cored material are in preparation at the time this abstract was submitted. Some of these publications have now been integrated in the cursus of the University Centre in Svalbard's geology program.

The main findings include: i) the Permian-Triassic boundary, defined First Appearance Datum (FAD) of H. parvus ca. 252 My ago, now lies within the Reduviasporonites chalastus Assemblage Zone, 2.50 m above the extinction event (LPME) and its associated sharp negative δ13Corg excursion. ii) High-resolution environmental proxies indicate a dramatic change in provenance from an acidic to a more basic source of sediments across the PTB, and a transition towards a more arid climate in the earliest Triassic. This transition was contemporaneous with prolonged bottom-water dysoxic or anoxic conditions, following an increase in volcanic activity in the late Permian, probably linked to the emplacement of the Siberian Traps Large Igneous Province. Statistical analysis conducted on each elemental ratios suggests that the system recorded about two full, long eccentricity (400 kyr) cycles during the Induan. ii) A smaller δ13Corg negative excursion occurs 22 m above the major, extinction event, negative δ13Corg shift. This excursion has been recognised in other Panthalassic and Tethyan sections as the "Dienerian Crisis", suggesting a global extent of this crisis. ii) The ichnological information highlights the absence of a total extinction of the trace-maker community despite a marked reduction in abundance and ichnodiversity during the extinction event, as well as the rapid recovery of the benthic fauna during the Induan Age, ca. 150 kyr after the mass extinction occurred.

This Deltadalen results serve now as a basis for a larger palaeoclimatic study recorded in the sedimentary record of Svalbard (SVALCLIME). Overall, this project has shown that, with a limited budget, pristine cores can be recovered quickly, and with minimal environmental impact using a portable drilling rig. Such unweathered material, combined with traditional outcrop data, can then be used for a multitude of analyses which will improve the understanding of any targeted interval of the Earth's history. Some of these analyses can then be used as analogue(s) to help refined climate models of the anthropogenic climate change, and predict the some of the consequences associated with extreme rates of greenhouse gases emissions.'

Session 37

Geology, landscape, and the human past – recent approaches to geoarchaeology

Session Chairs:
Mark Peternell,
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Buried by sand – the abandoned medieval town at Falsterbo, S Sweden

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Archaeological investigations have revealed cultural layers with remnants of houses and streets below up to four metres of sand at the southern end of the Falsterbo peninsula in southernmost Sweden. The cultural layers have been dated to the 15^{th} – 16^{th} centuries, based on finds of, for example, coins and ceramics, and interpreted to represent the medieval town Falsterbo. It has been assumed that the houses in this once central part of town, close to the church, were abandoned due to strong sand drift that eventually buried most of the structures.

Here we will present results of luminescence dating, portable luminescence analysis and other geological analyses of the sand below, between and above the cultural layers. The lowermost sand is interpreted as beach sand, while all other sand beds – separating and covering the different phases of houses – are interpreted as aeolian sand. Preliminary results suggest a hiatus between the deposition of the beach sand and the first aeolian sand, followed by relatively rapid sand accumulation after final abandonment.

Complex crack formation in metavolcanic rocks accommodating tool making

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Many Early Archaic quarries and artifacts are in metarhyolite source material in the Carolina Terrane of central North Carolina, USA. The Carolina Terrane in Montgomery County, NC, comprises the Albemarle arc, a Neoproterozoic to Cambrian peri-Gondwana massif accreted to eastern Laurentia during the Late Ordovician to Early Silurian Cherokee orogeny. The arc rocks deformed under greenschist facies into regional folds that trend northeast-southwest and verge southeast; some folds are periclinal. Today, erosionally resistant metavolcanic rocks – rhyolite to rhyodacite - in the Tillery and Cid formations cap ridges separated by lowlands underlain by argillaceous metasedimentary rocks. This area is called the Uwharrie Mountains.

Geoarchaeological surveys determined several rhyolitic variants based on phenocrysts, flow banding, lithophysae, and color and grain size extracted from prehistoric quarries (Daniel and Butler, 1996.) It appears that the preferred stone tool rhyolite was dark gray, aphyric, and flow banded.

