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The Fennoscandian School of Ore Genesis in Layered Intrusions

Online Workshop 1

Extended abstracts

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Content

(Presenting author's name is underlined. * – additional abstracts that is planned to be discussed after the Online Workshop 1)

Preface

Europe needs to make better use of its internal resources, not only through enhanced recycling and substitution, but also through improved efficiency in mineral exploration, mining, and beneficiation. The Fennoscandian layered intrusions, located in the Arctic area or close to it, host a wide range of resources of critical metals (PGEs, Cu, Ni, Co, Cr, V). However, most of these mineral resources are currently sub-economic due to either low grade or low tonnage. One of the major obstacles for discovering the next minable deposit is a lack of deep understanding of the ore-forming processes and incorporation of this knowledge in our exploration models. A series of workshops under the title "The Fennoscandian School of Ore Genesis in Layered Intrusions" is organized within the ARLIN international project bringing together organizations from Finland, Norway, and Russia in 2021. The workshops aim to discuss orthomagmatic mineralization in layered intrusions from source to deposit formation at a range of scales from global/regional to deposit-specific case studies. The first workshop took place completely in the internet as a virtual meeting 25th February 2021 and included 16 presentations providing a good overview on current research of the Fennoscandian layered intrusions. Professor Wolfgang Maier, Cardiff University, UK, and Professor Rais Latypov, Wits University, South Africa, gave outstanding invited talks. This volume contains extended abstracts of the workshop according to the programme.

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Nikolay Groshev

An overview of global layered intrusions, with a special focus on the Bushveld Complex, South Africa

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Summary Layered intrusions host some of the world's most important ore deposits, yet their global distribution, age, and petrogenesis remain poorly known. Here we provide an update on our current understanding and highlight some key outstanding research questions, notably on the potential importance of reactive flow. We present some preliminary data on water contents of Bushveld orthopyroxenes from which we calculated the water contents of the magma. The analysed Bushveld rocks, including the Merensky Reef, crystallised from relatively water-poor magma, similar to many other continental basalts.

1. Introduction and background to current research

Layered igneous intrusions have been identified in every continent on Earth (Fig. 1) and their existence has been hypothesised on the Moon and Mars. The greatest density of terrestrial intrusions occurs within stabilised Archaean cratons, particularly the Kaapvaal (e.g., Bushveld, Uitkomst, Stella, Molopo Farms, Trompsburg), Zimbabwe (e.g., Great Dyke), Pilbara (e.g., Munni Munni), Yilgarn (e.g., Windimurra, Jimberlana), Nain (e.g., Kiglapait, Fiskanaesset, Ilimaussaq), Superior (e.g., Duluth, Sudbury, Coldwell, Ring of Fire), Wyoming (Stillwater), Kola (e.g., Monchegorsk, Fedorova Tundra, Imandra) and Karelia (e.g., Kemi, Penikat, Portimo, Koillismaa) cratons. The dilated margins of cratonic blocks appear to be equally favourable, e.g., the Brasilia Belt of the Amazonia craton (hosting the Cana Brava, Niquelândia, and Barro Alto intrusions), the Halls Creek Orogen of the Kimberly craton (e.g., Hart, Savannah, Panton), the Kibaran Fold Belt of the Tanzania craton (e.g., Kabanga, Musongati, Kapalagulu), the Kotalahti Belt of the Karelia craton (e.g., Kotalahti, Rytky, Laukunkangas), the Central Asian Orogenic Belt (e.g., Heishan, Huangshandong, Tulargen, Xiadong) and the Giles event of the Musgrave province, Australia (e.g., Wingellina Hills, Kalka, Mantamaru). There are relatively few intrusions that show no obvious connection with Archaean cratons or their periphery, examples being the Chilas Complex of Pakistan and the Beja and Aguablanca intrusions of Portugal and Spain.

Layered intrusions occur throughout geological time, from the Archaean (including the ~ 3123 Ma Nuasahi intrusion, India and the ~ 3033 Ma Stella intrusion, South Africa) to the Cenozoic (including the ~ 55-45 Ma east Greenland intrusions, e.g., Kruuse Fjord, Skaergaard, and Lilloise). There is no clear correlation between age and size; giant intrusions occur from the Archean, e.g., the ~ 2.8 Ga Windimurra intrusion, Australia, to the Phanerozoic, e.g., the ~ 0.18 Ga Dufek intrusion, Antarctica. Amongst the intrusions compiled in this study, 11.0% occur in the Archaean, 25.2% in the Proterozoic and 41.0% in the Phanerozoic (Fig. 2; 22.8% are unconstrained). The ages of layered intrusions correlate positively with the amalgamation of supercontinents, with numerous intrusions occurring at ~ 2.5-2.4 Ga (Kola and Karelia cratons, Great Dyke), ~ 2.0-1.8 Ga (Kaapvaal and Superior cratons), ~ 1.2-1.0 Ga (Midcontinent Rift), and 0.3-0.25 Ga (China and New Zealand). Intrusions temporally related to supercontinent dismemberment likely formed in response to mantle plume activity, whereas those occurring during intervals of supercontinent assembly have been explained either by (i)

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slab-rollback and consequent lithospheric extension, (ii) trans-tensional rift zones during oblique collision, or (iii) sub-continental lithospheric mantle (SCLM) delamination in response to enhanced subduction.

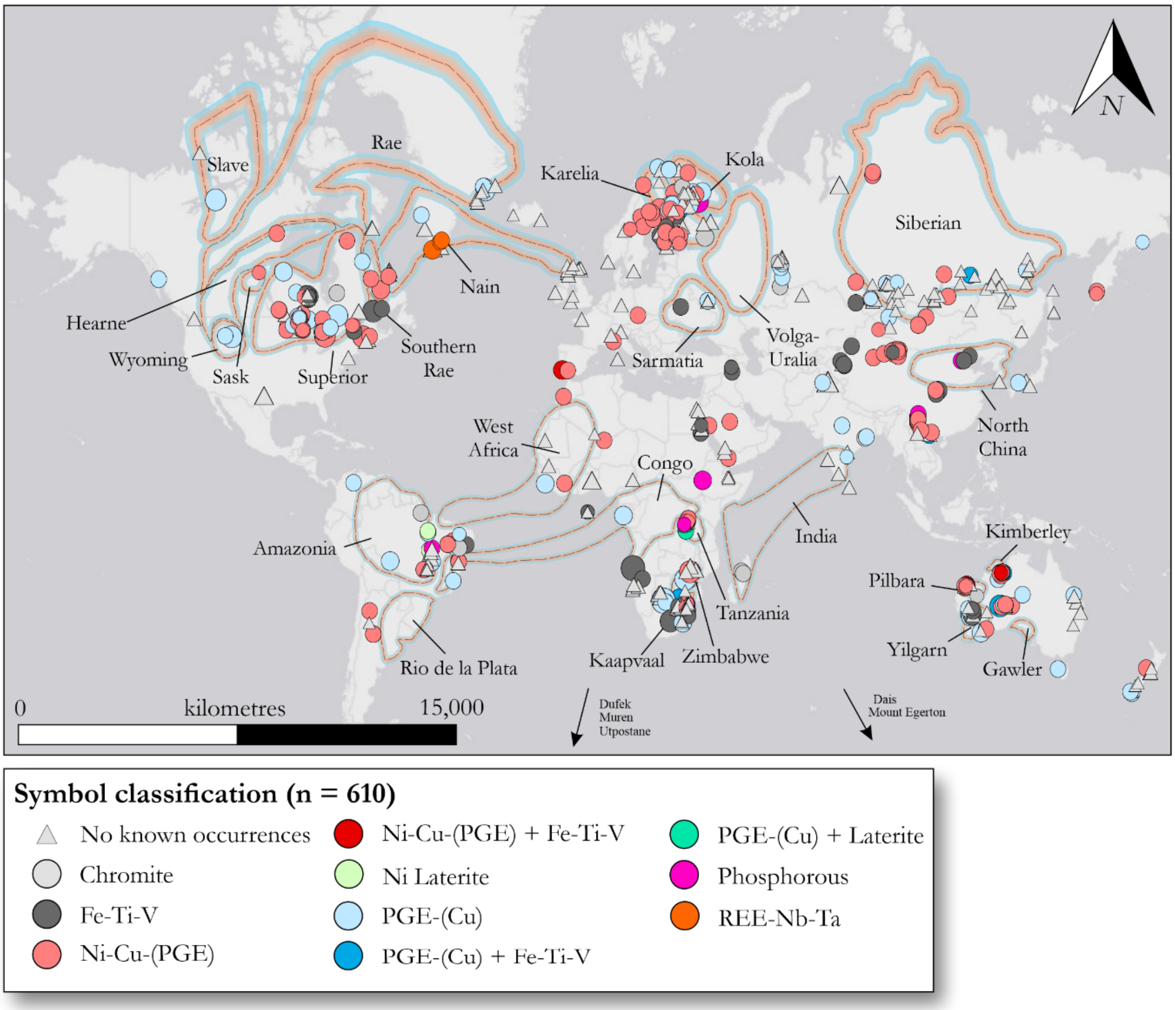

Figure 1: Distribution of global layered intrusions

2. Research questions at hand

Conventional models for the origin of layered intrusions (i.e. via tank-like chambers, Wager and Brown 1968) are increasingly challenged by new concepts including sill-like, out-of-sequence emplacement of melts or slurries (Bedard et al. 1988; Mungall et al. 2016), or recrystallisation of proto cumulates in response to percolation of volatiles and/or hydrous melt (Irvine 1980; McBirney 1987; Maier et al. 2021). Boudreau (2019) has gone as far as to suggest that large layered intrusions in general have undergone complete recrystallisation due to slow cooling and reactive flow of fluids. He went on to suggest that, in order to unravel the origin of the layering, the study of small intrusions that have experienced little recrsytallisation is more fruitful than that of large intrusions. The trouble is that the richest PGE reefs are hosted in the largest intrusions (Bushveld, Stillwater, Great Dyke), implying that when it comes to ore formation, size very much matters. Thus there remains a lot to be learned from studying the largest body of them all, ie the Bushveld.

Apart from the problem of unravelling the petrological complexities, another major problem is the sheer size of the Bushveld which prevented a systematic cataloguing and understanding of the range of compositional variations; In small intrusions, a single profile can be broadly representative of the compositional variation. In contrast, the 100000km2 Bushveld Complex is underlain by a range of country rocks, basement structures, and lithospheric mantle types, and it has vastly different thickness and stratigraphic successions along its strike of 100s of km. There is currently only 1 profile (based on drill cores and mine shaft samples) across the bulk of the complex (ie from the base to the top of the MZ). Detailed analysis of specific stratigraphic intervals along strike has only been done for the ~50-200m thick UG2-Merensky Reef interval (Maier and Eales 1997) and the ~30-100 m Bastard Unit (De Klerk et al. 1992) and detailed along-strike comparison of a specific layer has only been done for PGE in the Merensky Reef (Naldrett et al. 2009).

3. Future prospects

In order to constrain the origin of the layering and the role of reactive flow, we will study a complete profile across the Bushveld Complex, and individual layers along, using FESEM element maps, micro X-ray maps, and water contents of pyroxenes (using EMP and FTIR). Reconnaissance data suggest relatively low water contents of the parent magmas (Fig. 2).

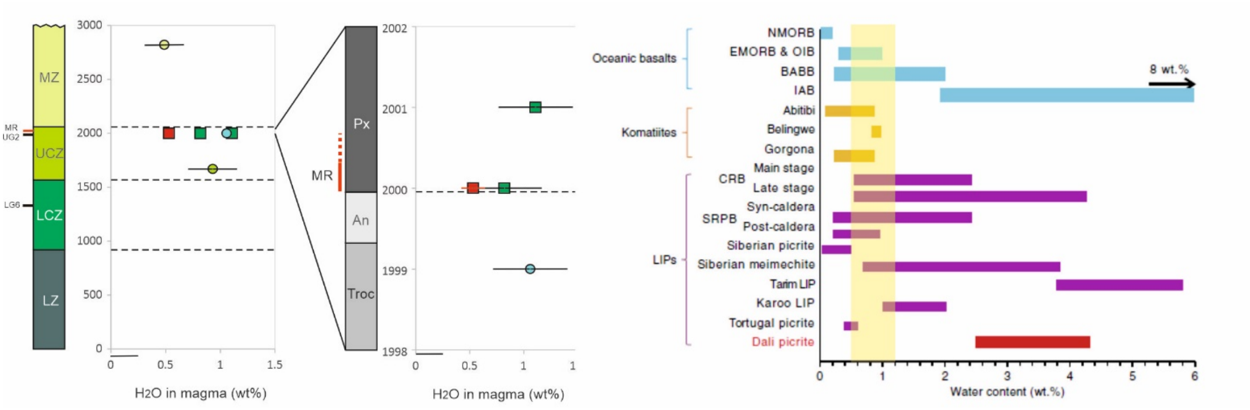

Figure 2. Calculated water contents of melts parental to Bushveld cumulates, based on water contents in orthopyroxene. LIP data from Liu et al. (2017).

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Testing of an 'amalgamated sill' hypothesis for the origin of mafic-ultramafic layered intrusions

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Summary Five major lines of petrological research are proposed to rigorously test a recently emerged 'amalgamated sill' hypothesis for the origin of mafic-ultramafic layered intrusions.

