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UNIVERSITY OF OULU

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Thermodynamic Constraints on the Petrogenesis of Massif-type Anorthosites and Their Parental Magmas

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Development of computational modeling of igneous processes from binary mixing equations to thermodynamically controlled geochemical assimilation-fractional crystallization (AFC) tools has revolutionized the field of igneous petrology. The Magma Chamber Simulator (MCS) is a thermodynamic + geochemical modeling software that can be used to model simultaneous magma crystallization, magma recharge, and crustal assimilation in an evolving multicomponent-multiphase open magmatic system (Bohrson et al., 2014).

Although anorthosites (>90 vol% plagioclase) and their less feldspathic derivatives (i.e. anorthositic rocks, 65–90 vol% plagioclase) show simple mineralogy, the origin and composition of their parental magmas have remained as a petrological dilemma. Proterozoic massif-type anorthosites are usually found in anorthosite-mangerite-charnokite-granite (AMCG) suites together with minor fine-grained monzodiorites. Massif-type anorthosites have been suggested to originate either from mantle-derived and crustally contaminated high-Al basaltic parental melts (Emslie et al., 1994) or monzodioritic parental melts derived directly by melting of lower crust (Duchesne et al., 1999). Regardless of the source, the parental magmas have been suggested to have undergone polybaric fractional crystallization and density separation while ascending through the lithosphere (Emslie et al,. 1994). Some studies have also suggested that monzodiorites represent the residual melts left after crystal fractionation rather than parental magmas for the anorthosites (Fred et al., 2020).

We used high-pressure (1000 MPa) assimilation-fractional crystallization and isobaric (1000,900,..100 MPa) fractional crystallization modeling conducted with the MCS combined with-high pressure lower crustal melting (1000 MPa) and polybaric (~1000–100 MPa) fractional crystallization modeling conducted with rhyolite-MELTS (Gualda et al., 2012) to study the petrogenesis of massif-type anorthosites. We compared our modeling results to a data set of previously suggested massif-type anorthosite parental melt and monzodioritic and anorthositic rock compositions.

The models suggest that the massif-type anorthosite parental melts were of high-Al basaltic composition and were produced when mantle-derived partial melts assimilated lower crustal material at higher pressures. These basaltic parental magmas then experienced polybaric fractional crystallization at different crustal levels, which produced residual melts of monzodioritic composition. Model outcomes also indicate that density separation played an important role in production of the plagioclase-rich anorthositic rocks. We suggest a four-stage model where 1) AFC produces high-Al basaltic parental melts, 2) fractional crystallization of the parental melts and density separation produce plagioclase-rich mushes, 3) crystal mushes undergoing polybaric crystallization and ascent through the crust, and 4) the anorthositic rocks and monzodioritic residual melts crystallize at emplacement levels.

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Thermodynamic constraints from the Magma Chamber Simulator on assimilation of silicic crust in primitive magmas

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Some studies of basaltic and more primitive rocks suggest that their parental magmas have assimilated tens of percent of crustal silicate wallrock. But what are the thermodynamic limits for assimilation in primitive magmas? This question has been considered for over a century, first by N.L. Bowen and by many others since then. Here, we pursue this question quantitatively using a freely available thermodynamic tool for phase equilibria modeling of open magmatic systems – the Magma Chamber Simulator (MCS; https://mcs.geol.ucsb.edu).

In the models, komatiitic, picritic, and basaltic magmas of various ages and from different tectonic settings assimilate progressive partial melts of average lower, middle, and upper crust. In order to pursue the maximum limits of assimilation constrained by phase equilibria and energetics, the mass of wallrock in the simulations was set at twice that of the initially pristine primitive magmas. In addition, the initial temperature of wallrock was set close to its solidus at a given pressure. Such conditions would approximate a setting with tabular chambers and high magma input causing concomitant crustal heating and steep geotherms.

Our results indicate that it is difficult for any primitive magma to assimilate more than 20−30 wt.% of upper crust before evolving to compositions with higher SiO2 than a basaltic magma (52 wt%). However, if assimilant is lower crust, typical komatiitic magmas can assimilate up to their own weight (range of 59−102 wt.%) and retain a basaltic composition. Even picritic magmas have a thermodynamic potential to assimilate 28−49 wt.% of lower crust before evolving into intermediate/felsic compositions.

The parental melt composition and the assimilant heavily influence both how much assimilation is energetically possible in primitive magmas and the final magma composition. Assimilation of upper crustal materials by komatiites leads to compositions similar to Precambrian siliceous high-magnesium basalts. The fact that mantle melts have potential to partially melt and assimilate significant fractions of lower crust may have fundamental importance for how trans-Moho ultramafic-mafic magmatic systems evolve and how crustal growth is accomplished. Examples include mineralization related to large-scale melting-infiltration fronts and anorogenic anorthosite-mangerite-charnockite-granite complexes with geochemical evidence of considerable geochemical overprint from crustal sources. The MCS provides a powerful tool to study such processes.

Non-igneous "pseudogranites" in southernmost Finland

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Before granites were recognised to have formed through crystallisation of melts, many geologists working in high-metamorphic terranes believed that they formed through metamorphic and/or metasomatic processes (e.g., Cobbing 2000). In southwestern Finland, Edelman (1972) interpreted that fluids had initially caused secondary potassium feldspar crystallisation and subsequently full "granitization" of originally supracrustal rocks, resulting in metamorphic granites with preserved bedding. As partial melting and the crystallisation of granite from melt have become better understood, the purported bedding can now be explained as layer-parallel leucosomes in migmatite. However, the development of large potassium feldspar crystals in seemingly supracrustal layers so that the rocks resemble granites is difficult to explain with partial melting or melt crystallisation. Thus, it has been unclear if the megacryst-bearing rocks are true, igneous granites or altered supracrustal "pseudogranites".

In the inner archipelago of Ekenäs in southernmost Finland, volcanogenic supracrustal rocks originally formed during the early Svecofennian orogeny (1.90-1.89 Ga, Hopgood et al. (1983)) contain secondary orthoclase megacrysts sized around 1 mm to 1 cm. Megacrysts appear in compositionally different layers of the supracrustal rocks, megacryst size varying with the host rock composition. In the outer archipelago of Ekenäs and Hanko, megacrysts in the supracrustal rocks are larger, frequently over 1 cm across. A granitoid containing similarly large orthoclase megacrysts is also common in the outer archipelago. Both megacryst-bearing rocks were heavily deformed and partially melted during the late Svecofennian stage (1.84-1.81 Ga), and they are similarly oriented in the field. Some cross-cutting contacts between the granitoid and the megacryst-bearing supracrustals exist, indicating that the granitoid intruded between supracrustal layers.

The megacryst-bearing supracrustal rocks of the outer archipelago and the megacryst-bearing granitoid are similar in mineral and geochemical composition, having compositions similar to true granites. Possible mineral textures indicative of the differing origins of the supracrustal and granitoid rocks were likely obfuscated during the anatectic event, as micrographic comparisons show no differences between the rock types. Apart from the field evidence, only U-Pb in zircon age data reveal some differences between the rocks: those with supracrustal origins were formed around 1.89 Ga, whereas the granitoids crystallised around 1.88 Ga.

The potassium influx that caused orthoclase megacryst formation in the supracrustal rocks likely came from fluids. The fluids may have accompanied the 1.88 Ga granitoid as it intruded between the supracrustal layers. Alternatively, fluids may have passed through the area independent of any magma intrusions. We have found evidence of potassium-rich fluids altering a 1.84 Ga leucogranite in the area, and suspect that fluids were involved in the anatectic event at 1.84-1.81 Ga. In either case, metasomatism was an integral part of the Svecofennian evolution in southernmost Finland.

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The tholeiitic intraorogenic Kaiplot gabbro in Nagu, SW Finland – an extensional phase in the Svecofennian orogeny

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The Southern Finland Subprovince (SFS) of the Svecofennian orogen has been described as an accretionary orogen with arc systems that collided with each other during the synorogenic stage ca 1880-1870 Ma. During the oblique collision between Sarmatia and Svecofennia, the SFS was reactivated in a transpressional regime with large scale folding and the generation of migmatites and granites of the Late Svecofennian Granite and Migmatite zone ca 1840 – 1820 Ma. (i.a. Nironen (2017) and references therein).