In a study area of a few hundred hectares, about 20 quarries were identified. The more extensive quarries are often on or near the shoulders of rhyolite ridges and have extensive colluvial aprons that contain flakes, intact cobbles and boulders, and a variety of rock fragments and quarry debris. It has been suggested that much of this colluvium is flaking debris, yet some ridges have few or no bedrock exposures. Investigators (Daniel and Butler, 1996) indicated that these slopes contain filled prehistoric pits.

How much of the supposed quarry debris results from natural mechanical weathering? Detailed geologic mapping in the study area finds several planar structures in metavolcanic rocks, including anastomosing axial plane cleavage, multiple systematic planar fractures or joints, exfoliation fractures, and curviplanar discontinuities related to mesoscopic cracking and spallation. Fin-like bedrock exposures have as many as six systematic fracture orientation maxima compared to two in lowland metaargillites. Exfoliation discontinuities that waver in orientation around cleavage are mode I cracks that coalesce in concave or convex detachment fractures that release sharp-edged fragments onto the erosion surface. This structure is unique to fin outcrops of very fine-grained aphyric rhyolite; they are rare on bedrock pavements, probably because the fins experience thermal cracking.

In addition to the semi-conchoidal fracture property, I suggest that the unique and inherent weathering features in aphyric rhyolite make this rock an ideal source for toolmaking because of a “natural” lithic reduction and pre-cracking bedrock. This could explain why some quarry sites do not have significant bedrock exposures. Mechanical cracking continues to operate on cobbles and boulders embedded in colluvial blankets. Many of these have cracked *in situ* in the soil.

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Stoneage site detected by high resolution seismic method

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In 2014, we first noticed on high resolution seismic profiles acquired by a Teledyne high-resolution Chirp III subbottom profiler in the well-documented Stone Age settlement of Atlit-Yam, located off Israel's Carmel coast irregular disturbances in the water column and we named it "haystacks". We speculated if these disturbances could be related to the flint debitage (blades) documented at the flint workshop in the survey area. The ChirpIII instrument sweeps the frequency interval 2 kHz – 20 kHz and operate in two bands 2-8 and 8-20 KHz. Acoustic experiments in laboratory had previously shown that flint blades could exhibit resonance when exposed to certain frequencies (3–23 kHz, with the main area being 7–12 kHz). Acoustic modeling confirmed this and modelling showed that even flint debitage buried below 2 m of sand could resonance. In Demark practical ChirpIII (that sweep the frequency interval 2 kHz – 20 kHz) used on flint debitage and natural cracked flint placed at the seafloor showed that flint debitage produced "haystacks" on seismic profiles whereas the natural cracked flint did not. Test of buried debitage showed that it created resonance and produced "haystacks".

In the dredged part of the Svanemøllen Harbour, Copenhagen we by coincidence located "haystacks" while testing instrumentation setting. In the following three years, we recorded data on three days to outline the area where "haystacks" are present and to confirm that the "haystacks" were a permanent phenomenon. The interpretation of the seismic data reveal that the haystacks are related sub bottom areas characterized by shallow basins and rivers in a near coastal setting and that the "haystacks" are located at the rim of the basins or in the basins. In order to test if there was a correspondence between the "haystacks" and possible debitage 11 shallow vibrocores, with a max length of 1 m, were drilled below locations of "haystacks". Based on the cores we found up to 36 cm of silt below the dredged seafloor before we reached a sandy cover of up to 80 cm representing part of the basin configuration. The sandy interval is underlain by till clay. Two cores centrally placed in the surveyed area confirmed the presence of man knapped flint at a depth of 80-90 cm below the sea floor.

The Svanemøllen Harbour site is a hitherto unknown buried Stone Age settlement and this is the first time that such a site has been acoustically detected (Teledyne Chirp III) and verified by drilling. Acoustic modelling of the retrieved pieces of man knapped flint is carried out to confirm that the debitage can be brought to resonance.

Due to the relative sea level rise a significant part of the submerged Stone Age sites must worldwide be expected to be buried in the seafloor sediments. This paper underlines the importance of the development of cost-effective methods for detecting such buried cultural deposits.