1. Introduction and background to current research

For over a century, a classical paradigm of a magma chamber has been underpinning all studies of mafic layered intrusions. The paradigm envisages a magma chamber as a large body of the molten, long-lived, and slowly fractionating magma ('a big magma tank') enclosed in cold crustal rocks (Wager and Brown, 1968; Parsons, 1987; Cawthorn, 1996; Charlier et al., 2015). A key feature of this classical paradigm is that it explains readily why the rock sequences of layered intrusions – that form in a sequential stratigraphic order from the base (oldest) to the top (youngest) – are fully consistent with fractional crystallization of basaltic melts (Irvine, 1970, 1979). In the recent years, this traditional view of a magma chamber has been questioned by many geoscientists who contend that such long-lived and largely molten 'big magma tank' chambers are either very short-lived or never existed in the Earth's history. One alternative to a classical view is an "amalgamated sill" hypothesis that portraits the layered intrusions as a stack of sills (crystal-rich slurries) that often invade pre-existing cumulates in a random fashion (Mungall et al., 2016; Wall et al., 2018; Scoates et al., 2021). This re-interpretation is mostly motivated by a discovery that absolute ages of zircons do not become progressively younger from the base towards the top of the layered intrusions, as it would normally be expected from the stratigraphic law of superposition. Rather, the zircon ages are out-of-sequence, i.e. they change a few times from old to young ones and backwards with moving up-section of the complexes.

2. Research questions at hand

As any new concept in science, an "amalgamated sill" hypothesis for the origin of layered intrusion needs to be subjected to rigorous testing. I propose that this testing can be done using five major approaches:

1. Field relationships between layers of cumulate rocks:

An "amalgamated sill" hypothesis predicts that the intrusive bodies should display cross-cutting relationships with both underlying and overlying layers. This feature can be employed to prove/disprove the intrusive nature of layers/units in layered intrusions.

2. Textural observations in cumulate rocks:

The zircon dating indicates that the age difference between individual sills in layered intrusions can be up to a few million years (Wall et al., 2018; Scoates et al., 2021). This implies that internal chilled margins can locally develop within a stack of incrementally intruded sheets of magma. The existence of the late-stage sills can thus be proven by chilled margins.

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3. Stratigraphic chemical trends through the rock sequences:
The interpretation of the layers/units as randomly-emplaced sills implies that their mineral, whole-rock and isotopic compositions may be substantially different from the host cumulate strata of layered intrusions into which they have been intruded. This feature can thus be used for testing the sill's nature of layers/units by their chemical composition.

4. Phase equilibria-controlled crystallization sequences of layered intrusions:
The cumulate stratigraphy of most layered intrusions is consistent with a few major crystallization sequences that are expected from liquidus phase equilibria in basaltic systems (Irvine, 1970, 1979). The random emplacement of sills into pre-existing strata is expected to disturb the systematic order of phase crystallization in layered intrusions. The abrupt reversals and/or chaotic changes in crystallization sequences may therefore be used to identify the late-stage sills.

5. Isotopic zircon ages in potholes:
Some layered intrusions show potholes - roughly circular depressions in the chamber floor in which footwall rocks were removed by magmatic erosion (Latypov et al., 2016; 2019). The crosscutting relationships between the rocks in potholes allow to safely define the relative ages of the layers/zones. The absolute ages of zircons extracted from the rocks in the potholes can thus be a primary tool for proving/disproving the out-of-sequence geochronology that lies at the heart of the "amalgamated sill" hypothesis.

3. Future prospects

A "amalgamated sill" hypothesis has been developed based on the study of two world-known layered intrusions – Bushveld Complex in South Africa (Mungall et al., 2016; Scoates et al., 2021) and Stillwater Complex in Canada (Wall et al., 2018) and. In this context, the ARLIN project has a great potential to explore the validity of this new hypothesis using numerous mafic-ultramafic layered intrusions located on the Fennoscandian Shield. The research may provide an important step beyond the current state-of-the-art in theoretical and applied fields of modern igneous petrology and mineral deposit geology. This would significantly improve and strengthen the overall global position and competitiveness of Fennoscandian-based geosciences.

Acknowledgements

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History of studying the Fedorova-Pana Layered Complex and associated Cu-Ni-PGE mineralization, Kola Peninsula, Russia

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Summary The intrusive layered complex of mafic and ultramafic rocks on the Fedorova and Pana Tundras (Tundra – a mountain in the Sami language) in the central part of the Kola Peninsula has been studied since the late 19th and early 20th centuries. Searches for Cu-Ni ores were carried out in the 30s-80s of the XX century, but no rich ores were found. Prospecting for platinum group elements (PGE) mineralization started at the end of the 20th century and led to the discovery of four PGE deposits and numerous ore occurrences. Large areas of the Fedorova-Pana Layered Complex remain poorly studied.

1. Prospecting for Cu-Ni ore in the Fedorova-Pana Layered Complex

Geographical and geological survey of the Kola Peninsula was launched by expeditions of N. Kudryavtsev (1881), Ch. Rabot (1884), Finnish scientists A. Kihlman, W. Ramsay and A. Petrelius (1887-1889), topographers B.A. Rippas and P.B. Rippas (1890s) in the second half of the 19th century. In 1898 P.B. Rippas led an expedition on the south of the Kola Peninsula to the Varzuga River basin and the Fedorova-Pana Tundras area. Characteristic gabbros of dark, almost black colour, in some places influencing the magnetic needle, were discovered in the Pana Tundras (Rippas, 1899).

In 1927, an expedition of the USSR Academy of Sciences led by geologist N.N. Gutkova obtained the first information about intrusive rocks of the Fedorova-Pana Tundras. A geological survey at a scale of 1: 1 000 000 was carried out on the Fedorova-Pana Tundras in 1931-1932.

In 1933, an expedition of the USSR Academy of Sciences headed by F.P. Kharchenko carried out a geological survey at a scale of 1: 50 000 and small mining operations on the Fedorova Tundra area. Norites with sulfide dissemination were found. Prospecting for Cu-Ni ores on the Fedorova-Pana Tundras started in 1934-1941. The Severonikel plant was constructed during these years near Monchegorsk. It was established to process the rich Cu-Ni ore from vertical sulfide veins of the Monchegorsk Layered Complex. In addition to the rich ores of Monchegorsk, the Fedorova-Pana ore was assumed to increase the Cu-Ni ore reserves in the central part of the Kola Peninsula.

In 1939, D.V. Shifrin discovered Pt and Pd in a total amount of 0.5 to 2 ppm in individual samples from sulfide-bearing gabbronorites of the Fedorova intrusion. However, the data raised no interest in those years. The reserves of Cu-Ni ores in the Fedorova intrusion were insufficient for industrial development, thus the work was pretermitted.

In the 1940s-70s, the study of the Fedorova-Pana intrusion geology and the search for rich Cu-Ni ores were continued. In 1960, the entire territory of the Fedorova-Pana intrusion was covered with aeromagnetic and airborne gamma surveys at a scale of 1: 50 000. Geophysical work and numerous drilling works were carried out. S.M. Chikhachev discovered poor sulfide dissemination in the “banded complex” (the Lower Layered Horizon) of the Pana Tundras Ridge in 1961. The find preconditioned complex geological and geophysical works organized by the North-Western Geological Department of the USSR Ministry of Geology. The works were carried out by V.V. Proskuryakov in 1961-1964. A number of sulfide occurrences

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were established in the Lower Layered Horizon of the West Pana intrusion. Petrographic and geochemical studies were held in the Geological Institute (E.K. Kozlov, A.Yu. Odinets, G.N. Staritsina, S.M. Chikhachev, etc.). These studies provided the conclusion that there was no rich Cu-Ni ore in the Fedorova-Pana Tundras.

In 1979, M.K. Radchenko and V.S. Dokuchaeva found elevated PGE content (up to 4 – 5 ppm) in samples with sulfide Cu-Ni mineralization from the eastern flank of the Fedorova intrusion (Pakhkvaraka, Last'yavr) and from the Lower Layered Horizon of the West Pana intrusion. Yu.N. Neradovsky was the first to find merenskyite, a rare telluride of palladium, in these ores.

2. Prospecting for PGE in the Fedorova-Pana Layered Complex

In the 80s of the 20th century, there was a change in the prospecting trend – from Cu-Ni to PGE mineralization. A detailed geological and petrological analysis of the data was carried out by GI KSC RAS in the mid-1980s (V.S. Dokuchaeva, N.N. Veselovsky, etc.). The analysis showed a great similarity between the rocks of the Fedorova-Pana Complex and the Stillwater Complex in the USA. GI KSC RAS has been studying the complex ores (Pd, Pt, Rh, Au, Ag, Cu, Ni, Co) of the Fedorova-Pana Complex since 1986. It was found that sulfide Cu-Ni-PGE mineralization was associated with two horizons of finely layered rocks in the West Pana intrusion, the lower and upper.

Four bore holes were drilled by GI KSC RAS in the Lower Layered Horizon at the Suleipakhk area in 1989. For the first time, the aim of drilling on the Fedorova-Pana Tundras was to find PGE rather than Ni and Cu. The bore holes crossed four intervals with complex PGE mineralization. The analysis of the obtained materials allowed Academician F.P. Mitrofanov as a director of GI KSC RAS to suggest the existence of the Kola platinum-metal province in 1989.

Geological mapping of the West Pana intrusion was followed up by a group of GI KSC RAS in 1990. A.U. Korchagin, L.A. Vinogradov, E.M. Bakushkin, Yu.L. Voitekhovsky, A.I. Mednikov, S.M. Karpov and other scientists participated in this work. It was carried out within the Lower Layered Horizon in the West Pana intrusion. In result, the North PGE Reef was traced for more than 11 km.

GI KSC RAS initiated the creation of a small innovative enterprise JSC "Pana" in 1991. F.P. Mitrofanov became the Chairman of the Board of Directors. A.L. Gritsay was General Director of the small enterprise in 1992–1999, and A.U. Korchagin has been General Director since 2000. In the same year A.U. Korchagin as senior geologist of the JSC "Pana" conducted a detailed study of the North PGE Reef structure at the Eastern and Central Kievey areas that included tracing the reef with 30-60 m deep drill holes.

Drilling and blasting works were carried out in the East Kievey area, and 1400 tons of complex platinum-metal ore as a technological sample were prepared in a pilot pit. From 1993 to 1999 prospecting works in the Fedorova-Pana Tundras were implemented jointly with and with the financial support from the "BHP Minerals" company. During these years, geological surveys at a scale of 1: 5000 and sampling for PGE have been carried out in almost all exposed areas of the West Pana and Fedorova intrusions by, in particular, A.U. Korchagin, S.M. Karpov, V.V. Subbotin, A.S. Osokin, A.N. Kulakov and A.E. Borisov. In 1993, a chain of high PGE boulders was traced in the South Suleipakhk area. Currently, these boulders are well-known to be fragments of the South PGE Reef in the Upper Layered Horizon of the West Pana intrusion.

The petrology of the West Pana intrusion was studied by M.I. Dubrovsky, V.V. Borisova, R.M. Latypov (GI KSC RAS). R.M. Latypov studied the structure and genesis of the Lower Layered Horizon of the West Pana intrusion at the Maryok area (Latypov et al., 1999). During fieldworks within the Maryok and South Kamennik areas of the West Pana intrusion in 1995, R.M. Latypov and P.V. Pripachkin provided a detailed mapping and sampling of profiles through the Lower Layered Horizon and Upper Layered Horizon, including bodies of magnetite gabbro. The study of these materials became the basis for constructing petrological models of formation of layered horizons and magnetite gabbro bodies (Latypov, Chistyakova, 2000).

The mineralogy of ore occurrences was investigated by N.L. Balabonin, V.V. Subbotin, Yu.N. Neradovsky, D.A. Gabov and E.E. Savchenko; more than fifty minerals and mineral phases of platinum group metals have been identified, including mitrofanovite Pt_3Te_4 and panskyite $Pd_9Ag_2Pb_2S_4$ as two new mineral species (Subbotin et al., 2012a; Subbotin et al., 2012b; Subbotin et al., 2019; Vymazalová et al., 2020).

Until recently, the East Pana intrusion used to be considered non-sulfide-bearing and unpromising in terms of PGE mineralization. In 1995-1998 JSC "Pana" prospected several sites of the East Pana Intrusion for PGE mineralization. Geologists S.M. Karpov, V.V. Subbotin and A.N. Kulakov discovered ore occurrences with an industrial PGE grade here.

"Barrick Gold Corporation" has been interested in PGE ore occurrences in the Fedorova-Pana Tundras since 2001. This provided financial opportunities for large-scale prospecting, appraisal and exploration work in cooperation with "Barrick Gold Corporation" (E. Nozdrya, V. Clemens, V. Komar and others). The main ore body of the Fedorova Tundra was traced to a depth of 300 m from the surface; its reserves were preliminarily estimated in 2001–2003 as a result of cooperation of JSC "Pana" and "Barrick Gold Corporation". In 2004-2005, detailed exploration was carried out in the contour of the boundaries of the proposed quarry.

In 2001, JSC "Pana" provided a detailed geological survey of the surface at a scale of 1: 5000 and drilling of 26 bore holes in the North PGE Reef of the West Pana intrusion, from the Maryok to the Central Kievey areas. This study confirmed the continuity of the North PGE Reef and allowed detecting objects of greatest interest. Further work on this territory was carried out by JSC "Pana" with the financial support of the "Ural Minerals Investment Company". The main ore body was preliminarily explored with an estimate of reserves to a depth of 400 m from the surface (Kievey deposit).

In 2002-2005, JSC "Pana" (A.U. Korchagin, V.P. Pavlov, S.M. Karpov, P.V. Pripachkin, S.V. Ivanov, V. Lobanov, etc.) together with "Kola Mining and Geological Company" (M. Vard, O. Kazanov, A. Kalinin, P. Dubchak, S. Pevzner, V.S. Voitekhovich, etc.) representing the "Bema Gold" company in Russia performed prospecting and economic evaluation of ore occurrences in the East Pana intrusion (Churozerskiy, South-West Peshempakhk, Predgorniy-Kuksha, East Chuarvy areas). Further works at this facility were continued by the "Kola Mining and Geological Company". As a result, the East Chuarvy PGE deposit was put on the state balance sheet in 2008.