Simonen (1980) proposed an "intraorogenic" episode with amphibolite dyke intrusions between these two collisional stages. It has since been identified as a bimodal magmatic phase that occurred in the SFS and the Swedish Bergslagen-Ljusdal area. Mafic intrusions dated to 1865-1848 Ma are intermingled with more felsic coeval magmas (i.e.Väisänen et al. 2012, Nevalainen et al. 2014, Kara et al. 2020, Johansson & Karlsson 2020). Mature quartzites found in both SFS and Bergslagen-Ljusdal imply the existence of clastic sedimentary basins during this intraorogenic phase (Bergman et al 2008, Lahtinen & Nironen 2010).

This study concerns an area of bimodal magmatism in northern Nagu in the archipelago of SW Finland. The mafic part of this intrusion is the Kaiplot gabbro, which occurs as both plutons and dykes. This study has determined the age of the Kaiplot gabbro to be 1865±2 Ma (U-Pb, zircon).

The Kaiplot gabbro is tholeiitic and shows MORB affinities. The highest Mg# of the analysed samples is 65, the amount of Cr ≤ 260 ppm, Ni ≤ 70 ppm which indicates that the magma source is relatively primordial. Geochemical modelling (non-modal batch melting models) suggests that the magma source for the Kaiplot gabbro is a spinel – garnet lherzolite situated in the transition between the lithospheric and asthenospheric mantle. In the discrimination diagram of Cabanis & Lecolle (1989) and Shervais (1982) the Kaiplot gabbro falls in the fields of volcanic arc and back arc basin tholeiites during extensional conditions.

To conclude, the Kaiplot gabbro confirms an extensional tectonic episode with upwelling of astenospheric material during the intraorogenic interval between the two collisional phases of the Svecofennian orogeny. The bimodality of the intrusions suggests anatectic melting of, and mingling with, the surrounding rock. How much felsic magma that was generated by the mafic intrusions is unclear.

Extension of a modern arc – Rapid detachment faulting in the Banda Sea, Indonesia

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Subduction zones, and the orogens that form adjacent to them, are complex and dynamic tectonic environments. A subducting slab will typically be heterogeneous in composition, thickness, and density, and will also be riddled with pre-existing structures that will strongly influence how the slab deforms and interacts with the mantle during subduction. The structure and configuration of the overriding plates and adjacent subduction zone systems will also influence how a single arc environment will evolve through time. The subduction history will ultimately be recorded by the magmatic, volcanic, deformation, and metamorphic record of different components of the arc system; but reconstructing a detailed arc history is notoriously difficult. These challenges are exacerbated greatly when investigating old (Proterozoic) orogens, for which the polarity, location, or even the very existence of a subduction zone may be tricky to infer.

The advantage of studying young metamorphic and magmatic rocks is that they are often found within, or close to, the same tectonic environment that formed them. In contrast to high-grade rocks in Paleoproterozoic cratons, or even within mature mountains belts such as the Himalaya or Alps, exhumed metamorphic and igneous rocks in active arc settings can be linked, more-or-less directly, to their tectonic drivers. A further advantage of 'modern' arc settings is that their seismicity typically enables the geometries of subducted slabs to be inferred relatively accurately.

Eastern Indonesia lies at the heart of the Australia-SE Asia collision zone, and comprises multiple subduction zones and arc settings that are actively accommodating that overall convergence. Here, we focus on the Banda Arc, demonstrating how rapidly exhumed high-grade metamorphic rocks and ultramafic complexes derived from the upper mantle may be used to chart a history of pulsed subduction rollback and extension of the upper plate. Here, the timescale of high-temperature metamorphism, driven by subduction-induced extension, is on the order of just a few million years, with the exhumation history being exceptionally rapid (Pownall et al., 2014, 2018). Substantial lithospheric extension in the upper plate was accommodated by a major, previously unidentified, low-angle normal fault system termed the Banda Detachment (Pownall et al., 2016), whose operation produced Earth's deepest forearc basin, the 7.2 km Weber Deep, in as little as 2 Myr.

The Banda Arc documents an intricate history of extremely rapid and short-lived metamorphic pulses, and rapid dismemberment and transport of newly-formed tectonic slices. However, this picture is in stark contrast to models inferred typically from older terranes involving extremely slow, long-lived, and continuous metamorphic and magmatic events. Do these two scenarios represent two fundamentally-different tectonics styles operating during different regimes of Earth history? Or perhaps the level of complexity resolvable in the modern Earth is currently inaccessible with current approaches when looking back deeper in time?

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(Fin)gerprinting the origin and ascent of (mag)mas through the crust in rift zones (FINMAG): A case study of the Fjallgarðar Volcanic Ridge (Central East Iceland)

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The Icelandic extensional intraplate environment has experienced extensive changes in lithostatic pressures during deglaciation. The newly established project "FinMag" will undertake a multifaceted study aimed at improving our understanding of mantle melting regimes in response to isostatic uplift (i.e. post-glacial lithospheric rebound) and its effects on the volume and composition of melts produced. The currently ongoing study is focuses on the central volcanoes (e.g., Askja) and the Fjallgarðar Volcanic Ridge (Central East Iceland), which extends for almost 190 km from the northern extent of the Vatnajökull glacier to the Slétta peninsula in the north. The ridge consists of a series of interglacial and sub-glacially erupted volcanic strata, likely formed during dyke-fed fissure eruptions over the last 0.8 Ma [1]. In general, this region preserves a relatively homogenous crustal section that may permit for an undisturbed view into the upper mantle and the processes of magma ascent. A strong extensional, structural component and changing post-deglaciation isostatic pressures at <11 ka [2] have imparted changes on magma composition with those in the crust at both spatial and temporal scales. The stratigraphic evolution of flow series from individual eruptive centres, as well as the chemical and petrological variability of the dyke systems, however, remain poorly constrained.

We present an overview of the objectives of the FinMag project and its aims to determine: i) changes in composition and heterogeneity of the mantle source in the Fjallgarðar Volcanic Ridge region, ii) constrain the depths and rates of magma ascent, iii) determine the depths and timescales of magma storage to eruption, and iv) develop a geodynamic model underpinning the response of melting and magma ascent to the effects of postglacial rebound lithospheric rebound. Furthermore, preliminary overview geological and geochemical data collected on the Holocene Sveinahraun lava flows and the Sveinar-Randarhólar crater rows from a 75km fissure swarm in this region is presented.

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Quantitative mineral analysis for revealing sediment provenances and rock characteristics: review and outlook

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A quantitative evaluation of minerals in sediment and rocks has been coming increasingly useful in geosciences as in-situ micro-analytical automated techniques have developed, however, originally devised and introduced for industrial needs. These techniques enable a quick identification the most useful rock-forming and ore indicator minerals and quantify their relative abundances especially when looking for critical metals or minerals. The analysed phases are classified as specific minerals according to their chemical composition compared to that within a user developed reference mineral library. In more advanced varietal analysis even trace and isotopic signals of single grains of a specific mineral can be utilised in provenance studies and in determination of maximum depositional ages (Weltje & von Eynatten, 2004). All factors controlling the compositional modifications need to be always clarified when a parent rock transform to a final deposit. The variation in chemical composition of individual heavy minerals, however, is valuable information in identifying parent rocks for the sediment, sampled from older sedimentary successions.