Micro-scale clues to transport-scale questions: How LA-ICP-MS trace-element composition maps can reveal steatite's hidden secrets

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Steatite is an easily carved, talc-rich, metamorphic rock with a high heat capacity, which made it especially popular in Viking Age Scandinavia for crafting household objects, especially cooking pots. Such pots have been found even in settlement locations with no local sources of steatite. Archaeologists and geologists have tried a variety of approaches over the past 50 years to characterise steatite quarries sufficiently to demonstrate the sources for steatite artefacts (e.g. Allen et al. 1975; Bray 1994; Jones et al. 2007; Keulen et al. 2022); each of these studies have furthered our understanding of the complexities of steatite and the challenges inherent in such provenance studies.

These challenges stem from the hot, fluid driven, metamorphic processes, which typically results in heterogenous steatite outcrops showing substantial variations in the concentrations of the major minerals. This can result in different bulk rock chemistry for each sample from the same outcrop and can affect even the Rare Earth Element (REE) distribution patterns.

However, while this style of metamorphism comes with such built-in challenges, each outcrop forms under a unique set of conditions (temperature, pressure, and the composition of precursor rock and fluid flow), which results in certain trace elements being favoured, or rejected, during the growth of the various accessory minerals included in the steatite, as dictated by those conditions. Therefore, this study focuses on these accessory minerals, particularly the opaque sulphide and oxide minerals, which are the phases most likely to contain many of the sample's trace elements.

Laser-ablation ICP-MS trace-element composition maps of accessory minerals (and their surrounding matrix minerals) have been made for samples collected from a variety of Swedish and Norwegian steatite outcrops to illustrate the ways in which these minerals are, or are not, zoned with respect to their major and trace elements, and to investigate the differences in these patterns from one location to another, with the goal to develop a more reliable method to quickly determine if a given steatite artefact could have come from an analysed quarry.

This contribution presents LA-ICP-MS trace element maps of iron oxide and pyrite crystals from two steatite artefacts from Haithabu and compares and contrasts them with one another, and with maps of iron oxide and pyrite crystals from several steatite quarries in Sweden and Norway.

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Subfossil trees as proxies for long-term climate dynamics and ecosystem changes

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Our understanding of long-term climate dynamics, environmental changes, as well as our possibilities to evaluate climate models predicting future climate scenarios are largely based on proxy records with a high temporal resolution and a wide geographical distribution. This study present results from an ongoing initiative to develop multi-millennial Scandinavian tree-ring width (TRW) chronologies from subfossil oak (*Quercus* spp.) and pine (*Pinus* spp.). About 1000 oak trunks extracted from Danish and South Swedish sites have been analyzed, and at present, the material consists of a mixture of absolutely dated, radiocarbon dated, and not yet dated TRW records showing a temporal spread over the last 8500 years. The material has been collected during dendrochronological fieldworks and archaeological excavations since the 1970s, but since there are still gaps in between the chronologies, new efforts are under way to find materials that can bridge the gaps. Regarding the pine trees, the material consists of remains from about 800 trees from south Swedish peat extraction sites (Edvardsson et al. 2012, 2014). The main part of the pine material covers the period 5200 - 1100 BCE (approximately 7200 - 3100 BP), which corresponds to the Holocene Thermal Maximum (HTM) and the transition period towards a colder and more unstable climate following HTM.

Significant long-distance cross-dating statistics between Swedish – Danish – German TRW chronologies proves that there is a valuable (palaeo)climatic signal in the TRW data (Edvardsson et al. 2012, 2014, 2016). Moreover, several oak dying-off and burial events coincide with wet shifts causing expanding peatlands, which makes the oak material a valuable complement to the Scandinavian bog-pine chronologies, whereas peatland pine colonization phases correspond to relatively warm and dry periods. The importance of these TRW chronologies should therefore not be underestimated as (1) climate records of comparable length and resolution are rare for southern Scandinavia, (2) the TRW chronologies can serve as an important dating tool for archaeological artefacts from the region, and (3) there is a widespread lack of detailed moisture proxies spanning several millennia. Our data clearly show that a continuous 8000-year bog-oak chronology and multi-millennial pine chronologies from South Scandinavia is a realistic objective and would doubtlessly fill a major geographic gap in an ecologically sensitive region located at the interface between the temperate and boreal vegetation zones. Furthermore, these data can be helpful in detecting and dating extreme climate changes that have influenced societal development during prehistoric times.