Scientific research of the Fedorova-Pana Layered Complex was devoted to isotope dating of different magmatic phases (T.B. Bayanova and others) and to the construction of petrological models of individual intrusions of the complex (M.I. Dubrovskiy, N.Yu. Groshev). Several lines of evidence show that the intrusions were crystallized out of its stratigraphic sequence (Dubrovskiy and Rundkvist, 2008; Groshev and Karykowski, 2019; Groshev et al., 2019).

The "Fedorovo Resources", a representative of the "Barrick Gold Corporation" in Russia, and JSC "Pana" provided additional exploration works in 2006. The management of "Barrick Gold Corporation" decided to mine the Fedorova Tundra deposit as an open pit. Extensive drilling operations, more than 100 km of drill core, were carried out at the Fedorova Tundra in 2007-2008. The Fedorova Tundra deposit and the Kievey deposit were put on the state balance sheet in 2008-2009. JSC "Pana" continued prospecting and economic evaluation at the North Kamennik area of the West Pana intrusion. In result of these works, a new PGE deposit was identified and approved by the State Reserves Committee in 2015 (Korchagin et al., 2016).

3. Conclusion

Thus, a hundred years after obtaining first data on the Fedorova-Pana Tundras and 80 years after the first mentioning of PGE-enriched rocks, four deposits were discovered, all awaiting commercial development. These deposits are the Fedorova Tundra (Fedorovotudrovskoye), Kievey, North Kamennik and East Chuarvy. The potential for new PGE discoveries is high at the Fedorova-Pana Tundras. The most promising target is the North PGE Reef. It is about 15 km long on the surface and cut by two bore holes at a depth of 400 m. Studying this object all along its length and measuring its size at depth are interesting challenges for further research.

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Ore formation and PGE prospectivity of the Fedorova-Pana Layered Complex, Kola Region, Russia

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Summary Ore formational models of contact- and reef-style platinum-group element (PGE) mineralization of the Fedorova-Pana Layered Complex are briefly considered including some prospecting recommendations.

1. Introduction and background to current research

The Fedorova-Pana Complex is the most thoroughly studied among the layered intrusions of the Kola region in terms of PGE. It contains four PGE deposits (Fig. 1). The large Fedorova Tundra deposit is confined to a 300-m-thick unit of varied-textured mafic rocks with sulfide disseminations in the basal portion of the Fedorova intrusion, in the west of the complex. To the east, economic PGE mineralization occurs as thin layers of disseminated sulfides within rhythmic interlayering of leucocratic, mesocratic and melanocratic cumulates occurring among homogeneous gabbronorites of the West Pana intrusion. Relatively small deposits have been explored at the North Kamennik and Kievey areas, respectively. Thin interlayers of unevenly distributed along strike sulfide dissemination continue further to the east. The East Chuarvy deposit is confined to the contact between two megacyclic units of the East Pana intrusion. The authors who took part in the discovery and initial geological study of these deposits discuss here some of the proposed ore formational models with an emphasis on their use in prospecting.

2. Research questions at hand

The recently discovered PGE deposits in the Fedorova-Pana Complex have triggered major scientific debate. Firstly, the origin of contact-style PGE mineralization remains unresolved. An example is the high-tonnage Fedorova Tundra deposit with characteristic relatively low concentrations of precious metals (0.08 ppm Au, 0.29 ppm Pt and 1.20 ppm Pd). Studies of similar deposits (Monchegorsk, Portimo) show that percolation of PGE-enriched sulfide droplets through partially molten cumulates of the near-contact zone of the intrusion is one of the key processes in the formation of such ores (Karykowski et al. 2018). This process is largely facilitated by the long-lived nature of the magmatic system and preheating of country rocks during early intrusive phases, due to which the near-contact zone become fluid-enriched lowering the melting point of intercumulus material in incompletely solidified rocks. As a result, a thick zone of cumulates (50–100 m) becomes permeable to sulfide liquid, which accumulates in its lower part by gravity. Since the mineralized varied-textured mafics at Fedorova Tundra, forming the basal intrusive breccia, have cross cutting relationships with the overlying rocks at all places (Groshev et al. 2019), it is suggested that the Fedorova intrusion mineralization is the result of additional entrainment of metal enriched magma from depth.

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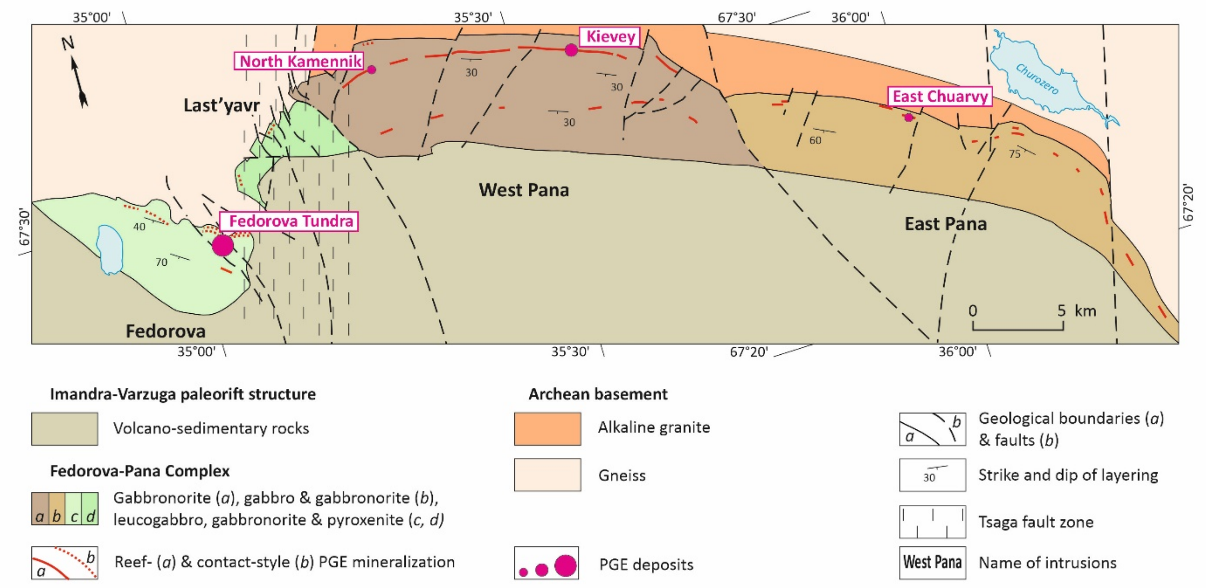

Figure 1. Simplified geologic map of the Fedorova–Pana Complex, showing the location of PGE deposits. Modified after (Groshev et al. 2019).

The remainders of the Fedorova-Pana deposits belong to another genetic type, characterized by laterally extensive thin ore bodies of disseminated sulfides with higher PGE concentrations (3–5 ppm). There are eight main hypotheses for reef-style PGE mineralization (Maier et al. 2018), addressing questions about reasons for sulfide immiscibility (mixing of magmas / contamination with crustal material / pressure increase), localization of the main ore-forming process (observed magma chamber / deep magma chamber), mechanisms of PGE concentration (injection of enriched sill, remobilized from the observed chamber or originating from depth / PGE transfer by fluids / hydrodynamic sorting).

3. Future prospects

3.1. Fedorova Tundra deposit

The deposit is considered to have formed as a result of "out-of-sequence" injection (Fig. 2A) of the ore-bearing basal unit of the intrusion (Schissel et al. 2002; Dubrovskiy and Rundkvist 2008; Groshev et al. 2009, 2021), although it contradicts the results of studies of contact-style PGE mineralization in other layered complexes (Karykowski et al. 2018). Further development of this model requires new high-precision dating of the rocks to date specific layers of the intrusion. Prospecting should target potential continuations of the orebody to depth (see Fig. 1 in Groshev et al. 2021).

3.2. North Kamennik deposit

The North Kamennik deposit belongs to the so-called North PGE Reef of the West Pana intrusion (Korchagin et al. 2016). Initial prospecting revealed an outcrop with up to 13 ppm PGE. However, a drillhole located 100 m from this outcrop intersected only unmineralized rocks. Subsequently, it was found that PGE mineralization is unevenly distributed in this part of the reef and is mainly concentrated in synforms of the ore-bearing horizon, which form channels in a plan view. PGE mineralization gradually disappears towards corresponding antiforms of the horizon (Fig. 2B).

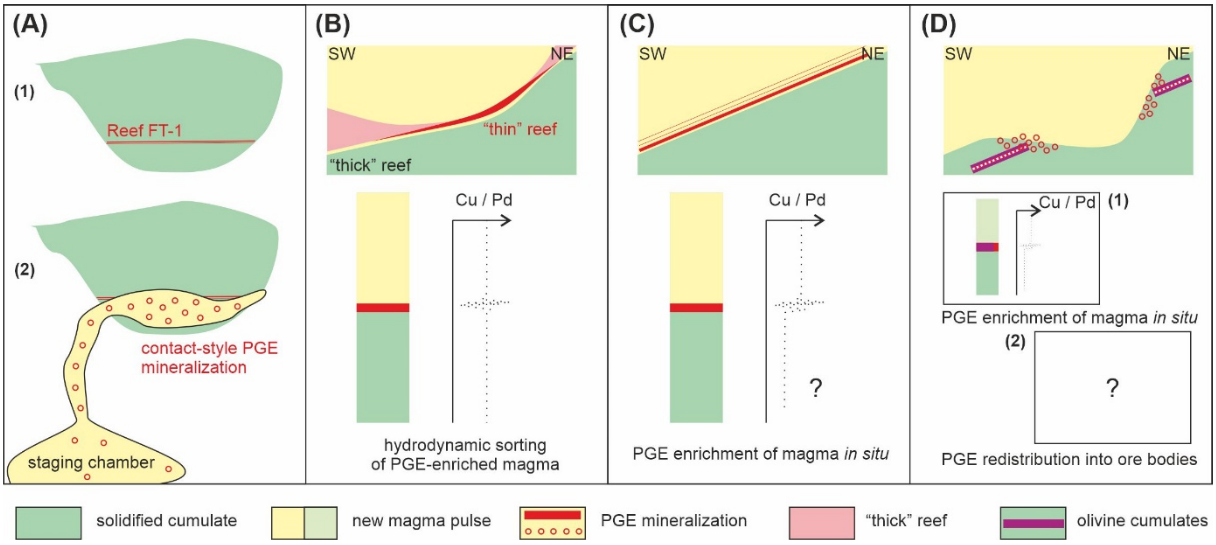

Figure 2. Sketched models of ore formation for the Fedorova-Pana deposits. (A) Fedorova Tundra. (B) North Kamennik. (C) Kievey. (D) East Chuarvy.

The mineralization in the synform can have a thickness of 5 m at a PGE grade of 3-10 ppm (drill hole 124). In the nearby antiform (drill hole 119), PGE concentrations between 40 to 200 ppb are observed over a 50-m-thick interval, reaching 1000 ppb in a few samples towards the base. Thus, the example of the North Kamennik deposit, which has "thin" and "thick" reef facies (Fig. 2B), apparently indicates an essential role of hydrodynamic sorting in the formation of reef-style PGE mineralization. To constrain the origin of the "thick" reef, it is necessary to conduct detailed geochemical sampling of drill holes.

3.3. Kievey deposit

The 5-km-long Kievey deposit is the most explored target of the North PGE Reef. Mineralization, containing on average 0.15 ppm Au, 0.53 ppm Pt and 3.32 ppm Pd, is almost continuously traced along the strike of the ore-bearing horizon dipping to the southwest at an angle of 30°. The mineralization was drilled in detail to a depth of 250 m, with several intersections measuring up to 500 m. The mineralization is associated with melanocratic rocks at the bases of melanorite-gabbronorite-anorthosite cycles of the ore-bearing horizon, suggesting a link to magma replenishing events. Sampling data, in particular variations in chalcophile elements and Cu / Pd ratio (Groshev 2020), suggest that the mineralization formed *in situ* (Fig. 2C). This is an important difference to the North Kamennik deposit (Groshev, 2021, unpublished data) which has mantle-level PGE concentrations and practically the same Cu / Pd ratio in the underlying and overlying rocks, not revealing the enrichment process inside the chamber and, conversely, indicating sulfide liquid enrichment with PGE in an intermediate magma chamber at depth. This contradiction should be resolved because of a comparative study of a series of deposit sections using drill cores. A scientific drill hole at the Kievey deposit with an intersection of the ore body at a depth of 1000 m may be of particular interest.

3.4. East Chuarvy deposit

The East Chuarvy deposit is confined to the contact of the megacyclic units GNZ1 and GNZ2 in the East Pana intrusion. The mineralized rocks containing on average 2.43 ppm Pt, 5.17 ppm Pd and 0.29 ppm Au were studied for 1200 m along strike and to a depth of 500 m (Kalinin 2021). The megacyclic unit GNZ2 has an erosional relationship with the underlying rocks of the GNZ1, represented by gabbronorites with several horizons of olivine gabbronorite. The ore body dipping to the southwest at an angle of 70° has an extremely complex shape. The richest portions are found in areas where the GNZ2 rocks are in contact with the GNZ1 olivine gabbronorites, which are believed to be a source of ore material redistributed and concentrated because of the intrusion of magma from the GNZ2 megacycle. This model has not been previously described in the literature and requires a comprehensive study.

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Precious metal mineralization in the East Pansky layered massif

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Summary Three PGE mineralized zones are defined in the western and central parts of the East Pansky intrusion, the zones are controlled by the boundaries of the divisions of layering. Each zone is of complicated geological structure, it can consist of two or more mineralized horizons. These horizons are located mainly at the basement or at the upper contact of olivine-bearing rocks, or move away for dozens meters. As a rule, petrographic control of PGE mineralization is not clear, or is absent. Composition and geochemical characteristics of PGE mineralization change along the cross section of the intrusion: sulfide content decreases from 3–5% in the lower zone to zero in the upper one, and Pd/Pt ratio decreases from 4–6 to <1.