Varietal mineral analysis has been utilized successfully for a retreat history of the southwestern sector of the Barents Ice Sheet by studying late glacial ice-rafted debris (Kaparulina et al., 2018) and to evaluate the Barents-Kara Ice Sheet history from the Lomonosov Ridge sediments (Kaparulina et al., 2016). Heavy mineral varieties (chemical fingerprints) can be established based on electron microprobe analyses and heavy mineral types can easily quantified by Mineral Liberation Analysis (MLA), which utilize a rapid scanning electron microscope particle analyser. Trace element contents and isotopes in certain heavy and light minerals opens new insights. Pb and Nd isotopic compositions of detrital feldspars can be seen a valuable new provenance tool, as detrital feldspars commonly represent one sedimentary cycle and grains can be tracked back directly to their sources. Also, zircon dating has been successfully utilised to determine maximum depositional ages of Paleoproterozoic sedimentary rocks with excellent examples from the Pretoria Group, South Africa (Schröder et al., 2016) and northern Fennoscandia (Köykkä et al., 2019).

When mineral varieties in trace elements and isotopic tracers are combined with automated mineral analysis, which does not store compositional data for each mineral grain, a broader understanding can be reached in characterizing rocks and ore deposits and give tools also for cross-validation. The quantitative study of the mineralogical, and geochemical composition of sedimentary deposits and rock is even further essential presently for improving our capability to exploit natural resources and to understand and manage environmental change.

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SEM-based automated mineralogy (SEM-AM) and unsupervised machine learning studying the textural setting and elemental association of gold in the Rajapalot Au-Co area, northern Finland

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Automated mineralogy techniques have grown their popularity during the last decades. They allow fast and effective way of studying the textural settings of valuable minerals and overall modal mineralogy of rocks. Unsupervised machine learning (e.g. self-organizing maps) is an intuitive way of processing multi-dimensional geochemical datasets in order to reveal hidden patterns potentially represent different mineralization stages. In this study, these two methods are combined for studying the relationship of gold and cobalt within different occurrences in a Paleoproterozoic gold-cobalt mineralized area known as Rajapalot. Gold is found as a texturally late phase, occurring in fractures of silicates and sulfides. The elemental associations observed from the whole-rock geochemical dataset using self-organizing-maps revealed distinct groups characterized based on the nature of Au and Co, 1) Co-only, 2) Au-Co and 3) Au associations possibly related to different mineralization stages or different fluid-host rock interactions. Also, the dominant mineralization-related alteration in different occurrences within the Rajapalot Au-Co prospects are reflected as elemental associations with gold in the geochemical data. Our study shows the effectiveness SEM-AM methods for studying distribution of valuable minerals. Unsupervised neural networks provide for easy and intuitive processing technique that can be validated with the mineralogical observations.

Integrated development of geochemical and indicator mineral research techniques, and professional competence for ore exploration

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The mining industry is growing steadily in Finland. The most significant growth and strongest investment are focusing on Central Lapland and especially in Sodankylä. At the same time, there is increasing demand on developing services for the on-site indicator mineral concentration and analytical techniques as well as educating staff for the exploration companies need. To support the demands, two projects were launched in Sodankylä: the project 'Pilot testing and demonstrating on-site methods for mineral exploration in Sodankylä' (Indika Au) funded by European Research Develop Fund and lead by the Sodankylä municipality, and the project 'Development of competence for ore exploration and research' (METSO) funded by the European Social Fund and lead by the Lapland Education Centre REDU, Sodankylä. Partners are the Geological Survey of Finland and the Oulu Mining School.

An aim of the Indika Au project is to produce practical information on new on-site mineral exploration methods to develop the service offering and new operation opportunities in the exploration business and to reduce the environmental impact. The project will produce experimental data for the assembly of a mobile unit suitable for mineral exploration with a view to on-site pre-treatment and analysis of soil and weathered bedrock samples related to indicator mineral exploration directly in the field or at a field camp. The methodological development is focusing especially on techniques suitable for gold prospecting, but the methods are also suitable for exploring many other types of ores, such as critical metals needed for high-technology and batteries. Sample pre-processing and analytical testing directly on the exploration site reduces the need to transport samples, enables a rapid and resource saving research process, lower environmental impact, and provides an opportunity for new business and operating models in a key exploration area, in Central Lapland.

An aim of the METSO project is to increase the technical know-how of subcontractors doing simple ore research, for example by providing sampling services, field pre-processing and analyses, to improve and expand their product range and thus add value to their products. In addition, REDU will develop educational packages to further educate people in some related field, such as the civil engineering side of the business so that they could develop their services to suit better in the ore exploration and thus expand their service offerings extractive industries or, at best, create a whole new SME business in northern Finland. During the project, the readiness of teachers at REDU will be increased by giving professional geoscience education and producing teaching materials in the field of modern ore exploration, and by planning and piloting exploration projects and equipment procurement. Based on the competence needs of companies, locally offered degree components or entities consisting of already existing degree components are planned. The project will create and pilot at least two training modules including, for example research assistant and technician who have readiness to work in challenging Arctic conditions and are experienced in modern field techniques in ore exploration.

Trace element and isotope analyses of sulphide minerals in mineral deposit fingerprinting: A case study from Petäjäselkä Au occurrence, northern Finland

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Geochemical and indicator mineral research methods are widely used in mineral exploration in the glaciated terrains. Transported cover sediments such as unconsolidated till and upper soils are typically used in targeting the source areas and detecting mineralizations under transported cover. Composition of heavy minerals such as sulphides in till can be potentially used to fingerprint mineral deposits. The LA-ICP-MS analytical techniques allows extremely detailed analyses of trace elements and isotopes from individual mineral grains down to a few tens of micrometres in size. In this study, we present preliminary results from in-situ trace element and S isotope compositions of pyrite in heavy mineral separates collected from the Petäjäselkä area, in the Central Lapland Greenstone Belt, northern Finland. The results are compared against pyrite compositions from the Petäjäselkä Au occurrences in order to trace the source rocks and fingerprinting capabilities. The study is a part of first author´s PhD project within the EIT Raw Materials funded Enhanced use of heavy mineral chemistry in exploration targeting (MinExTarget) project. The goal of project is to develop effective fingerprinting techniques using various minerals in tills which can be used in the greenfield exploration stages. Furthermore, the project develops a new service for mineral exploration by a novel combination of the available technologies of automated mineralogy and mass spectroscopy.

Apatite composition in the Siilinjärvi glimmerite-carbonatite complex, eastern Finland

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This contribution details a part of the first author's doctoral project, which focuses on the trace element chemistry of apatite in various magmatic rock types. This case study deals with the composition of apatite in the glimmerite-carbonatite rocks of the Archean Siilinjärvi complex (e.g., O'Brien et al. 2015). The composition of apatite in different phases of the complex has previously been the subject of only one dedicated study (Decrée et al. 2020).

Rock samples from the Särkijärvi main pit and the Saarinen satellite pit of Siilinjärvi were provided by Yara Suomi Oy. Apatite was studied in thick sections in situ with electron microprobe (EPMA) and laser ablation inductively coupled plasma mass spectrometer (LA-ICP-MS), combined with cathodoluminescence (CL) and scanning electron microscopy (SEM) imaging techniques.

Apatite is a major rock forming mineral in all of the samples and is present as subhedral crystals, up to several centimetres in size, which are often fractured or broken. The apatite grains often exhibit complex zoning, which can be seen in CL images but not in backscattered electron (BSE) images. Apatite from both pits is fluor-hydroxylapatite with typically low concentrations of chlorine, yet some grain zones have up to 1.9 wt% Cl. Such elevated apatite Cl values have not previously been reported from Siilinjärvi. Mean fluorine concentrations are stoichiometrically 1.4 and 1.2 apfu F in Särkijärvi and Saarinen, respectively. Calculated mean hydroxyl concentrations are 0.6 apfu and 0.8 apfu in Särkijärvi and Saarinen, respectively. The elevated Cl concentrations correlate positively with SrO in some grains. Stoichiometric calcium concentrations are 9.92±0.04 apfu in both pits. Besides Ca, the cation sites are occupied primarily by Sr and Na, typically less than 0.2 apfu combined.

Total REE (TREE) concentrations are generally 3000–4000 ppm but some grain zones have concentrations up to 7000 ppm. All apatite analyses show strong light REE enrichment and very gentle slopes from light REE to middle REE. The apatite compositions show slight differences between the two pits. Apatite grains from Särkijärvi have higher F, TREE, Sr, and Zr concentrations than the ones from Saarinen, which have higher concentrations of Pb, Th, and U.