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Genesis of limonite ores in the "Röda Jorden" area from a hydro-geological perspective

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It has been found that bloomery iron making commenced in Sweden already during the Middle Bronze Age. During the latter part of the Late Bronze Age, iron production sites began to appear in areas relatively distant from settlements and burial sites. An example of such an area is "Röda Jorden" (the Red Soil) near Riddarhyttan in the province of Västmanland. Among archaeologists it is considered obvious that organized prospecting activity took place in connection with iron making. Skilled people were searching for abundant iron deposits in the form of various types of limonite ore. In addition, abundant access to fuel was important (cf. Hjärthner-Holdar et al. 2018).

The "Röda Jorden" is considered an "area of national interest for cultural heritage" in Sweden and is subject to re-examination in terms of geographical demarcation (Jensen, 2019). Within an area of approx. 5 km^2, the oldest remains of iron production in Sweden have been found. Carbon-14 dating shows that operations have been ongoing from the 7th century BC until the 1st century AD (Grandin et al., 2000). Sixteen sites of bloomery furnace remains for iron production have been found.

The scientific background descriptions of the "Röda Jorden" area are archaeological studies of the individual remains with an emphasis on archaeometallurgy, industrial history and past social context (see e.g., Berglund (ed), 2015;). However, there is no rigorous geoscientific description of the red soil genesis, which should be an important knowledge basis for proposing the area bounds seen from a community planning perspective.

A project is currently being carried out with the aim of investigating the geoscientific conditions. Two survey sites, with ongoing red soil creation, have been established in the area. Geological mapping and groundwater surveys with e.g., water sampling in observation wells make it possible to describe the geo-scientific conditions in more detail. Initial project results show that several hydrogeochemical processes in combination with area-specific hydrogeological conditions are of decisive importance for the extensive past and ongoing red soil formation.

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Invetory and investigation of peatlands to reveal possible human settelements in south central Sweden

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Introduction

Geology very crusial to archaeology in different ways. One important part is the changing and developing landscape, that during the time from the last glaciation (Weichsel) to present time mean changes due to land uplift (isostacy) in many parts of Sweden and different resources available for humans. A very typical effect of the land uplift, is the development of water environments in the landscape, like lakes, water cources and wetlands. The former situation with sea, change to land and lakes, that in time means natural drainage of the lake and a change to a peatland, a mire or a bog. More recently the drainage was speeded up by human management of the landscape. This means that looking for the human settlements means to look in or in connection to mire and bogs, representing the former settlements along the lake.

If there is peat, there might be human settlements

In a project as pilot study initiated by the organization "Vätternvatten", a new pipeline for freshwater from lake Vättern to the town Örebro is planned. To implement this, a preparation is to study the area that will be affected from several viewpoints, where the former landscape and archaeology is one important part. The pipeline will go through or by several known and unknown mires and bogs (peatlands) along the way. The peatlands are known to be places where to find former human settlements from prehistorical times, since the peatland at the time for the settlements where lakes and open water.

The region around town Örebro in south central Sweden (west of "Mälardalen valley"), is known for former extensive change of both lakes, mires and rivers due to drainage during second part of 19th and first part of 20th century. In order to manage inventory of the archeological situation along the planned pipeline, one importand part was to evaluate present and known peatlands as well as finding and investigate unknown or severly changed peatlands (disappeared because of former drainage activity).

The region is a former classical Swedish Quaternary area, with many investigations by for example Erik Fromm and Lennart von Post (e.g. Fromm 1972, von Post 1909, 1927). In the project was several resources used to investigate former lakes and other open water areas, wetlands and peatlands. Resources used in the project is peat arcive at Swedish geological survey (SGU), mapping and investigations of south Swedens peatlands (*e.g.* "torvinventeringen"), geodata interpretation, site visits at all places consicered as present or probable peatlands and coring at some sites.