1. Introduction

Geological structure and PGE mineralization in the East Pansky intrusion is not studied in detail, if compared to West Pansky or Fedorova Tundra segments of the Fedorovo–Pansky layered intrusive complex. First indications of low-sulfide PGE mineralization in the East Pansky were found by JSC "Pana" in 1995–2000 during exploration of the areas Sungjok, Chuarvy, Churozersky with small volume of drilling. Mineralized zones were defined and traced along strike for more than 10 km, and the intrusion was considered as a promising one for PGE mineralization. In 2002–2008 "Kola mining-geological company Ltd" (KMGC) carried out intense exploration for PGE in the East Pansky intrusion. As a result, the East Chuarvy deposit, the first PGE deposit in the region, and a number of ore occurrences were found (Ward et al., 2008, Kazanov, Kalinin, 2008, 2011). After 2008 there was no intense geological study in the area. The present article summarises the results of prospecting for PGE in the East Pansky intrusion in 2000s.

2. Materials and methods

Geological information for the article was presented by KMGC. The complex of geological study (2002–2008) included fieldwork with sampling of outcrops and boulders, drilling, logging and sampling of the drill core, assaying for PGE, Cu, Ni, S. The samples were assayed in Mekhanobr Analyt in S-Petersburg.

3. Geological structure of the East Pansky intrusion

The East Pansky intrusion is separated from the West Pansky by the Belotundrovsky fault. The length of the East Pansky intrusion is more than 30 km, and its thickness reaches 4.5 km in the central part. The intrusion is thinning in the east, and east of river Kuksha it is only a few hundred meters thick, and it can be traced farther east for another 25 km as minimum.

The following layers (zones) are defined in the East Pansky, from the bottom to the top: the Lower Marginal Zone (LMZ), the Gabbronorite Zone (GNZ), consisting of the lower (GNZ1) and the upper (GNZ2) subzones, and the Gabbro zone (GZ), which includes the lower (GZ1) and the upper (GZ2) subzones. Formation of each subzone was an independent stage of the intrusion development, connected with intruding of a new portion of magma. Mineral composition and cumulus associations, petrochemical and geochemical characteristics of the

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rocks change abruptly at the subzones boundaries. Rock evolution from high-temperature associations with primitive geochemical characteristics to low-temperature associations, formed of fractionated melt, enriched in non-coherent elements, can be seen within each subzone.

Steeply dipping faults of NE direction divide the East Pansky intrusions in 8 blocks, displaced for hundreds meters. Each block reveals its individual geological structure, because of different erosion level.

Bedding of the primary structural elements (contacts of the layers, trachytoidness of the rocks) is generally conformal to the lower intrusion contact, with dipping to SW 200-220º. In the lower part of the cross section, the rocks steeply dip at 70–75º, in the GNZ2 the dipping is 60-70º, and the tendency to more gentle dipping preserves farther up the cross section. Anomaly vertical, or even overturned rock bedding was found in the block of Bezymyanny.

4. Results

Three main zones of PGE mineralization, named A, B, and C zones, were defined in the East Pansky intrusion (Kazanov, Kalinin, 2008, 2011), the zones are controlled by the boundaries of the divisions of layering (subzones). The mineralization is of stratiform character, conformal to general layering of the intrusion, the mineralized horizons are rhythmically thin layered, the rocks contain anomaly cumulus associations (olivine, plagioclase, ensthatite-augite cumulates). Each PGE mineralized zone has specific 'stratigraphic' position, and peculiar mineral composition and geochemical characteristics – Pd/Pt ratio.

4.1 Mineralized zone A

Mineralized zone A is located at the basement of GNZ1 or in the lower part of it. PGE mineralization was traced from Sungjok mountain in the west to the area of lake Churozero in the east, and includes ore occurrences Sungjok, Chuarvy, East Chuarvy. The mineralization has high Pd/Pt=5–6, and Pd mineral phases are frequently found in the ore. PGE content correlates with S, but high sulphide content does not guarantee high PGE in the rock.

In the Sungjok occurrence, zone A is not outcropped, but it was drilled. Thickness of the mineralized zone varies from 0.3 to 1.7 m, dipping is 70°. The best section is Pt 0.37 g/t and Pd 2.0 g/t for 1.7 m.

In the Chuarvy occurrence zone A consists of 2 mineralized levels, one at the bottom, and another one at the upper contact of the olivine horizon. Thickness of the lower horizon reaches 43 m, dipping is 75° on the average. The ore zone consists of 3 ore bodies with total thickness of 7 m, with Pt 0.769 g/t and Pd 3.428 g/t. The upper mineralized level includes only 1 mineralized body 0.6 m thick with Pt 2.13 g/t and Pd 5.12 g/t. Compared to other ore occurrences, the mineralization in the Chuarvy contains high Cu 0.25% and Ni 0.36%. Chalcopyrite and pentlandite together with pyrrhotite can be visually identified in the rocks.

In the East Chuarvy mineralized zone A is located in the lower part of the horizon of the irregular grained gabbronorite (GNZ1), and partly in the underlying fine grained ensthatite gabbro in the LMZ. The rocks contain disseminated and veinlet-disseminated pyrrhotite-pyrite mineralization up to 5 vol.%. Content of Cu is 0.02–0.22 %, Ni 0.02–0.17 %, S 0.04–1.77 %, Pt 0.12–0.28 g/t, Pd 0.72–1.59 g/t, Pd/Pt ratio is 5.6 on the average.

4.1 Mineralized zone B

Mineralized zone B is controlled by the contact GNZ1–GNZ2, the mineralization is located mostly in the upper part of GNZ1. Pd/Pt ratio is 1.5–2.5. The main ore object of zone B is the East Chuarvy PGE deposit, other ore occurrences are Sungjok, Chuarvy, and Bezymyanny.

In the Sungjok, PGE mineralization was traced for more than 3 km along strike in elluvial boulders, and confirmed with drilling only in the central part of the occurrence. PGE mineralized rocks contain 0.5–2 vol.% sulphides, mainly pyrrhotite and chalcopyrite, the latter makes 25–50% of sulfide mass. The mineralized specimens collected in the outcrops, contain Pt+Pd+Au 7.0 g/t on the average, Pd/Pt = 2.41. The most rich samples with Pt+Pd+Au >21 g/t were collected not in the area with drillholes, but to the east and to the west from it. In the drillholes ore zone thickness varies from 0.7 (in case of one ore body) to 44 m (three ore bodies with Pt 0.89–1.94 g/t, 1.14 on the average, and Pd 1–2.6 g/t, 1.64 g/t on the average. The ore zones dipping is 75°.

In the Chuarvy occurrence PGE zone B includes two mineralized levels, one of them below the GNZ1-GNZ2 boundary, another one above it. The mineralization is very changeable along strike. Due to the phenomenon of magmatic erosion, GNZ2 contacts different rocks of GNZ1, and in the areas, where GNZ2 contacts the olivine horizon, thickness of the ore body and PGE content increase significantly. If GNZ2 contacts the rocks below the olivine horizon in GNZ1, mineralization is absent. Content of sulfides is 0.5–1%, pyrrhotite and chalcopyrite prevail, with ratio 70/30. The best section in the lower level is 1.5 m thick, Pt 0.89–2.13 g/t, Pd 1.12–5.12 g/t, and in the upper level is 0.8 m thick, Pt 10.81 and Pd 13.5 g/t.

The East Chuarvy deposit is the biggest ore object in zone B. The deposit consists of the Main Ore Body and 9 minor lenses. The main ore body was traced for 1200 m along strike and to the depth of 500 m. It is conformal to general layering of the intrusion, and dips at an angle of 70°. The ore body is of complicated form, with thinnings and bulges. Inner structure is not homogenous due to irregular alternation of mineralized and not mineralized rocks.

No clear petrographical control was defined. Mineralization morphology is irregular sulfide and sulfide-oxide dissemination, rarely – veinlet-disseminated mineralization. The main sulfides are pyrrhotite, chalcopyrite, and pentlandite, sulfide content is 0.6 mas. % on the average. Precious metals content is Pt 2.43 g/t, Pd 5.17 g/t, Au 0.29 g/t (Ward et al., 2008).

Two levels of PGE mineralization were found in the Bezymyanny occurrence. The upper one is, in fact, the eastern continuation of the East Chuarvy Main Ore Body. PGE mineralization is controlled by GNZ1-GNZ2 boundary and located mainly below it in melanocratic gabbronorite–pyroxenite. The rocks contain about 1 vol.% of sulfides, and chalcopyrite makes about 50% of sulfides. PGE mineralization forms one ore body up to 8.6 m thick with 1.80 g/t Pt and 2.68 g/t Pd.

The lower mineralized level is located 50–100 m below the GNZ1-GNZ2 boundary in the horizon of taxytic gabbronorites, including those melanocratic and olivine-bearing. The horizon was crossed by drillholes, the rocks contain Pt 0.30 g/t, Pd 0.97 g/t, thickness of the mineralized interval is 1.85 m. Pd/Pt ration varies from 3 to 4. Geological position of this mineralization, petrography of the mineralized rocks, geochemical characteristics differ from those in zones A and B, this is another zone, not defined in the ore occurrences in the western part of the intrusion. The horizon of taxytic gabbronorite in the same geological position in the East Chuarvy deposit and in the Chuarvy occurrence is slightly enriched in PGE, but is not considered as an ore. In the eastern part of the intrusion, this horizon is more important, and, probably, it hosts PGE mineralization in the ore occurrences Predgorny and Chorozersky.

4.1 Mineralized zone C

Mineralized zone C is controlled by the boundary GNZ2-GZ1. Mineralized rocks of this zone were found in outcrops only in the western part of the intrusion in the Sungjok and Chuarvy blocks. Two drillholes crossed poor precious metal mineralization of zone C in the Sungjok occurrence, and in the Chuarvy it is not confirmed by drilling. This mineralization is of specific character: the mineralized rocks has very low sulfide content (or even do not contain sulfides), Pd/Pt ratio is less than 1, and gold content is high (up to 2.2 g/t in some specimens from the outcrops).

5. Discussion and conclusions

Three PGE mineralized zones are defined in the western and central parts of the East Pansky intrusion, the zones are controlled by the boundaries of magmatic layers. Similar stratigraphic control of PGE mineralization, connected with inflow of new portions of magmatic melt in the intrusive camera, is known in many layered intrusions in the world, for example, in Stillwater (the USA), Pennikat (Finland), Olanga group of intrusions (Northern Karelia).

Each mineralized zone in the East Pansky intrusion is a complicated geological body, consisting of two or more mineralized levels. These levels are most often connected with the upper or lower contacts of the olivine horizons, but in some cases move away for dozens meters. Mineralization is not continuous along strike and dip, and PGE rich rocks alternate with non-mineralized in the neighbouring drillholes. PGE content correlate with S, but high content of sulphides does not guarantee high PGE.

Composition and geochemical characteristics of mineralization change along the cross section of the intrusion. Content of sulphide mineralization is relatively high in the lowermost zone A, intermediate in the intermediate zone B, and close to zero in the upper zone C. Pd/Pt ratio changes in the same direction from 5–6 in zone A to 1.5–2.5 in zone B and to <1 in zone C. The reason for this tendency is not clear now, some additional investigation is needed. But, for example, we do not see similar tendency in the Pennicat intrusion.

In the western part of the East Pansky intrusion we see three PGE-mineralized zones A, B, and C, in the central part (East Chuarvy block) we have two zones A and B. In the Bezymyanny one of two defined mineralized levels correlates with zone B, and another one is connected with taxytic garronorite horizon, which is only slightly enriched in PGE in the East Chuarvy and Chuarvy. This mineralization is located in between A and B zones, and its characteristics (content of sulphides and Pd/Pt ratio) are at intermediate position between A and B too. This mineralized level probably is the main one in the eastern part of the intrusion (the Predgorny and Churozersky).

Increase of price for PGE, most notably for Pd, may raise interest to the mineralized zone A, especially in the Chuarvy occurrence, where this zone is continuous and with stable high Pd content.

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Formation of layering of the Lovozero peralkaline intrusion (Kola Peninsula, Russia): new data

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Summary The Lovozero peralkaline massif is a layered intrusion. To establish the mechanisms of the formation of layering, studies of the chemical composition of rock-forming minerals (clinopyroxenes, amphiboles, eudialyte-group minerals) were carried out. It was assumed that the layering was formed as a result of fractional crystallization of relatively small portions of the alkaline melt.

1. Introduction and background to current research

The Lovozero peralkaline massif intruded through the Archean granite-gneiss and Devonian volcaniclastic rocks ca. 360 Ma ago (Kramm, Kogarko, 1994) and formed a large laccolith-type body. According to geophysical studies, alkaline rocks are traced to a depth of 7 km, the lower limit of their distribution is not detected (Gerasimovsky et al., 1966). In the upper part, the intrusion contacts with host rocks are almost vertical. The Lovozero massif consists of two macro units: the Eudialyte complex (at the top) and the Layered complex (Fig. 1). Among the rocks of the Eudialyte and Layered complexes, there are many xenoliths of volcaniclastic rocks. There are both unchanged xenoliths, which consist of olivine basalt, basalt tuff, tuffite, sandstone, quartzite, and intensely metasomatized xenoliths. Additionally, poikilitic foid syenites form lenses and rounded bodies among rocks of the Layered and Eudialyte complexes. Almost all pegmatites and hydrothermal veins of the Lovozero massif containing various rare-metal minerals are associated with these rocks.