The apatite morphology, textures, complex zonation patterns in CL images, and chemistry allow to distinguish post-crystallization reworking such as deformation, metasomatism, and possibly recrystallization. These characteristics indicate a complicated history following the initial crystallization. The low REE concentration is likely inherited from the parental magma.

Many recent contributions show that apatite chemistry holds a great potential in the study of magmatic systems. Thus, collection of comprehensive compositional datasets from well-studied localities with diverse geochemical contexts opens new avenues on multiple scales of petrogenetic studies from global comparisons to detailed microanalytical applications. In Siilinjärvi, apatite shows compositional variance between the magmatic glimmerite-carbonatite rock types and the surrounding metasomatic fenite but also within the magmatic domain as is evident from the results presented here.

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Simulations of lakeshore infiltration and groundwater interactions of the glacial aquifers at Lahti site, southern Finland

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Lake infiltration has been an important source of groundwater recharge in many areas. However, it has been also implicated as a source of nutrients and other potentially harmful substances to the aquifer. Moreover, the impacts of human activities such as the pumping of groundwater nearby the lake shore area can accelerate the solute transports in to the aquifer, which can cause degradation of groundwater quality. Understanding the interactions of surface water and groundwater and the factor controlling the lakebed infiltration is essential for water supply and resource managements.

In this study the hydrogeological characteristics of the glacial aquifer system in Lahti was first investigated to provide the hydrogeological framework for the groundwater flow modeling. Three-dimensional groundwater flow MODFLOW model coupled with the UZF model package was then used to simulate water flow from the unsaturated zone to the aquifer. The snow and PET models were utilized to calculate the surface water availability for infiltration from the precipitation data used in UZF. Infiltration rate, flow in the unsaturated zone and groundwater recharge were then simulated using UZF. In the lake shore, the River (RIV) package was used to estimate the surface water and groundwater interactions through the lakebed infiltration. Results showed that at the constant pumping rates, the spatial and seasonal variability of the lakebed infiltration flux rates corresponded directly to the continuity of the fine-grain (clay) layer and the magnitude of surface water. High infiltration flux rates were observed along the lake shore where the fine-grained layers are thin or absent and during the high lake levels due to snowmelt or heavy rains.

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Ultra-high resolution sediment sequence from coastal Littorina sea spanning the Holocene thermal maximum – environmental magnetic study from Kurikka, Southern Ostrobothnia

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Both natural and anthropogenic factors cause present day hypoxia in the Baltic Sea basin (BSB), leading to the formation of sulfide sediments (Zillén et al. 2008). Moreover, acid sulfate soil is a common environmental challenge in areas of raised littoral deposits. Before present and medieval times, the BSB has experienced widespread hypoxia during the Holocene thermal maximum (HTM, ca. 8–4 ka) (Zillén et al. 2008). The extensive laminated sulfate sediments have thought to represent hypoxic conditions in the Bothnian bay throughout the early Littorina sea (Sohlenius & Öborn 2004). Yet past occurrences of BSB hypoxia have been recorded primarily in deep basin sediments cores with resolutions seldom exceeding ~0.01 cm/a. Little is still known of the seafloor redox condition variability in the littoral zone during HTM (van Helmond et al. 2017).

A promising novel proxy for oxygen depletion and redox zonation is occurrence of greigite (Fe3S4), a magnetic mineral that forms in sulfidic and methanogenic redox zones of the sediment-water interface (Roberts et al. 2018). Greigite has been identified from BSB sediments, (e.g. Sohlenius 1996, Kortekaas 2007, Lougheed et al. 2012, Reinholdsson et al. 2013) but the formation pathways are still under discussion.

Here, the environmental magnetic (EnvMag) methods are used to study the occurrence and characteristics of greigite in a HTM ultra-high resolution (0.75 cm/a) sediment succession from Kurikka, S. Ostrobothnia, Finland. A 40-m long sediment core was analyzed for lithology, magnetic susceptibility, organic matter content, grain size and EnvMag characteristics to construct the stratigraphy and magnetic mineral composition. The sediment core covers local deglaciation, Ancylus lake and Littorina sea evolution until isolation from the sea (~10 800–4500 a).

Authigenic single-domain greigite was found from Littorina sediments with signs of sulphidic redox origin. The results propose diagenetic origin for greigite in BSB littoral sediments, contradicting the earlier suggestion - derived from deep sea environment - of bacterial-only origin for greigite in the BSB (Reinholdsson et al. 2013). Furthermore, unlike previous studies, no greigite was found from Ancylus clays. The findings indicate different greigite formation processes for the littoral zones compared to those of deep-sea basins in the BSB. This suggests that even within the same basin and sediment units, the formation pathways of greigite differ.

Susceptibility was coupled to EnvMag results and used to assess hypoxia variation along the sediment sequence. Hypoxia was found to be frequent although discontinuous during the HTM in the shallowing Littorina sea bay. The large-scale trends of hypoxia were perennial, but possibility for (sub)annual variation could not be ruled out. Two periods of centennial hypoxia were identified, while the varying greigite concentrations indicate unstable oxygen conditions. Signs of short-termed oxic conditions between low-oxygen periods (~6500–7000 cal BP) were identified. The period has been previously identified with higher salinity levels and relative sea level rise in the BSB.

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Hydrogeological characterization of bedrock using Borehole Magnetic Resonance at a mining development site, Northern Finland

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The aim of this study was to test Borehole Magnetic Resonance (BMR) method for determining groundwater flow parameters (e.g. porosity, permeability and transmissivity) required for hydrogeological modelling at a hard rock mining project site. While BMR is widely used for determining storage and flow properties of hydrocarbon reservoirs, there are not many studies that have utilized BMR in hard rock environments. The BMR method measures response of the hydrogen nuclei (of the water molecules present in subsurface materials) when external alternating magnetic fields are introduced as a sequence of pulses. The measured response is inverted to give a continuous distribution of relaxation time T2 which is a direct measure of the amount of water, or pore volume. The main hydrogeological property determined from the T2 distribution is the total water content or total porosity. This can further be divided into bound water and free water using specific cut-off values for each lithology, which can then be used to calculate estimates of hydraulic conductivity.

Our study area comprises the Sakatti Cu-Ni-PGE deposit in Northern Finland, located below the Natura2000-protected Viiankiaapa mire, displaying complex and heterogeneous subsurface geology, hydrogeology and structural setting. The BMR data were acquired by QTeq and AA Sakatti Mining Oy from six 50-350m deep drillholes in order to obtain specific information about the structural heterogeneity and free water content within this depth interval, and thus estimations of the flow parameters. Other available data, such as natural gamma ray, acoustic image data and core logging, and packer tests were compared with the BMR data in order to calibrate the groundwater flow parameters calculated based on the BMR measurements.

The results indicate that the BMR method is suitable for the lithologically and hydrogeologically heterogeneous fractured crystalline bedrock environment, and it may reduce the more time-consuming methods such as flowmeters and packer tests, as BMR can also provide information within the more fractured bedrock in a more detailed and continuous manner. Flow parameters derived from the measured T2 distributions vary significantly throughout the intervals. In this crystalline bedrock setting, independently from the lithological composition, the measured intervals locally display relatively high hydraulic conductivities, and may be correlated to the more intensely fractured and/or brecciated zones. The interpretation of the BMR data, in particular adjusting the cut-off values for the free water component of the T2 distribution, has a great impact on the porosity characterisation within the crystalline bedrock environment. However, the method may not be reliable within zones with increased magnetic susceptibility (presence of ferromagnesian minerals) and where higher background noise in log readings is recorded (e.g. formation effects or radio-frequency interference).

This work is one of the first studies that investigates the applicability of the BMR method in the hard rock environment. BMR may offer more accurate, non-invasive and cost-effective solutions to quantify the parameters for constraining hydrogeological modelling within fractured and altered bedrock. The characterization of hydraulic properties of deep bedrock, shallow fractured bedrock, surficial deposits as well as groundwater and surface water flow patterns and interactions between them is informative already during ore prospecting phase. These hydrogeophysical parameters will be integrated into a 3D hydrogeological model in order to aid planning of the mineral extraction in a sustainable way.