Many sites that used to be peatlands, are today gone or completely changed from their former status. Some where still peatlands, but just smaller mires with thin peat layer. The most pronounced peatland that is still present, even though it has been severly changed because of peat extraction, is the mire "Ekebymossen". A classical mire in Swedish Quaternary geology. This mire is a former lake and in other parts of the mire complex there are exposed prehistoric settelements. A peat core was taken from the mire where the water pipeline is supposed to go to evaluate is status. The stratigraphy of the core sequence was complete in many ways, corresponding to former descriptions (e.g. Fromm, 1972) and possible to use for immerse studies, even though the Ekebymossen mire is affected by peat extraction.

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Paint it red – Investigating the impact of painting rock art in Sweden through thermal imaging

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Swedish rock art dating to the Nordic Bronze Age (1700-500 BC) consists of engravings on bedrock surfaces which bear witnesses to the religion and practices of past societies that did not leave a written record. As such, they are an invaluable source of information for studying contemporary societies. Intriguingly, these images were intentionally self-reflecting, providing us with a glimpse into what people in the past thought about their lives.

UNESCO recognized the outstanding value of the rock art by inscribing Tanum (Bohuslän, Sweden), an area with the densest distribution of such images, onto the world heritage list. Even before this, Tanum and other rock art locales in Sweden attracted tourists, and to facilitate this the images of the most famous sites are painted red to make them more visible.

We here present an initial study using thermal imaging of the paint to investigate how it may be affecting the rock, and therefore the rock art. We have determined that the paint creates high temperature differentials when it is heated up by the sun and then cools at night. We discuss the potentially detrimental effect of these thermal differences, especially given that the changes are so spatially close.

Application of ultrasonic soundwave velocity for investigation and documentation of Bronze Age rock art in Tanum, Sweden

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The Bronze Age rock carvings in Tanum, Western Sweden, have been the topic of research for more than a century, and in 1994 the area was designated as world heritage site due to the exceptional density and quality of the engravings. Although the meaning of the depictions and their role in Bronze Age society is widely discussed (Horn et al. 2020, Skoglund et al. 2022, Tilley 2021), while very little is known about the carving process itself (Lødøen 2015). For this study we focus on carvings made in the monzogranitic Bohus granite.

Here we present pieces to the puzzle on why the Bohus granite was such a great canvas and why the people at the time were able to carve in this hard rock. The glacial polished surface of the Bohus granite created not only a great contrast to the later carved images, but also impact the rock properties of the upper few mm to cm (Blackburn et al. 2019, Siman-Tov et al. 2012). We present data from soundwave measurements of 4 localities (panels), which indicate the pressure release after the melting of the glacier resulted in surface parallel microfractures (relaxation fractures), causing a weakening of this uppermost layer with its polished surface. Comparing the depth of the carved images, using advanced 3D photogrammetry analysis, with the thickness of this top layer shows that none of the images are deeper than the thickness of that layer. We believe that this weakened top layer is a key element for the Bronze Age artists to be able to carve the rock with tools available at the time.

The impact of the carving process itself created another generation of microfractures. Those are expected to mostly incline medium to steep and are therefore already by orientation differentiable from the relaxation fractures. The increased fracture density inside a carving comparing to the surrounding matrix leads to a decrease in soundwave velocity. This provides us with a tool for documentation of the images as well as monitoring their state of weathering. While monitoring the effect of local weather changes on the signal we found heat stress to be one of the most important ones. Especially during the spring to early summer month, the temperature variation in the rock from heating through sun radiation in change with the still freezing temperature at night are stressing the rock to a high extend, and increases the risk of rock spalling, which will damage the carvings.

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Modeling the social process behind the selection of rocks and the positioning of rock art figures in Aspeberget during the Bronze Age

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Scandinavian Bronze Age rock art (1700–500 BC) constitutes one of the world’s richest prehistoric legacies. Over the years, rock art has been used as evidence to verify ideas about Bronze Age ideology, religion, long-distance exchange, warfare, landscapes, and social organization (Ling 2008). However, because of the large number of motifs in the region and their complex distribution over time and space, fitting these theoretical models to the available data is always a hard task.

One of the topics that most debate has generated among the research community in the last few years is the landscape dimension of the phenomenon (e.g. Bradley 2002; Ling 2008; Goldhahn 2010; Ling 2013; Tilley 2021). It has been argued that the selection of panels was closely linked to, for example, the evolution of the coastline (Ling 2008; 2013), the symbolic value of the place before being carved (Goldhahn 2010), or the creation of narratives (Tilley 2021). Recently, it has also been shown that figures were placed on the panels according to how water naturally flows over the rock (Horn, Potter, and Peternell 2022; cf. Bengtsson 2004). However, other potential confounders, like the geological properties of the rock or the constraints of social practices, have been overlooked.