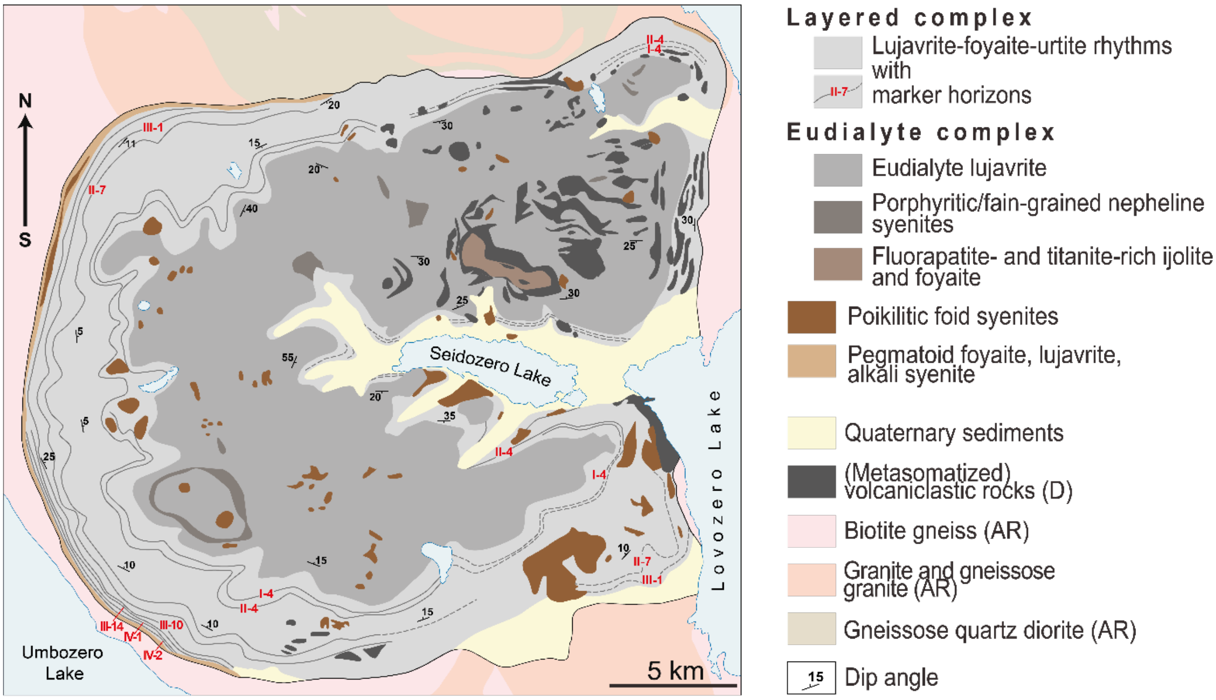

Figure 2. Geological scheme of the Lovozero massif (after Bussen, Sakharov, 1972).

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The Layered complex is the largest complex of the massif. It consists of the subhorizontal layers (or rhythms). The bottom of each rhythm is composed of urtite (Fig. 2c). Higher in the cross-section, the content of alkali feldspar increases, and urtite gradually turns into foyaite (leucocratic nepheline syenite, Fig. 2b). At the top of the rhythm, the content of mafic minerals, such as pyroxene and amphiboles, increases, and foyaite gradually passes into lujavrite (trachytoid melanocratic nepheline syenite, Fig. 2a). Contacts between rhythms are sharp. In addition, there are pegmatites at the contacts between the rhythms. Ideal rhythms (Fig. 2d) are found only in the upper part of the Layered complex. The middle part consists of lujavrite with foyaite lenses, and the lower part consists of lujavrite-foyaite rhythms with urtite lenses.

The mechanisms of the formation of the Lovozero massif layering are considered in the classical investigations of the 50-70s of the last century. Its formation was proposed to be a result of the rhythmic crystallization of a single magma chamber from top to bottom (Vlasov et al., 1959), from the bottom upwards (Gerasimovsky et al., 1966), by isolation in a single magma basin portions of silicate melts of different composition (Bussen, Sakharov, 1972).

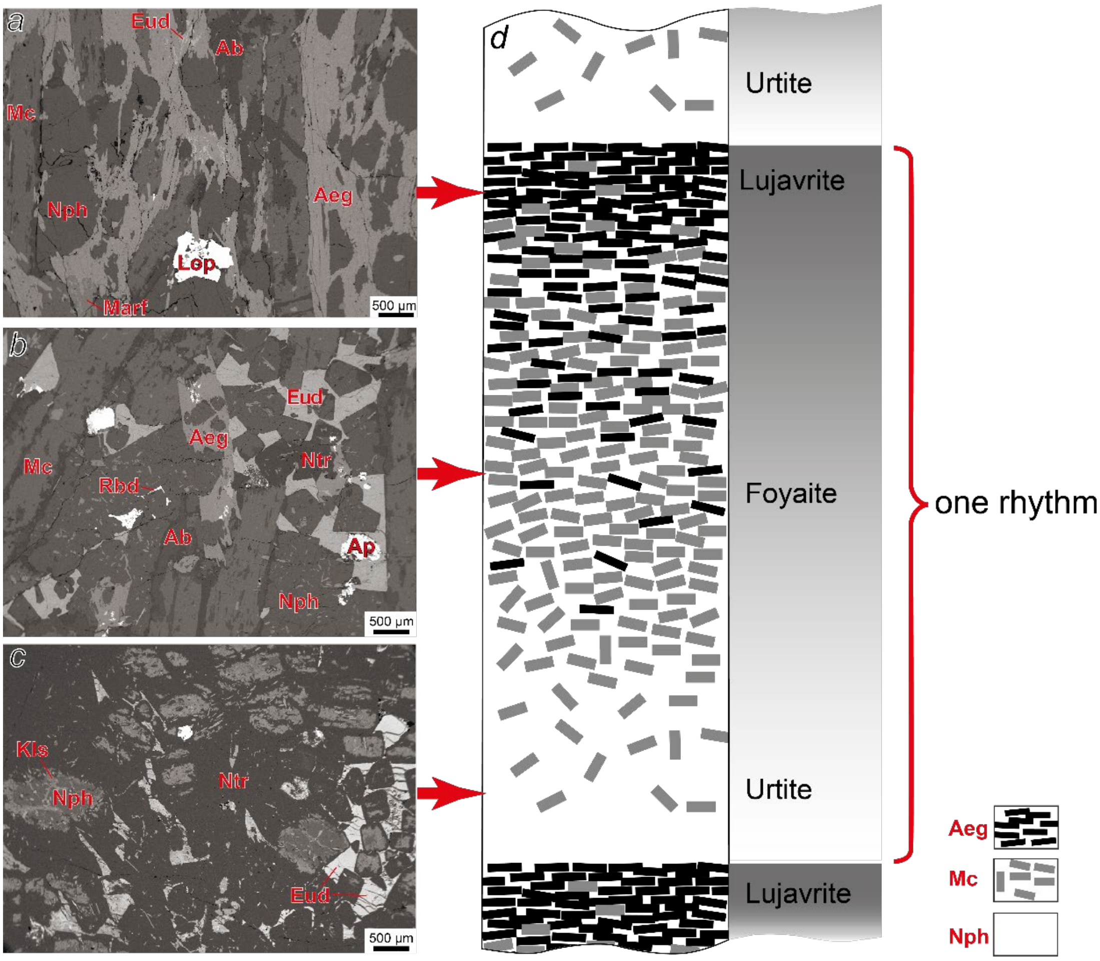

Figure 2. Varieties of rocks of the layered complex: (a) melanocratic nepheline syenite (lujavrite); (b) leucocratic nepheline syenite (foyaite); (c) urtite. Backscattered electron (BSE) images. Ab – albite, Ap – fluorapatite, Eud – eudialyte-group minerals, Kls – kalsilite, Lop – loparite-(Ce), Marf – magnesioarfvedsonite, Mc – microcline, Rbd – rhabdophane-(Ce), Ntr – natrolite. (d) – schematic representation of an idealised cyclic unit or "rhythm" (after Arzamastsev, 1994).

Kogarko (Kogarko et al., 2006) concluded that fractional crystallization from bottom to top of a single batch of peralkaline magma was the main process governing the formation of the Lovozero pluton layering. Féménias and colleagues (Féménias et al., 2005) concluded that the rhythm II-7 was formed as a result of intrusion into solid host rocks. In other terms, this rhythm is a sill.

2. Research questions at hand

Our research is aimed at establishing the mechanisms of the formation of the Lovozero massif layering. We are currently focusing on the study of changes in the chemical composition, morphology, and mineral associations of rock-forming minerals, such as pyroxenes, amphiboles, nepheline, potassium feldspar, minerals of the eudialyte group, minerals of the lovozerite group.

We compared the compositions of rock-forming minerals from lujavrite, foyaite, and urtite. Clinopyroxenes (aegirine and aegirine-augite) in lujavrite form small, long-prismatic crystals, and in urtite – large poikilitic grains. Yet, apart from morphology, they also differ in chemical composition. Clinopyroxenes from lujavrite are enriched in diopside component, while pyroxenes from urtite contain more aegirine end-member. Clinopyroxenes from foyaite are in an intermediate position. The evolution from diopside-rich pyroxene compositions towards aegirine-rich pyroxene is typical of alkaline massifs worldwide (Larsen, 1976). The major difference between various complexes is the amount of Fe^{2+} enrichment relative to Na and Fe^{3+} enrichment during their evolution (Korobeinikov, Laajoki, 1994).

The composition of eudialyte-group minerals also changes during the transition from lujavrite to foyaite and urtite. The ratio of manganese to ferrous iron in the eudialyte composition is maximum in urtite, while in lujavrite, it is lower. Such change indicates that lujavrite is the earliest rock of each rhythm, and urtite is the more evolved and latest one (Shilling et al., 2011). Amphiboles (arfvedsonite and magnesioarfvedsonite) in urtite and foyaite form large poikilitic crystals with inclusions of all surrounding minerals, and in lujavrite, amphiboles form anhedral grains located in the center of clinopyroxene segregations. In amphiboles from lujavrite, the aluminum and calcium contents are higher, and the silicon and sodium contents are lower than in amphiboles from leucocratic rocks. It is known that sodic amphiboles are stable only at low temperatures (below 650ºC) and pressures (Mitchell, 1990).

Thus, changes in the compositions of clinopyroxenes, amphiboles, and EGM indicate that each rhythm of the Layered complex consists of less- (lujavrite) and more-evolved (urtite) rocks. Fractionation of the melanocratic melt proceeded in the direction of enrichment with nepheline and a decrease in the aegirine content, i.e., from lujavrite to urtite. Such fractionation path occurs experimentally (Bailey, Schairer, 1966) in the Na_2O-Al_2O_3-Fe_2O_3-SiO_2 system, where melt of the “ijolite” type (approximately 50% of aegirine) evolves towards “phonolitic eutectic” (approximately 10% of aegirine). The results of our research are consistent with the conclusions of Féménias and colleagues (Féménias et al., 2005). We assume that the Lovozero massif was formed as a result of the injection of relatively small portions of alkaline melt into Devonian volcaniclastic rocks. Fractional crystallization took place *in situ*, in each such portion.

3. Future prospects

We plan to continue a detailed study on rock-forming minerals from different rocks of the Layered complex of the Lovozero massif. In particular, studies on the distribution of rare earth elements in minerals of the eudialyte group and loparite, crystal chemical studies of nepheline will be conducted. In addition, we are planning textural studies on magmatic rocks.

Acknowledgements

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Critical processes in the formation of contact-style PGE-Ni-Cu mineralization: Evidence from the Gabbro-10 intrusion as an additional intrusive phase of the Paleoproterozoic Monchegorsk Complex

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Summary Several studies on the Monchegorsk Complex suggest that the gravitational accumulation of sulfide droplets enriched in platinum group elements (PGE) near the bottom of the magma chamber under the condition of preliminary heating of the host rocks by early intrusive phases is a key process in the formation of contact-style PGE-copper-nickel mineralization. Using the example of Gabbro-10 intrusion, which is a late low-volume magmatic phase of the Monchegorsk Complex, we aim to demonstrate the importance of magma enrichment with sulfides occurring at depth in intermediate magma chambers. Moreover, this work substantiates the PGE prospectivity of the Gabbro-10 intrusion and its prospects for scientific drilling.

1. Introduction and background to current research

As a result of our previous studies of outcrops and drill holes on a drill section in the western part of the Gabbro-10 intrusion (Fig. 1), it was possible to establish the following general features of its geological structure and ore mineralization. The Gabbro-10 intrusion is located near the southern contact of the Nyud-Poaz intrusion of the Paleoproterozoic Monchegorsk Complex (2.5 Ga) and represents a flattened subhorizontal metagabbro lens hosted by Archean diorites. The metagabbros are covered with metadiorites separating these rocks from the melanorites of the Nyud-Poaz intrusion. The profile of the Gabbro-10 massif can be subdivided into two zones: (1) marginal zone and (2) gabbro zone. The marginal zone, up to 10 m thick, is composed of fine- to medium-grained schistose metagabbro, geochemically similar to mesocratic gabbronorites (Groshev et al., 2018a) according to classification (Dubrovsky, 2002). The gabbro zone consists of coarse- to medium-grained metagabbro, often characterized by taxitic texture due to the alternation of rocks with different grain sizes. The thickness of the zone is 30–40 m, increasing towards the east reaching up to 80 m. The geochemical composition of the metagabbro corresponds to quartz mesoleucocratic gabbronorite. The metagabbro contains xenoliths up to 10 m × 15 m in size. In terms of structural and textural features as well as geochemical composition, most of the xenoliths correspond to melanorite from the Nyud-Poaz intrusion and its endocontact zone (Groshev et al., 2018a). The metagabbro overlaps with the so-called metadiorite, at the base of which a magnetite layer of 1–2 m thickness is present. It is believed that the metagabbro and the metadiorite represent differentiates of the same intrusion. The U-Pb isotope age of the metagabbro is 2497 ± 9 Ma (unpublished data), whereas the age of the metadiorite is 2498 ± 6 Ma (Groshev et al., 2018b), which is within error and coincides with an isotope age of 2504 ± 2 Ma for the Nyud-Poaz intrusion (Amelin et al., 1995). Despite the indistinguishability of isotope ages at a given accuracy, the Gabbro-10 intrusion is clearly a late differentiated magmatic phase of the Monchegorsk Complex.