Flexible seismic data management with NorDB and NorLyst

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The NorDB seismological database toolset and NorLyst graphical seismic analysis software have been developed at the Institute of Seismology, University of Helsinki (ISUH) since 2017. These tools have been used to produce and store seismic event metadata in the daily analyses of local seismic events (Veikkolainen et al. 2021) at ISUH since June 2020.

The data structure of NorDB closely follows the Nordic data format (Institute of Seismology, 2020) yet it incorporates several improvements beyond the Nordic standard. For example, recording of full seismic phase arrival times from arrival data files is possible. Tools for Nordic data validation and transfer to other formats are available. The database also has structures for storing seismic station metadata. To manage station data graphically, another program called StationTool is under development at ISUH. NorDB input and output are compatible with Nordic, QuakeML and StationXML formats.

NorDB has been written in Python 3 language and relies on PostgreSQL database system. It can be installed on computers with Unix-based operating systems. The database can be accessed via a command line tool which allows the user to access most of its features. For example, these include searching existing events, inserting new events, and managing solution types used in association with events. Events can also be added or modified with the NorLyst program.

NorLyst is intended for analysis of seismic data that originate from the automatic event detection and classification system of ISUH (Kortström et al. 2016). The data are fed in to the database each night and typically reviewed within the daily analysis workflow within 3-5 weekdays. The main functionalities of NorLyst include core analysis tasks such as filtering seismograms, viewing spectra, as well as classifying and commenting events. Public comments can be added to data output. Private comments can be used for internal communication between the members of the seismic analysis team e.g. for further analyses of most important events as well as for compiling daily analysis data to monthly and yearly seismic bulletins.

The development of NorDB and NorLyst was heavily driven by the high (~94-97%) success rate of the automatic event identification that facilitated the main shift of seismic analysis from manual picking of events towards verification of automatically detected events. The vast majority of seismic events in Finland consists of obvious explosions that do not require manual picking of seismic phases and determination of magnitudes yet the source of these events is usually verified whenever possible. Currently the Geotool software (Henson and Coyne, 1993) of CTBTO is still used at ISUH for manual analysis of natural and induced earthquakes and other events of particular interest and will be used for that purpose also in future.

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Statistically generating particle number size distribution data through generative adversarial networks

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Atmospheric new particle formation (NPF), which is observed in many stations globally, is an important source of aerosol particles and cloud condensation nuclei, affecting the climate directly and indirectly (Yao et al., 2018, Kerminen et al., 2018, Su et al., 2021). To obtain the particle number size distribution (PNSD) data for NPF studies, expensive instruments and well-trained operators are required. Deep learning techniques such as the generative adversarial networks (GANs) (Goodfellow et al., 2014) provide possible tools to generate the PNSD data, leading to obtaining the PNSD data cheaply and conveniently.

Generally, GAN consists of a generator and a discriminator. The generator tries to find a function that can map samples in one distribution A (e.g., the normal distribution) to another distribution B (e.g., a distribution whose samples are images). Then the discriminator will check whether the distribution B is the same as the actual distribution C. As a result, the objective of a GAN is to solve the minimax problem for the generator and the discriminator, and theoretically, the best solution can be found at the Nash Equilibrium.

We constructed a GAN, and generated new PNSD data through the PNSD data collected in the SMEAR II station (Hyytiälä, Finland). Though the generated PNSD data do not have physical meanings, the generated data can help analyze the statistical properties of NPF events.

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Characterisation of Skarn Lithologies with Secondary Cosmic-Ray Muons

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Relativistic muons are heavy, energetic particles that can penetrate rocks for hundreds of meters. They are generated in the upper atmosphere due to the continuous interaction of the air nuclei with the galactic cosmic rays. In addition, also solar activity leads to the production of muons in the Earth's upper atmosphere. However, as the solar energetic particles are of much lower energy than those from the galactic sources, atmospheric muons produced by them do not significantly affect the muon flux underground deeper than a few meters. In contrast, the flux of high-energy muons is observable well below 1 km, but their counts also diminish drastically with increasing depth as more and more muons get attenuated by rocks. This property is exploited in muography to deliver directional information of average rock densities between the surface and muon detectors. Density images can be constructed radiographically in 2-D, tomographically in 3-D, or as a series of images ranged in time (time-lapse imaging mode).

There has been a steep rise in muography techniques and research publications in the last few years (Kaiser, 2019; Holma et al., 2021b). Geological applications include volcano imaging and monitoring, glacier imaging via underground tunnels, groundwater research and hydrogeophysics, structural geological studies, weathering crust characterisation (e.g., Holma et al., 2021a,c), and mineral exploration and mining engineering (e.g., Schouten, 2019; Zhang et al., 2020; Holma & Kuusiniemi, 2021; Holma et al., 2022). This work proposes that muography could be used in mineral exploration and resource delineation of skarn deposits as density variations between different skarn types and their immediate host rocks are often drastic. Furthermore, skarns typically show mineralogical zonation relating to their genesis from complex processes between wall rocks, heat and fluids. Kim et al. (2015) report densities from the Fe-Pb-Zn polymetallic skarn deposit located in South Korea. In this case, the garnet-rich and garnet ± pyroxene skarns accompanying Fe-oxides and sulphides have densities ranging 3.3–3.4 g/cm3, whereas the local quartz porphyry, wollastonite-rich skarn, and silicic hornfels have densities of 2.5–3.0 g/cm3. In addition, with a porosity of 1.8–8.4%, the local skarns are generally more porous than the other rocks (0.8–3.3%). Based on this example and the shared properties of most skarn systems, we propose that the density patterns within many skarn systems are adequate for muography, both in their physical dimensions and range of mineral density contrasts. However, a pilot study is required to demonstrate how well underground muography can differentiate between various skarn alteration zones and their protoliths.

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On the influence of K. H. Renlund Foundation

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K. H. Renlund Foundation has consolidated its position as a central player in the funding of especially applied geological research in Finnish universities and state institutions. The foundation transformed into a standard practise grant-making foundation at the beginning of this millennium, when it started to open annual calls for applications and an evaluation procedure to handle proposals was established. Since the year 2002 the foundation has granted altogether 13.8 M€ to 768 proposals covering topics specified in the statutes of the foundation. During the past 20 years the main share (37 %) of the funding has been allocated to mineral deposit and exploration studies. Projects on geo-environment cover 25 % of funded projects, groundwater studies 10 %, and geoinformation projects 10 % as well. During the past ten years there has been an increasing share of projects investigating problems of ore benefication or mining technology. The principal share of grant receivers represents the University of Oulu (30 %) and University of Helsinki (20 %). About 10 % of the funding has been allocated for small enterprises. Each year about 50 % of the applicants are awarded with the funding, which is an exceptionally high percentage.

The foundation has to be aware of how well it is achieving its goals announced in statutes. Therefore, the impacts and influence of the results of granted projects have been evaluated. The analysis has been conducted as a self-assessment based on internal documents, public databases and other internet resources. It can be considered as a preliminary overview supporting the activities of the foundation.

The scientific influence can be indicated by the amount of PhD dissertations. During the past 20 years, 34 doctors have graduated based on partial or full-time funding by the foundation. Of them, 29 doctors are graduated in geology, and during the past four years every other new PhD in geology has received our financial support. The continuous funding has also supported research achievements and made it possible to open novel research topics in our country, such as problems related to acid sulfate soils, questions of groundwater–surface water interaction or management of environmental impacts from tailings facilities. Current issues in our funding are studies on critical and battery minerals and investigations on recycling and reuse of geological materials. The foundation has been able to act as a risk financier backing new and unpredictable openings towards smart, sustainable and responsible use of earth resources.