To address this problem, I will present an exploratory data analysis of the rock art panels located on the Aspeberget hill in Tanum parish. All the panels were documented in 3D, segmented, and annotated with chronological and geological information. The data was incorporated into multi-level models to try to answer the following questions: why were panels initially selected? Why have some panels collected more figures than others? Did the geological properties of the rock constrain the selection of panels and the position of figures? How were panels approached and re-approached by the carvers over the Bronze Age?

The preliminary results show that the selection of panels and the creation of motifs followed non-linear temporal and spatial dynamics and that more complex modelling techniques will have to be used in the future to fully characterize the phenomenon.

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Aspects of geoarchaeology

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Geoarchaeology is an extensive subject mostly applying geological techniques and archives to solve problems in archaeology. Geology and archaeology share a range of similarities such as a reliance on fieldwork and the need to use observations to reconstruct the past, without reliance on experiments. Because of these similarities, geoarchaeology can help both archaeologists and geologist in unexpected ways. Two archives are presented to show how archaeological information can benefit geologists and how geological analytical techniques can benefit archaeology.

A Roman dining hall in Ephesos, Turkey (Passchier et al. 2019) was decorated with thin plates of marble mylonite, all cut from the same block. Detailed analyses of the folds in the plates in a 3D reconstruction allowed imaging of sheath folds in the original marble block, and a calculation of the amount of material loss during cutting and polishing of the plates. The sequence of the decorated plates on the wall could be reconstructed, and with this information, the decoration strategy of the dining hall could be determined.

Roman water supply systems belong to the most impressive remains from antiquity and contain an archive in the form of carbonate deposits (Sürmelihindi & Passchier 2023). This carbonate archive is a rich source of information on the environment, and for archaeology. Examples are given how this news archive can be used to reconstruct and date earthquake damage from a double aqueduct in Ephesos; to reconstruct the workings and maintenance of Roman watermills in the pre-industrial mill complex of Barbegal, France; and to determine the cleaning strategy of the Roman aqueduct of Cahors and its socio-economic implications

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Digitally reconstructing an iron production landscape: The spatiality and chronology of iron production sites within northern Sweden

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I aim to present the preliminary results of my MA thesis within archaeology, which analyses the spatial- and chronological distribution of bloomery iron production sites within Northern Sweden through GIS and statistical software. Given the notion that interdisciplinarity within research has been highlighted as important during recent years, an archaeological perspective of how natural resources have been utilized to produce iron in the past could be a fruitful way of broadening the discussion within a geological context. The thesis operates on a landscape scale where watersheds of major rivers have been applied to discern study areas for analysis. Iron production has been discussed on a landscape scale within previous research (e.g. Magnusson 1986; Svensson 1998). There is however a lack of applied GIS- and statistical analyses within previous archaeological iron production research, to which my thesis can contribute. The material that is being analysed consists of the spatial position of all known bloomery iron production sites registered in the Swedish National Register of ancient features, as well as a database of radiocarbon dates that has been developed for the thesis, which consists of over 1200 dates, and represent all the available radiocarbon dates of iron production sites within Sweden. By applying the latest methods of statistical modelling in analysing the radiocarbon dates, the thesis offers a refined and more nuanced understanding of chronological changes in iron production within different geographic areas of Northern Sweden, during the past. The analysis aims to answer research questions concerning regional and chronological differences in the spatial distribution of bloomery iron production sites and to discuss what these patterns can say about the organization and importance of iron production within past societies. Furthermore, the thesis also aims at developing a method to identify hot spots in the landscape of iron production, through the application of predictive modelling. One major research problem within archaeological outland research today is the lack of knowledge of where in the landscape outland sites, such as iron production sites are located (Hennius 2021: 51). The application of predictive modelling is therefore potentially a fruitful approach to narrowing down the areas of search within archaeological surveys, and in that way contribute to more future knowledge being gained within iron production research.

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