The PGE-Cu-Ni mineralization of the Gabbro-10 intrusion is associated with unevenly distributed and nested areas of disseminated sulfide (Groshev and Pripachkin, 2018). The dissemination is mainly confined to the marginal zone, but often spreads into the metagabbro

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and diorites of the basement. The sulfide content varies from single grains to 10 vol. %. The Pd concentration in the schistose metagabbro of the marginal zone is 0.58 ppm (drill hole 1808), whereas the metagabbro contains 1.78 ppm (sample G181-1 from the outcrop). The basement diorites show up to 2.28 ppm Pd (drill hole 1809). The Ni content in only a few samples of schistose metagabbro and basement diorites exceeds 0.1 wt. % with a relatively high Cu / Ni ratio. It is worth noting that according to the results of historic drilling for nickel carried out by S.M. Rutshtein and colleagues (1964) in the southwestern and eastern parts of the massif, there are two copper-nickel "ore stocks" (Fig. 1) confined to the bottom of the Gabbro-10 intrusion. The nickel concentration of these ore stocks varies from 0.2 to 0.9 wt. %, reaching 1.3 wt. % at most. Since these "ore stocks" were not drilled during PGE exploration in the Monchegorsk Complex, the concentration of precious metals remains unknown.

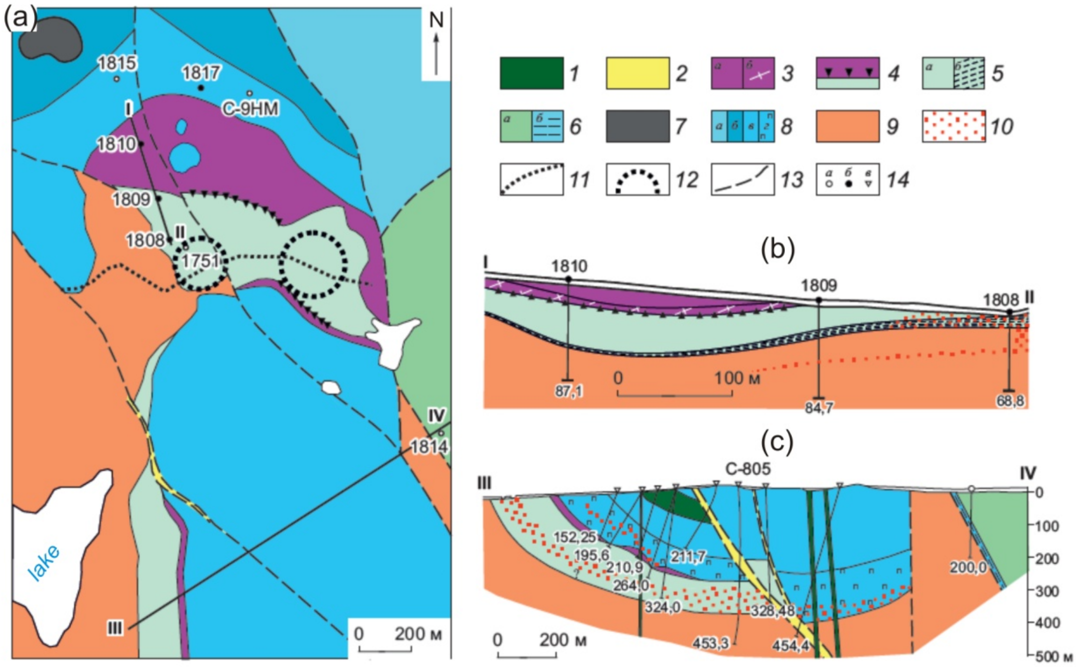

Figure 3. Schematic geological map (a) and simplified geological sections of the Gabbro-10 intrusion (b) and the Upper Nyud block (c) (Groshev and Pripachkin, 2018). 1 - metagabbrodolerite; 2 - tectonic zone; 3 - metadiorite (a), alternation of metadiorite, basement diorite and magnetite rocks (б); 4 - magnetite rock; 5 - Gabbro-10 intrusion (a - metagabbro, б - schistose metagabbro); 6 - Vurechuaivench massif (a - metagabbronorite, б - schistose metanorite); the Nyud-Poaz intrusion and the Upper Nyud block: 7 - critical horizon, 8 - norite (a), olivine norite (б), melanocratic norite (в), porphyritic melanorite (г); 9 - basement diorite; 10 - sulfide dissemination; 11 - 10th anomaly of electrical conductivity of the Monchegorsk ore region; 12 - approximate contours of copper-nickel ore stocks; 13 - faults; 14 – drill holes (a - assayed for PGE, б - studied by the authors, в - assayed only for base metals)

2. Research questions at hand

The confinement of the PGE-Cu-Ni mineralization at the bottom of the Gabbro-10 intrusion and its migration into the basement rocks by tens of meters (Fig. 2) indicate the critical role of gravitational sulfide drainage according to the mechanism described in Karykowski et al. (2018). A favorable factor for sulfide drainage in the Gabbro-10 intrusion is the thermal effect of the early magmatic phase represented by the larger Nyud-Poaz intrusion shortly before the emplacement of the Gabbro-10 intrusion. However, it could be assumed that one of the key roles or even the main role in the formation of the PGE-Cu-Ni mineralization of the Gabbro-10 intrusion is the enrichment of the magmatic crystal mush with sulfides and PGE in an intermediate magma chamber at depth. This assumption is supported by the numerous small vein bodies of quartz gabbronorites in the South Sopcha intrusion and the Moroshkovoye Ozero area located nearby (Pripachkin et al., 2016). Veins of quartz gabbronorites contain sulfide (3%), magnetite (3%) and nests of disseminated sulfide enriched in PGE reaching 6–8 ppm. It is highly probable that these veins are co-magmatic with the Gabbro-10 intrusion, which can be proved by high-precision isotope dating. An indirect confirmation of the enrichment of magmatic mush with metals at depth is the similarity of the breccia-like Gabbro-10 intrusion and the basal breccia of the Fedorova intrusion (Schissel et al., 2002; Groshev et al., 2019). The difference between the Gabbro-10 intrusion and the basal breccia at Fedorova is that the latter has a relatively uniform thickness in disseminated sulfide mineralization over hundreds of meters, containing up to 8 ppm PGE (1.2 on average). This is explained by a large time gap of more than 700,000 years (Groshev et al., 2009; Groshev et al., 2021). This temporal gap contributed to the cooling of the early intrusive phase. As a result, the pronounced sulfide migration in the additional magmatic phase, which is evidenced by the Gabbro-10 intrusion, did not occur at Fedorova.

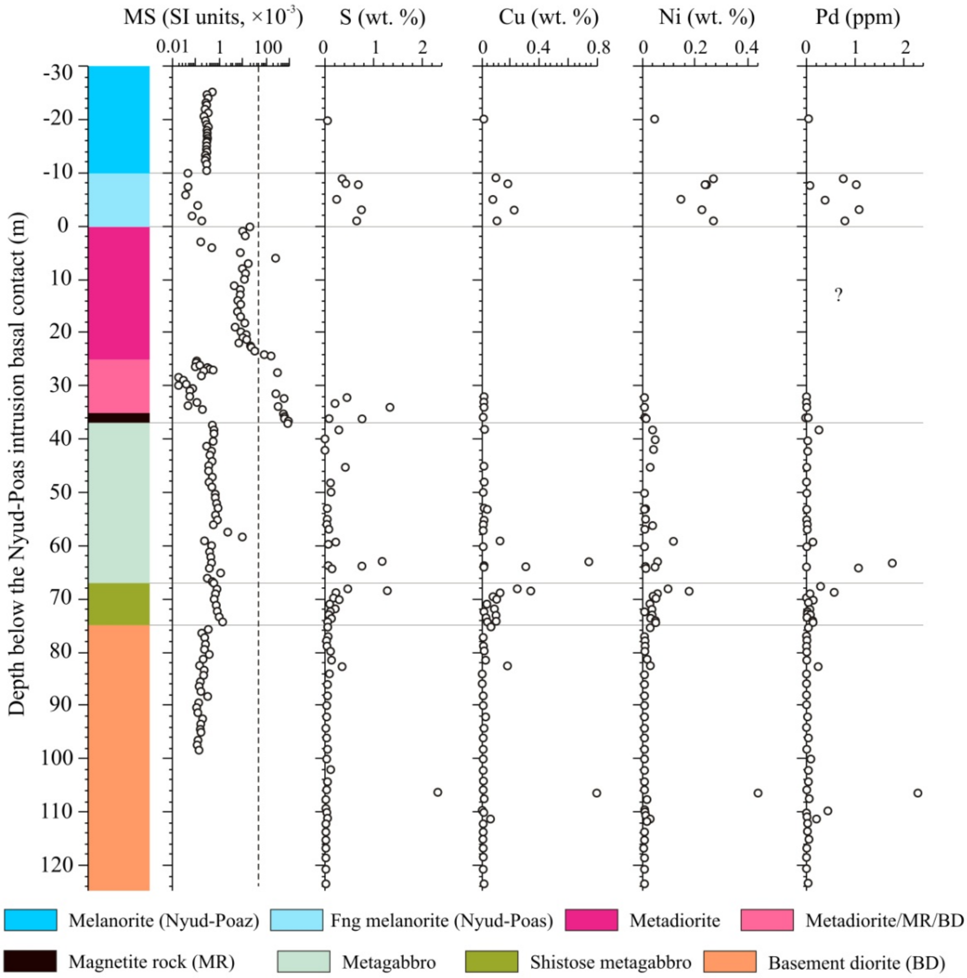

Figure 2. Simplified stratigraphic column across the Gabbro-10 intrusion with variations of magnetic susceptibility (MS) and S, Cu, Ni and Pd concentration (Groshev and Pripachkin, 2018).

3. Future prospects

To prove the co-magmatic nature of the gabbroids of the Gabbro-10 intrusion and vein quartz gabbronorites with sulfides and abundant magnetite, it is planned to conduct a comparative geochemical study to determine the concentration of lithophile and chalcophile elements in rocks (100 samples), analyze the composition of trace elements in sulfide and magnetite by LA-ICP-MS (20 samples), study the isotope composition of Sm, Nd and S in rocks (30 samples) and perform high-precision U-Pb isotope zircon dating using CA-TIMS (5 samples). From an economic point of view, the most important results will be obtained from drilling one or two holes up to 200 m deep in the area of the sulfide ore stocks with Ni contents up to 1.3 wt. %.

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An experiment on thermal modelling of the Paleoproterozoic Fedorova layered intrusion, Kola Region, Russia: implications for the origin of contact-style PGE mineralisation

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Summary This contribution presents the results of thermal modelling of the Paleoproterozoic Fedorova intrusion located in the central part of the Kola Peninsula, NW Russia. The intrusion hosts a large contact-style platinum-group elements (PGE) deposit in its basal 300-m-thick unit (Fedorova Tundra). This basal unit is composed of varied-textured gabbronorite and is believed to be an additional injection of sulphide-saturated magma, representing a second intrusive phase. The irregular distribution of sulphides across the entire basal unit and the absence of sulphide liquid migration into the underlying basement rocks suggest that this second injection exploited the cooled down contact between the first intrusive phase and the basement. The hiatus between the first and the second intrusive event allowed for some cooling of the former, however, the duration of the hiatus remains unknown. Assuming an average geothermal gradient of 30°C/km and a basement temperature of approx. 400°C due to preheating, thermal modelling indicates that the hiatus may have lasted for some 600–700 thousand years. These results are in agreement with a classic contact-style PGE mineralisation model for Fedorova Tundra and suggest an out-of-sequence formation of the layered succession.

1. Introduction

A critical factor in the formation of contact-style low-sulphide platinum group elements (PGE) mineralisation in layered mafic-ultramafic intrusions is the preheating of host rocks due to magmatic activity, preceding the emplacement of sulphide-saturated magma (Karykowski et al. 2018). Preheating of the basement to 400 °C by the intrusion of, for example, a series of dikes or sills that precede the main intrusion, creates conditions for the effective accumulation of sulphide droplets at the bottom of the magma chamber as well as for the percolation of sulphide droplets into the partially molten basement rocks. The Paleoproterozoic Portimo and Monchegorsk layered complexes on the Fennoscandian Shield are typical examples of intrusions where this factor played a crucial role (Iljina 1994; Karykowski et al. 2018).

The Fedorova intrusion represents the western block of the Paleoproterozoic Fedorova-Pana Complex located in the central part of the Kola Peninsula, NW Russia. The intrusion forms a 4-km-thick lens-like body that is steeply dipping to the southwest (Fig. 1a). Three zones are distinguished in the sequence of the Fedorova intrusion (from the bottom upwards): a Norite-Gabbronorite Zone (or ‘basal unit’), a Leucogabbro-Gabbronorite Zone, and a Leucogabbro Zone (Staritsina 1978). It is suggested that the Leucogabbro-Gabbronorite and the Leucogabbro zones comprise an early magmatic phase (2526-2515 Ma) with reef-style PGE mineralization, whereas the contact-style PGE mineralisation-hosting basal unit belongs to a later intrusive phase (2493-2485 Ma) (Schissel et al. 2002; Groshev et al. 2009; Groshev et al. 2019). The 300-m-thick basal unit is composed of varied-textured melanorite and gabbronorite containing abundant orthopyroxenitic autoliths and irregular patches of disseminated sulphide enriched in PGE (2–5 vol. %) (Fig. 1, b). Evenly disseminated sulphide accumulations (20–30 vol. %) are generally rare, whereas massive sulphides are absent. The PGE mineralisation is only hosted

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by the basal unit of the intrusion, showing no evidence for sulphide liquid percolation into the basement rocks. These sulphides form the Fedorova Tundra deposit with a total resources of more than 400 t of PGE (Rasilainen et al. 2010).