Modern society needs up-to-date knowledge of geological raw materials, their socially acceptable exploitation and managed environmental impacts. K. H. Renlund foundation has promoted a large number of book projects, exhibitions and internet resources to support these goals. Today, managing of environmental and social concerns are cornerstones of productive exploration and mining operations. To support this, the foundation has backed the environmental impact assessment (EIA) procedures of various mining projects and supported publication of best available techniques (BAT) reference guides for the management of waste from extractive industries.

The influence of foundation has economic bearing, which is obvious with the exploration projects we have been involved. In addition, there are projects, which have developed into patents and small size business activities. Finally, one must remember the personal significance and potential influence of the economic support to young researchers doing their dissertations or post-doctoral research. As encouragement, the foundation grants annual prizes for best MSc theses and gives economic support for active layman prospects.

Catch up with FIN-GEO

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FIN-GEO Education Collaboration Network is a joint project of five universities offering education in geoscience and adjacent fields: University of Helsinki, University of Oulu, University of Turku, Åbo Akademi University and Aalto University. The project is funded by ministry of education and culture for three years (2021-2023) and aims to improve and formalize education collaboration between the partner universities. FIN-GEO activities include developing joint teaching materials and courses, educational and pedagogical training for geoscience teachers, and improving the visibility of Geoscience education.

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Popularization of geology through the renovated Geologia.fi portal

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In 2005, the Finnish National Geological Committee (SKGK) set up a working group tasked to create a web portal for the popularization of geology. The purpose of the portal was to create an easy access to geological information, the specific target groups being children, students, teachers, geology enthusiast and media. The Geologia.fi portal was launched and made available to the public in the autumn of 2007. Currently, the portal is hosted in the servers of the Finnish Museum of Natural History (LUOMUS), and the daily operation is managed by a chief editor.

The content of the portal is widely related to geology. The base materials include popularized scientific articles ranging from the beginning of the universe and the formation of Earth to the regional geological features of Finland, educational materials, links, dictionary, and descriptions of rocks and minerals. Furthermore, news articles are being published, as well as information about geology-related events. The front page also includes a changing picture of the month, and a link to send questions to a geologist.

The number of visitors has varied throughout the years. In 2020, Google Analytics registered 114797 users and 152470 sessions. Of the users, 88 % were from Finland and 10 % from Sweden. Most visits to the portal take place on weekdays from 8am to 3pm. The lowest number of visitors usually falls on weekends and school holidays. From the times of the visits, it can be concluded that the portal is being used especially by schoolchildren, students, and teachers. Also, a surge in visitor numbers could be observed in March 2020, when the Finnish schools started distance learning.

During the years, the graphical layout and the technical platform of the portal has been updated several times. The first major renewal was performed in 2011-2012, the second in 2018, and the third in the end of 2020. The main improvements of the 2020 update include modernized layout, enhanced speed and security, the return of the questions-to-geologist form, and functionality of bilingualism. Currently, the harmonization of the Finnish and Swedish articles is underway. During the harmonization, articles will be updated, if necessary, and new articles and educational materials added.

The Geologia.fi portal is a powerful tool for popularizing geology, especially among schoolchildren, students, and teachers. The portal is actively being maintained and updated on regular basis. The portal offers an efficient platform to disseminate research results, educational material and other geology-related information. Therefore, the actors in the field of geology are encouraged to utilize the possibilities offered by the portal.

Acknowledgements

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Preliminary results of the Baltic Ice Lake sediment record from the Landsort Deep, Baltic Sea in response to deglaciation events

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The location of the Baltic Sea Basin in a glaciation-sensitive latitude high in the northern hemisphere has led to a very dynamic development during its geological history, and the basin's sediments have been affected by the waxing and waning of the Fennoscandian Ice Sheet. The Landsort Deep is the deepest part of the Baltic Sea, with a depth of 459 m. The deep is located just south from the postulated margins of the early Weichselian glacial, and it displays a high-resolution sediment sequence from late Weichselian and Holocene (Andrén et al. 2015). Cores recovered from Site M0063 in the Landsort Deep during the IODP Expedition 347 were used for multiproxy sediment analysis. The Site M0063 is divided into seven lithostratigraphic units (Andrén et al. 2015), and the samples are from Hole M0063C from Units VI (54–93 mbsf) and V (48–54 mbsf). The sediment analysis included clay mineral and grain size distribution, loss on ignition (LOI) determination, and the utilization of the IODP Expedition 347 physical properties dataset for interpretation of the sedimentation related to deglaciation in the Baltic Sea Basin. The relative age determination of the analysed cores is based on knowledge of certain geological events in the Baltic Sea Basin history. The sediments of the Landsort Deep reflect variations of salinity in the Baltic Sea Basin, and it enables the identification of four major stages in its history: Baltic Ice Lake, Yoldia Sea, Ancylus Lake, and Littorina Sea (Böttcher and Lepland 2000). The determination of the stratigraphic characteristics of the sediments from Units VI and V enables the interpretation of the late and postglacial stage of the Baltic Sea Basin. The stratification of a glacial lake is related to sedimentation processes controlled by meltwater flows, direct deposition in the front of glacier ice, rain-out from icebergs and lake ice, settling from suspension and, occasionally, by re-sedimentation from mass flows and turbidity flows, as well as some bottom current reworking. The objective is to distinguish proximal and distal varves in glacier lake sediments, and to look at Unit VI for deglaciation events seen in Baltic Ice Lake relating to warm interstadials (Bøling/Allerød) and cooling events (incl. Younger Dryas at 12.8-11.7 ka BP) and later deglaciation after 11.7 ka BP.

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Trace-element systematics of sulphides in the Kevitsa Ni-Cu-PGE deposit, northern Finland

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Although the Kevitsa Ni-Cu-PGE sulphide deposit is an important producer of platinum group metals as by products, the exact mechanism of PGE enrichment is still controversial. It has been suggested that hydrothermal processes have played a role in redistribution of PGEs, forming the unusual PGE enrichment found in parts of the intrusion (Gervilla and Kojonen, 2002). However, the good correlation between different PGEs suggests that the role of fluid redistribution is insignificant in the formation of the Kevitsa ores (Le Vaillant et al, 2016). In this study, an in-situ trace element study of base metal sulphide has been conducted to further constrain the metal enrichment process.

There are two main ore types that make up the Kevitsa deposit, named normal ore and Ni-PGE ore. The normal ore is continuous and comprises 90% of the economic resources, whereas Ni-PGE ore occurs as discontinuous lens-like bodies. The normal ore has average Ni and Cu grades of 0.3 and 0.42 wt.% respectively and the main sulphide minerals are pentlandite, chalcopyrite and pyrrhotite. The Ni-PGE ore consists predominantly of pentlandite, pyrite and millerite, with high Ni tenors (generally >10%) and lower Cu grades (Ni/Cu 1.5-15). There is also an uneconomic ore type, named false ore, which consists of pyrrhotite, minor chalcopyrite and pentlandite.

To examine the ore-forming processes at Kevitsa, this study utilizes trace-elements of the main sulphide minerals, analysed using laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS). Pd is found in all of the sulphide phases, although pentlandite is the richest, with Pd contents ranging from 0.3 ppm in false ore to tens of ppm in the Ni-PGE ore. Barnes et al (2011) suggest that millerite could form in a Ni-rich sulphide melt, though it more commonly occurs as a secondary alteration product. At Kevitsa, both millerite and pyrite show well preserved primary textures and contain traces of IPGE and PPGE, confirming that these two phases are formed by magmatic processes. Pyrrhotite contains relatively high IPGEs, but lower PPGEs, whereas chalcopyrite contains the lowest amount of PGEs overall, similar to other deposits globally (Godel et al, 2007). Pt contents remain low in all the base metal sulphides, with the majority of analyses falling below the detection limit, indicating that Pt is mainly hosted by platinum group minerals.

Generally, samples with higher PGE tenors show high PGE content in base metal sulphides. This indicates a magmatic origin for the high metal tenors in the Ni-PGE ore, with a negligible effect of post-magmatic fluid enrichment. The false ores show low metal contents for all chalcophile metals, suggesting a possible earlier stage of sulphide saturation at depth.