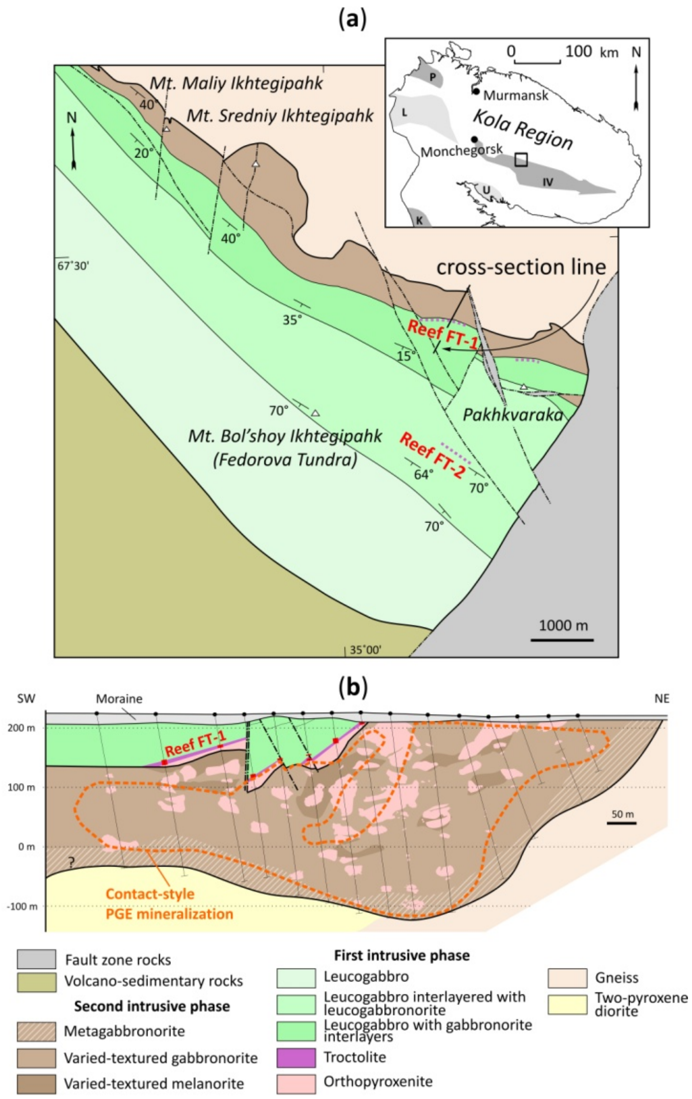

Figure 1. Simplified geologic map of the Fedorova Tundra intrusion (a) and schematic geologic cross section through the deposit (b). Purple dotted lines show a position of PGE reefs (FT-1 and FT-2) on the map; red rectangles on the cross section indicate mineralized intervals of the FT-1 Reef. Proterozoic structures of the predominantly Archean Kola Region (inset): Imandra-Varzuga (IV), Kuolajarvi (K), and Pechenga (P) paleorift structures; Lapland (L) and Umba (U) granulite belts. Modified after (Groshev et al. 2019).

It is believed that the first intrusive phase of the Fedorova intrusion preheated the basement before the second phase intruded along the lower contact of the first intrusive phase (Fig. 1). A thermal contact aureole of the first phase reaches several hundred meters as evidenced by partially molten two-pyroxene diorites observed in some drill holes (Groshev et al. 2009). In spite of this the second intrusive phase does not practically show features of sulphide accumulation within the basal unit or sulphide percolation into the basement rocks. Consequently the time gap between the intrusive phases was long enough for cooling of the basement below 400 °C (temperature supporting sulphide migration and accumulation). The purpose of this study is to estimate the time gap between the two intrusive phases comprising the Fedorova intrusion using thermal modelling and to discuss the results in the context of the crystallization duration of layered intrusions as well as the formation of a contact-style PGE mineralisation.

2. Methods

The cooling of the first intrusive phase of the Fedorova massif can be modelled by heat exchange between the magmatic succession with a temperature of 1200 ° C, which has intruded the Archean basement at a depth of 5 km (Dubrovskiy and Rundkvist 2008). The thickness of the body is assumed to be 4 km (Groshev et al. 2019). Discretisation of the one-dimensional heat equation gives the following recurrence formula:

$$T_i^{n+1} = T_i^n + k\Delta t\left(\frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{(\Delta x)^2}\right),$$

where k – thermal diffusivity ($k = 2\cdot10^{-6}$ m^2s^{-1}), and T_i^n – temperature at a depth of $i\cdot\Delta x$ m in $n\cdot\Delta t$ years. A detailed derivation of the equation is given in (Karykowski et al. 2018). To eliminate boundary effects, the depth of modelling was increased to 20 km. The thermal modelling was carried out using a FPC-based software (Stepenshchikov and Groshev 2019). Intrusive bodies are defined by four parameters: the boundary of the roof (m), thickness (m), temperature (°C) and the point in time of intrusion (years).

3. Thermal modelling results

The simulation shows that the emplacement of the Fedorova first phase will lead to a significant heating of the underlying rocks (Fig. 2 a–c; Table 1). The partial melting temperature of the basement (≈ 700 °C) will be reached approx. 250 m away from the lower intrusion contact after some 25 thousand years (Fig. 2 c, blue circle). This is in agreement with the thickness of two-pyroxene diorite below the intrusion (Fig. 1 b).

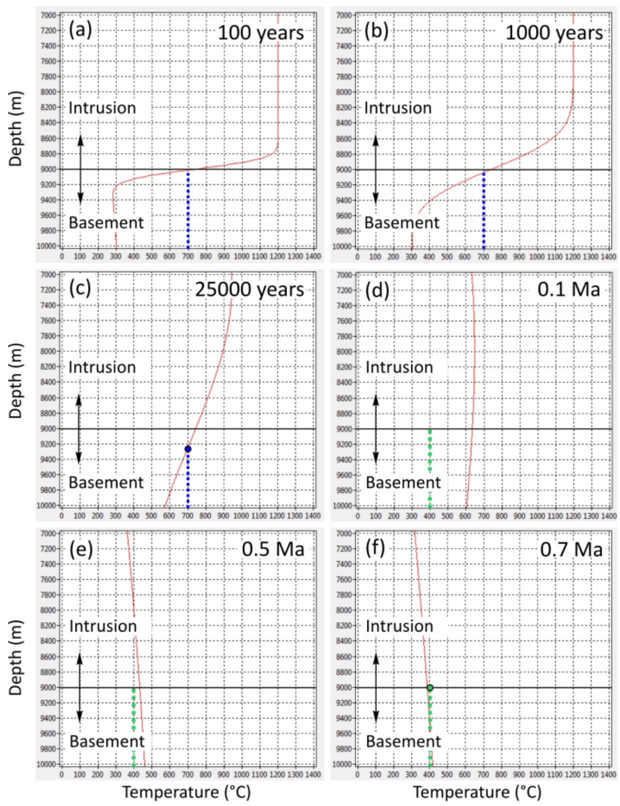

Figure 2. Temperature-depth graphs showing changes in temperature (red line) near the lower contact of the first intrusive phase of the Fedorova intrusion for different time moments (a–f). Note that an intrusion of the second phase could occur only after a contact cooling to 400 °C (green circle).

Since the magma of the second intrusive phase was sulphide-saturated, as a result of its emplacement in the preheated by the first phase contact with the basement the sulphides would have been concentrated near the bottom of the intrusion forming sulphide-rich layers and locally percolating into the Archean gneissic basement. Fig. 1 b shows that sulphides distributed unevenly and the migration of sulphide liquid is not observed at the Fedorova Tundra deposit. Consequently, the basal unit consisting of varied-textured gabbronorite that postdate the first intrusive phase were emplaced after the temperature at the lower contact of the first phase reached less than 400 °C. Under these boundary conditions, the minimum time separating the different intrusive phases is some 600–700 thousand years, as can be seen in Fig. 2 e–f (green circle) and Table 1.

Table 1. Thermal modelling results for the first phase of the Fedorova intrusion.

t (years)	Temperature, T (°C)		t (years)	Temperature, T (°C)	
	d=5 km	d=9 km		d=5 km	d=9 km
1	839	880	400000	306	462
10	732	787	500000	276	431
100	692	753	600000	254	407
1000	677	744	700000	236	386
10000	663	750	800000	223	369
100000	517	635	900000	211	355
200000	415	551	1000000	202	342
300000	350	500	–	–	–

4. Discussion

4.1. Duration of the Fedorova intrusion crystallization

The example of the Fedorova intrusion shows that the duration of crystallization under open-system conditions can be hundreds of thousands of years (Fig. 2). At the same time, the latest data on systematic isotope dating of open-system layered intrusions, show that the duration of their crystallization ranges from 1 to 3 Ma with an error of individual age determinations of up to 0.26 Ma modulo (Scoates and Wall 2015; Zeh et al. 2015; Wall et al. 2018). In this regard, it is worth noting that the currently available geochronological data on the Fedorova intrusion suggest a duration of crystallisation spanning some 40 Ma (Groshev et al. 2009), which appears to be greatly overestimated due to the likely inclusion of secondary zircon in the calculation of U-Pb ages (Groshev and Karykowski 2019).

Thus, the Fedorova Tundra deposit most likely represents a separate 'out-of-sequence'-type of contact-style PGE mineralization. The advancement of the isotope age determination on the intrusive phases of the Fedorova intrusion is possibly one of the most important unresolved problems in the petrology of layered intrusions on the Fennoscandian Shield.

4.2. Similar contact-style PGE mineralization in other layered intrusions

The presence or absence of sulphide liquid migration from the basal mineralised zones into the basement rocks is an important genetic feature of contact-style PGE deposits, revealing their thermal history. Except the Fedorova intrusion it can be shown by thermal modeling for the Nyud-Poaz massif (Monchegorsk Complex), which has two ore-bearing intrusive phases both containing disseminated sulfides, extending beyond the intrusion in the basement (Karykowski et al. 2018; Groshev and Pripachkin 2018). An additional phase (Gabbro-10), emplaced along the basal contact of the Nyud-Poaz intrusion hosts PGE mineralisation that percolates into the Archean basement for 30 m Consequently, the additional injection of sulphide-saturated magma occurred at a time when the basal contact of the Nyud-Poaz massif was characterised by elevated temperatures. The time gap between these two phases, according to the thermal modelling of the Nyud-Poaz massif, is no more than 150 thousand years. The accuracy of isotope dating cannot resolve such small time differences at the moment (Scoates and Wall 2015). This is also shown by the isotope dating of the Gabbro-10 intrusion whose age coincides with the age of the Nyud-Poaz massif within the error limits (Amelin et al. 1995; Groshev et al. 2018).

The South Sopcha intrusion of the Monchegorsk Complex is another example of contact-style PGE mineralisation that was likely formed out-of-sequence (Chashchin and Mitrofanov 2015; Pripachkin et al. 2015). The South Sopcha intrusion has an orthopyroxenitic lower unit, which is extensively intruded and brecciated by sill-like gabbro-pegmatites and coarse-grained gabbronorites containing PGE-rich disseminated sulphide. The issues of sulphide migration from the gabbronorites into the basement rocks as well as the duration of the South Sopcha crystallisation are to be solved in future research.

Acknowledgements
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The Koillismaa Deep Hole: insight to anomalous mafic intrusion

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Summary Geological Survey of Finland (GTK) is drilling a 3000 m long hole for solving mystery of deep geophysical anomaly zone located in the Koillismaa area, NE Finland. The diamond drilling campaign, Koillismaa Deep Hole, has been preceded by various geophysical surveys, such as gravity and magnetic measurement, seismic reflection soundings and AMT measurements which all show anomalous feature in depth.

1. Introduction

The anomaly zone, Koillismaa Deep Anomaly is ca. 60 km long zone connecting the distant parts of the 2.45 Ga layered intrusion blocks of the Koillismaa (Alapieti 1982; Karinen 2010) and mafic-ultramafic Näränkävaara intrusion (Alapieti 1982; Järvinen et al. 2020) (Figure 1). The anomaly was observed already in 1950's since the earliest ground gravimetric and airborne geophysical measurements were performed. Therefore, the source of anomaly has been struggling the minds of geoscientists already for many decades. GTK started to drill a 3000 m long drill hole in the heart of the anomaly in September 2020, to finally collect rock samples from the source of the anomalous zone. In this abstract we briefly describe the background, geophysical studies and present stage of the ongoing drilling.

2. Geophysical studies

Most of the scientific contributions related to the Koillismaa Deep Anomaly have been geophysical studies (Piirainen et al. 1978; Saviaro 1976; Salmirinne & Iljina 2003; Gislason et al. 2019). The anomaly zone is most distinctly observed and interpreted from gravity and magnetic surveys (Figure 2). The source of the anomaly is interpreted to be about 2.5-5 km wide with depth of the upper interface to country rock between 1 and 2 km below the present erosion level depending on the location along the anomaly. Interpretation of earliest AMT-surveys in 1970s brought up a weak conductivity contrast located in the same area with the gravity anomaly.

The latest geophysical surveys carried out by GTK were a seismic survey in 2018 and an AMT survey in 2019. The seismic reflection data was acquired along the road close to the drilling site with 90 wireless geophones with 20 m spacing and explosive sources with 40 m spacing (Gislason et al. 2019). The resulting seismic reflection profile shows prominent reflectors that are very likely due to lithological contacts or fracture zones that cause abrupt change of acoustic impedance within the subsurface (Figure 3). Furthermore, the AMT data confirmed the existence of the previously interpreted conductivity contrast.