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Unraveling the tectonic history of Southern Finland using metamorphic data and geodynamic modelling

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This project aims to better understand the metamorphic and tectonic evolution of Southern Finland through a two-stage approach: (1) The determination of pressure-temperature-time (P-T-t) histories of metamorphic rocks by detailed petrographic investigation, thermodynamic modelling, and geochronology; and (2) Exploring the tectonic and geodynamic implications of these P-T-t constructions through lithospheric scale numerical modelling. This project has only just begun, and the aim of this presentation is to share our plans and stimulate discussion.

The Paleoproterozoic Svecofennian province in Finland can be divided into Western Finland (WF) and Southern Finland (SF) tectonic subprovinces (Nironen, 2017). Both regions experienced low T- high P metamorphism during the main Svecofennian event at c. 1.89-1.86 Ga. Abundant 1.84-1.79 Ga migmatitic metasedimentary rocks and 1.84-1.80 Ga granitoids in SF, only very locally found in WF, testify of a second metamorphic event in SF (Hölttä et al., 2019). P-T paths during the metamorphic events, how metamorphism relates to deformation events, and how continuous metamorphism was in time, are largely open questions, that have great potential to aid and refine tectonic interpretations and models. Main metamorphic zones have been mapped at national scale (Hölttä and Heilimo, 2017), but detailed studies on metamorphism are few, confined to specific localities, and made before the development of modern phase equilibria modelling approaches. In consequence, the metamorphic evolution of SF is currently quite poorly known.

We have collected more than a hundred samples of metamorphic rocks from around 50 locations, roughly forming transects perpendicular to the SF-WF boundary, covering nearly the entire width of the country. Most of the samples are metasedimentary, and they vary in grade from andalusite field schists to granulite facies migmatites. The next step will be detailed petrographic work on thin sections, geochemical measurements of mineral and rock compositions, and phase equilibria modelling. P-T paths generated from pseudosection modelling will be compared to P-T predictions from numerical geodynamic models of various Paleoproterozoic tectonic scenarios including margin-normal and oblique continent-continent collision and terrane accretion. The geodynamical software used in the project is 3D thermo-mechanical creeping flow code DOUAR (Braun et al., 2008), which is designed to be used in high-performance computing environments. In DOUAR, material and heat flow equations are solved using the finite element method, leading to matrix equations containing millions of elements and very time-consuming simulations, solved efficiently by dividing code execution on hundreds of processor cores.

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Project and problem-based learning – Valajärvi project combining four BSc-theses

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Lake Valajärvi locates in the proximity of Salpausselkä II, in Kanta-Häme. The lake has been monitored and studied since 1960's by Valajärvi Conservation Society (Valajärven Suojeluyhdistys ry.). This project combines four BSc-theses aiming to interpret the role of the catchment (especially groundwater and peatland) in the lake development and characteristics. The project is financed by the Valajärvi Conservation Society.

Previous studies have detected numerous depressions/craters of unknown origin in the bottom sediments of the lake. Our working hypothesis was that the deprsessions were possibly originated by release of methane. Remote operated underwater vehicle (ROV) was used to gain more detailed information on the depressions and their origin. Furthermore, the possible release of gas (methane) was studied by sampling water column and ice cover. Samples were analysed with gas chromatography by Lammi Biological Station, University of Helsinki.

ROV investigations revealed no visible evidence of methane release from the depressions. Instead, most of the depressions were inhabited by bivalves. In addition, methane origin for the depressions is not supported by gas composition of the samples. Thus, bioturbation caused by bivalves is the most probable origin of the depressions. The ecological state of Lake Valajärvi is excellent. However, we found local increased levels of chlorophyll a and invasive alien species Elodea Canadensis.

Lake interaction with the catchment area was studied by 1. observing groundwater discharge into the lake with thermal infrared survey using unmanned aerial vehicle (UAV) and 2. analysing nine peat profiles from two bogs. Stable isotope composition of the water samples was used to confirm identified groundwater discharge locations. Groundwater discharge into the lake was observed in western and southern shores of the lake. The peat profiles were used to interpret local deglaciation history, peatland development and past changes in water level. Peat stratigraphy shows both impact of rising water level in Lake Valajärvi and impact of anthropogenic ditching.

Project and problem-based learning is highly applicable for academic studies, also for thesis work. Here we applied the concept to BSc-level. A group of students and supervisors worked simultaneously with several research questions related to the same research frame. From supervisors' point of view this kind of approach is motivating and seems to enhance student´s commitment and metacognition, but time consuming. Research plan should be detailed and separate parts should be well defined. We found communication between the students, researchers, stake holders and supervisors beneficial for the learning outcomes. From the student's point of view working on similar subjects and participating in each other's field work offered broader viewpoint on a larger subject, as well as peer support. Practical field work was welcomed by students as part of BSc thesis.

Paleomagnetic studies in Central and Northern Finland – Exploring solid Earth processes at 1.88–1.85 Ga and the evolution of the Svecofennian Orogen

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The episodic amalgamation of nearly all continents into a large cluster called supercontinent and its subsequent dispersal has played a key role in the evolution of the Earth probably since the Ar-chean times. The existence of the Mesoproterozoic supercontinent Nuna (also known as Columbia) was first proposed based on global 2.1–1.8 Ga orogens (e.g. Hoffman 1989; Zhao et al. 2002), and later it was further supported by abundant geological and paleomagnetic evidence. The formation of the Fennoscandian Shield during the Svecofennian orogen between ca. 2.0 and 1.75 Ga preced-ed the assembly of Nuna (Bogdanova et al. 2014) and many parts of the Archean cratons of Fen-noscandia (i.e. Karelian province) were strongly reworked in collisional processes during this orogeny (Hölttä et al. 2020). An abundance of geological and paleomagnetic evidence indicate that the Fennoscandia as a part of Baltica formed the core of Nuna together with Laurentia with coherent Laurentia-Greenland-Baltica margin. Coinciding with the onset of Nuna, Antonio et al. (2017) suggested a Paleoproterozoic 1.88–1.85 Ga true polar wander (a drifting of Earth's solid exterior relative to its spin axis; see Evans, 2003) event, based on analyses of paleomagnetic data.

Many of the several different Archean-Paleoproterozoic mafic dyke swarms on the Karelian prov-ince are totally remagnetized by pervasive Svecofennian orogen (e.g. Mertanen et al., 1999; Salminen et al., 2014). We explore the possibility to study the evolution of the Svecofennian orogen by using these remagnetizations on the diabase dykes in the Taivalkoski area of the Karelian Province. In addition, we provide a new high quality 1.89–1.87 Ga paleomagnetic data for Fen-noscandia from three distinct gabbro units, in purpose to test the true polar wander event suggested by Antonio et al. (2017). Our new data together with recently calculated minimum-motion veloci-ties for Paleo- to Mesoproterozoic cratons (Elming et al. 2021) contradict the true polar wander event.

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Implementing Terrestrial Cosmogenic Nuclide dating in provenance tracing of mineralized glacial erratics, pilot study of the method in Kaarestunturi, Sodankylä, Finland

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The Central Lapland Greenstone Belt in Northern Europe is an area of active ore exploration. The belt has been glaciated on multiple occasions and a great portion of it is masked by till. The till cover is often used in geochemical exploration in e.g., boulder/erratic sampling because the glacial erratics can resemble the underlying bedrock quite well. However, this is not always the case. For example, if a till unit is deposited on top of an older one it may bear no resemblance to the local bedrock.

In Kaarestunturi, Sodankylä, gold bearing quartz erratics have been found in the surficial till. Many of the erratics are underlain by multiple till units and local excavations have not revealed the source of the boulders. In this study, two of the mineralized quartz vein erratics and two bedrock outcrops were dated using the terrestrial cosmogenic nuclide (TCN) technique with the aim of finding their initial dislodgement or exposure event. The method is based on the accumulation of nuclides that form in minerals when they are irradiated with high energy secondary cosmogenic radiation, in this study 10Be and 26Al are used. The radiation flux typically attenuates within 2–3 meters of the Earth's surface, therefore cosmogenic nuclides are most abundant at the surface. Accumulating in the surface makes TCN dating a prominent geochronological tool for dating geomorphology, e.g., glacial erosion, that can reset the "clock".

The dated erratics yielded apparent 10Be exposure ages of 39.2 ± 1.3 ka and 30.6 ± 1.0 ka, and they are thus significantly older than the recent Late-Weichselian deglaciation. Likewise, the outcrop exposure ages predate the Late-Weichselian; the lower elevation bedrock outcrop yielded an apparent 10Be age of 98.0 ± 2.8 ka and the higher one an age of 53.0 ± 1.8 ka. Neither the outcrop nor the erratic samples indicate strong erosion or glacial plucking during the Late-Weichselian. For provenance tracing this means multi staged erratic transportation. 26Al/10Be ratios, indicative of reburial after exposure are not uniform in the sampling. The older erratic shows signs of long reburial, linking it to older erosion than what its' apparent age suggests. Plotting the apparent ages of the erratics on the local glacial history model allows picking till fabric orientations that correspond with the time of erratic dislodgement. The interpreted time of dislodgement paired with till fabric analyses suggests that the provenance of erratics of this age could lay NW to SW of their current location.

Does Magmatism Reduce Crustal Strength?

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Not always.

Arc magmatism is commonly thought to reduce crustal strength due to elevated temperatures and the presence of melt during and following the period of magmatic activity. However, how much the strength is reduced by different factors such as thermal weakening in the solid state versus weakening due to the presence of melt is poorly constrained. Furthermore, differences in host rock and intrusion composition may even lead to strengthening of the crust over the long term. This work explores the roles of various factors related to magmatism on the transient changes in crustal strength.

The effect of magmatism is quantified by solving the 2D heat conduction equation for a lithospheric cross section with periodic magma emplacements at various depths. The resulting thermal field is used to determine the integrated crustal strength (ICS) using a series of 1D crustal strength envelopes. Melt fractions are acquired using the rhyolite-MELTS software (Gualda et al., 2012), and the strength reduction from partial melting is calculated using a viscosity model by Schmeling et al. (2012). The model geometry is 150 km (depth) by 400 km (width). The timescale of the simulations is 40 Ma, and magma intrudes the crust in pulses at 45 km (Moho), 25 km (upper-lower crustal transition), and 10 km depth, during the first 10 Ma, after which the system cools down. Intrusion parameters are varied in different scenarios, to explore how the ICS changes as a function of time. For example, the different intrusion compositions compared to the host rock composition can change the crustal mechanical strength.

Over 20 different models were run, and the effects of magmatism shows crustal strength reductions during and after the active magmatic period, but crustal strengthening occurs in some cases as well. Based on the results of numerical experiments, the following can be stated:

1) The peak ICS is reduced by over 80% at the magma reservoir, but approximately 50 km from the mid-point of the reservoir the peak ICS reduction is less than 40%. The peak average ICS reduction can be anywhere between 55–75% depending on the magmatic scenario.

2) Mafic magmas are typically hotter than felsic magmas, but this thermal effect matters less than the change in mechanical properties of the intruded material. Even during the active magmatism, the ICS is similar using mafic or felsic intrusions. More importantly after the end of magmatic activity the felsic intrusions reduce the ICS significantly more than mafic intrusions, because of the differences in mechanical strength.

3) The proportion of latent heat to the ICS reduction is highest after the magmatic activity has ceased (even after 15 Ma). This proportion of ICS reduction can be over 30% in some cases but is more typically 20–25% at the magma reservoir, meaning that the latent heat keeps the crustal temperatures higher.

4) The presence of melt does not seem to be important in terms of crustal strength because the crystal-plastic strength has already been radically reduced due to the increased temperature. The proportion of peak ICS reduction from melting at the reservoir is less than 0.2%, and the mean crustal value is below 0.1%. In most extreme cases the peak ICS reduction from melt presence is less than 1%.

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Sr isotope stratigraphy across the Paasivaara PGE reef of the Penikat intrusion, Northern Finland – Insights into the genesis of reef-type PGE mineralization

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Layered mafic-ultramafic intrusions host the largest reserves of feasible PGE commodities. Worldwide, these deposits are rare in the geological record, well-constrained to a few large igneous provinces-. Dispite extensive research on layered intrusions and related PGE ores, the models regarding the PGE ore-formation are diverse, involving both magmatic and hydrothermal processes, and the subject remain largely debatable. Penikat is a Paleoproterozoic 2.44 Ga, layered intrusion occurring as part of the east-west trending Tornio-Näränkävaara belt in northern Finland. Traditionally, Penikat is split into five megacyclic units (MCU I-MCU V), and it hosts three main PGE reef horizons: the Sompujärvi Reef (SJ), located to the basal part of MCU IV; the Ala-Penikka Reef (AP), occurring within the lower proportion of unit IV; and the Paasivaara Reef (PV) which defines the hanging wall contact from the MCU IV to the MCU V (Huhtelin et al. 1990Halkoaho, 1993).

The study focuses on the upper proportion of the MCU IV and lower parts of MCU V, i.e. on the transition zone between MCU IV and V where the Paasivaara reef (PV) is emplaced. The study utilizes new in-situ Sr isotope data for plagioclase analysed by using the LA-ICP-MS laser ablation technique at the GTK facilities in Espoo, Finland, to gain new insights into the petrogenesis of the Penikat intrusion and the origin of the PV reef.

The results show a systematic smooth increase in Sr isotope signatures from MCU IV (Sr(i) ~ 0.7024 – 0.7028) to MCU V (Sr(i) 0.7031-0.7032) at the sight of the PV reef. This coinsides with appearance of high-An plagioclase (up to An86). The results indicate involvement and mixing of magmas with contrasting isotopic lineages, thus supporting the new magma pulse hypothesis (Huhtelin et al., 1990) as to the origin of the PV reef.

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Paleoproterozoic Rajapalot Au-Co system associated with evaporites: Chemical composition and boron isotope geochemistry of tourmaline, and sulfur isotopes of sulfates, Peräpohja belt, northern Finland

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The Paleoproterozoic Raja Au-Co mineralization in the Peräpohja belt in northern Finland is part of the wider Rompas-Rajapalot Au-Co mineralized area. Tourmaline is abundant mineral within the area, spatially associated with Au-Co mineralization. Four texturally distinct tourmaline types were identified from one of the Au-Co occurrences (Raja Au-Co). All analysed tourmaline types belong to the alkali-group and are classified as dravite. δ 11 B values and fractionation modelling indicates that at least two distinct fluids were responsible for the tourmaline formation with initial end member δ 11 B values of the fluids at -8‰ and -1‰. Possible sources for boron rich fluids are Svecofennian orogeny related (ca. <1.9 Ga) metamorphic fluids and magmatic-hydrothermal fluids related to the late-orogenic ca. 1.78 Ga granitoids. A distinctive rock unit with bright purple anhydrite layers and white gypsum veins has been intersected by drilling. Anhydrite has δ 34 S values in a narrow range from 8.1 to 9.8 ‰. Gypsum has slightly heavier δ 34 S from 10.6 to 12.2 ‰. Together with isotope fractionation constraints, textural evidence suggests the authigenic formation of gypsum with SO42- sourced from anhydrite. Significant similarities in textures and sulfur isotope values to well-known evaporite successions of the Onega basin, western Russia, strongly indicates the presence of evaporitic strata within the Peräpohja belt.

The 6th Finnish National Colloquium of Geosciences is held at the Linnanmaa campus of the University of Oulu, 27th-29th October 2021 as a hybrid event. The colloquium is organized by the Oulu Mining School at the University of Oulu, in co-operation with Finnish universities and the Geological Society of Finland. The colloquium gathers experts from all fields of Geosciences, from economic and bedrock geology, geochemistry, geophysics to environmental geology, to present and hear from the latest research and innovations. This publication contains submitted abstract from all the oral and poster presentations held at the colloquium. The editor would like to express gratitude to all the authors for their contributions.

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