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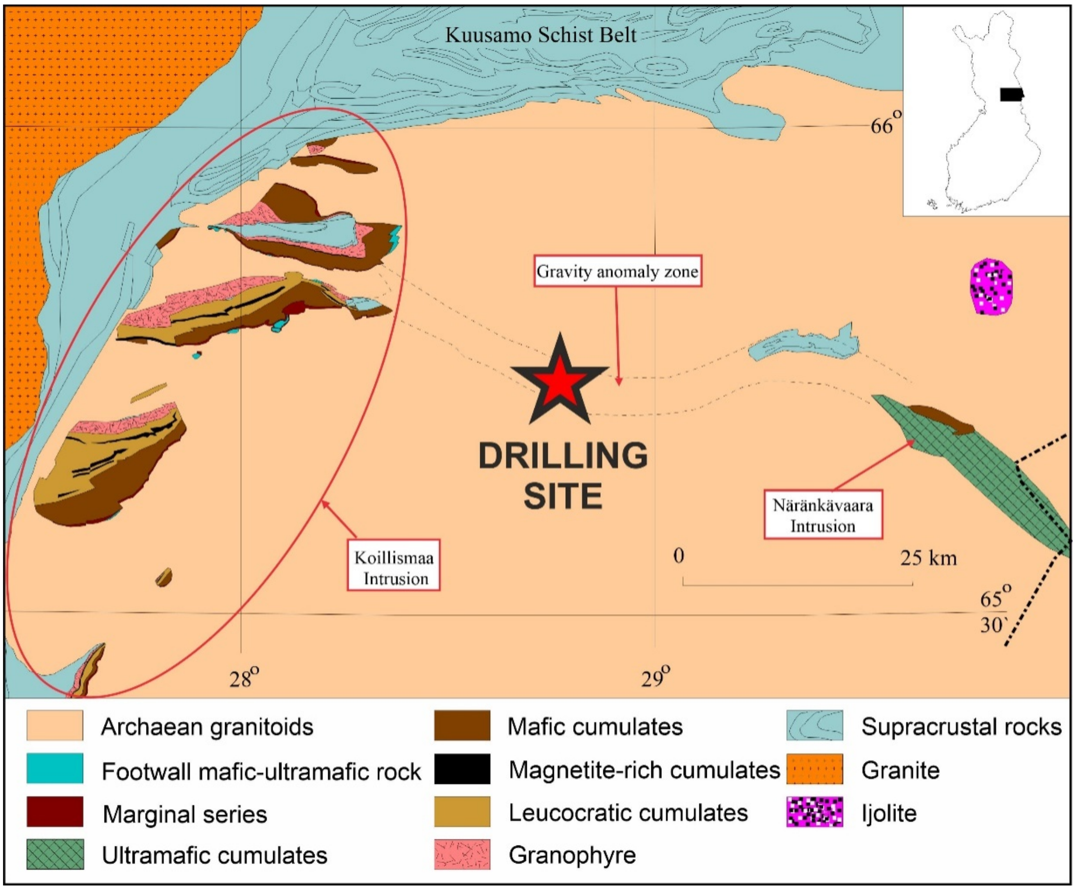

Figure 1. General geological map of the Koillismaa-Näränkävaara area.

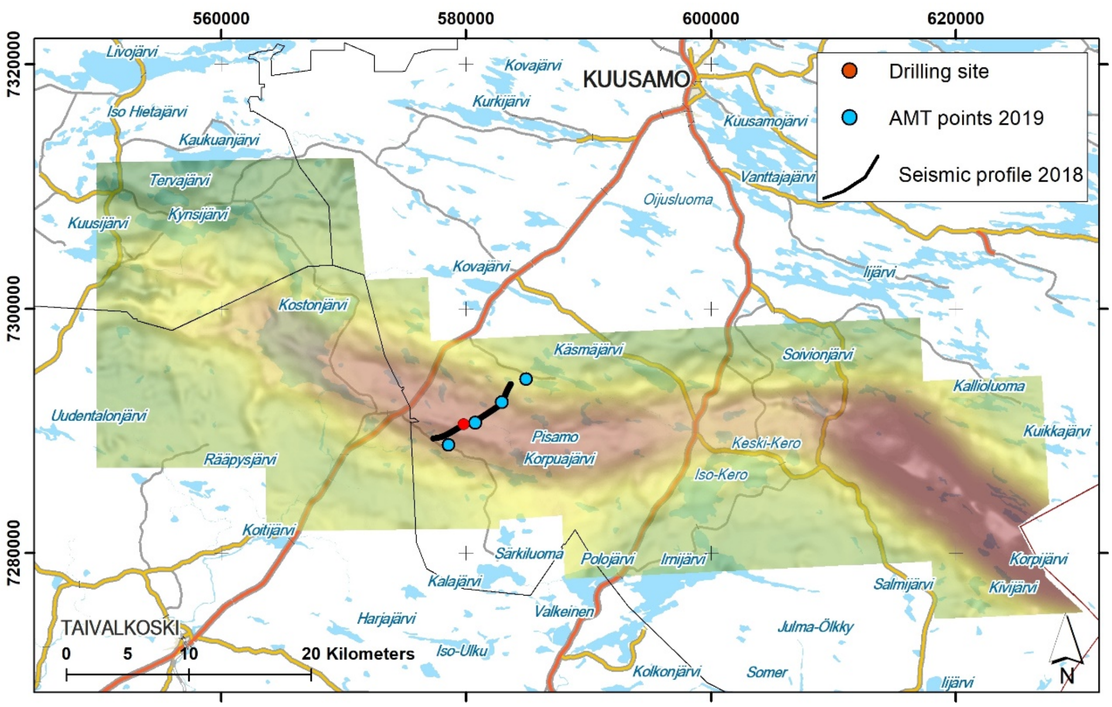

Figure 2. Drilling site on the regional gravity map. Locations of seismic profile 2018 and AMT surveys 2019 are plotted also.

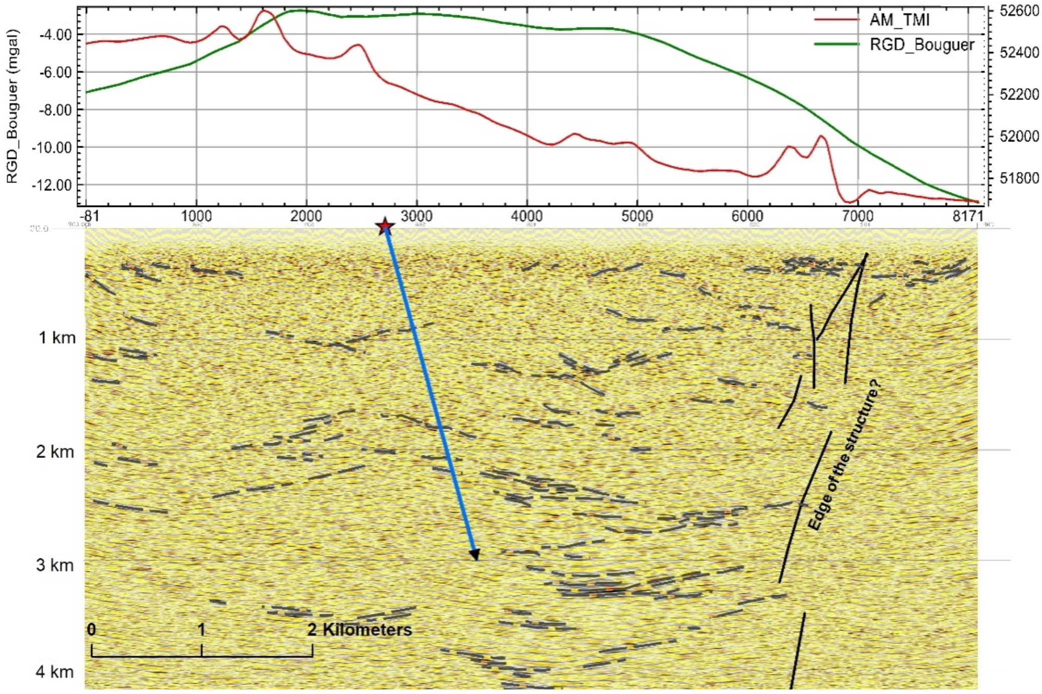

Figure 3. Planned drill hole projected to the seismic reflection profile. Bouguer gravity anomaly (RGD_Bouguer) and airborne magnetic (AM_TMI) profiles are plotted above the seismic section.

We believe that the anomaly reflects location of a gigantic chonolith-like feeder zone for the magmas of the exposed mafic-ultramafic intrusions in the Koillismaa. Alternatively, the anomaly could reflect the presence of mafic-ultramafic rocks representing some other magmatic episode than the 2.45 Ga intrusions, for example, the Archaean greenstone belt near the Koillismaa area. This kind of voluminous mafic-ultramafic systems are globally rare, and therefore, the target is very likely an example of plume derived magmatism of Fennoscandian shield. In addition, large mafic-ultramafic bodies are favourable to host significant orthomagmatic sulfide and oxide deposits.

3. Drilling campaign

On surface level, the anomaly is traceable by a narrow breccia zone. However, the petrophysical properties of the breccia do not explain the geophysical anomaly, and therefore, the project started the diamond drilling campaign in order to collect sample material from the depth that would result in observed geophysical signature.

In September 2020, GTK started diamond drill campaign the Koillismaa Deep Hole to reach the anomaly. The drill core is planned to be up to 3000 m in length. Presently the drill core has reached a depth of 1722 m. Luckily, we have been able to collect sample material which confirms that the source of anomaly is related to ultramafic cumulates, such as peridotite and pyroxenite (Figures 4a and b). These rocks were penetrated at about 1.5 km depth, where also prominent change in seismic reflectivity is observed.

4. Impact of the Koillismaa Deep Hole

In addition to scientific contribution increasing the understanding of the Koillismaa intrusion geology and mineral potential, the deep drill hole site also provides scientific platform and test environment for future studies. These are, for example, development of survey technology, 3D modelling, studies of geothermal energy, deep groundwater and bedrock stability.

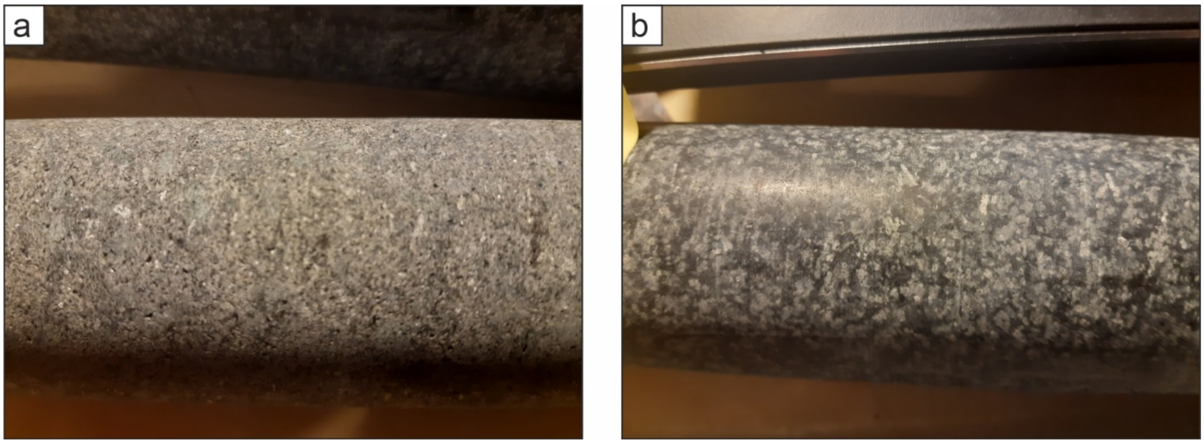

Figure 4. Samples from the depth. (a) Pyroxenite from ~1430 m. (b) Peridotite from ~1545 m of the diamond drill core.

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New reef-type PGE enrichment of the 2.44-Ga Junttilanniemi layered intrusion in Kainuu region, Finland

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Summary The Junttilanniemi layered intrusion is located in the Kainuu region, Finland. The intrusion contains three main units: marginal series, layered series and granophyre. The layered series being further divided into three megacyclic units (MCUs). Quite recently, during year 2010, Geological Survey of Finland (GTK) located from the Junttilanniemi intrusion a new reef-type platinum-group element (PGE) enrichment of the 2.44 Ga Fennoscandian layered intrusion.

1. Introduction and background to current research

The Junttilanniemi layered intrusion (2444±4 Ma old, Kontinen et al., 2014), is located the municipality of Paltamo, Kainuu region, in the area of Varisniemi about 25 km SW of the town centre and 20 km NW from Kajaani (Fig. 1). The 1:100 000 KKJ map sheet containing the area is 3432. The UTM map sheet is Q5224. It is about 7.5 km long and 0.6 to 3 km wide. Its footwall rock in the eastern side is possible Archean undefined serpentinite and southern side Archean tonalitic gneiss. The hanging wall rocks in the western side are metasedimentary and metavolcanic rocks of Sumi-Sariola formation (2350-2500 Ma old). The intrusion contains three main units: marginal series, layered series and granophyre. The layered series being further divided into three megacyclic units (MCUs) (Fig. 2). The thicknesses of MCU I and MCU II are only 40-45 m than the MCU III is about 3600 m thick. The intrusion dips to the SSE at 70–85°. It is overturned, as the top is to the NW. The intrusion has abundant outcrops, except in its southern part, which is under a lake. Very few drillings have been performed the area of the intrusion (Mäkelä, 1974; Halkoaho and Niskanen, 2011; 2013 and Rasilainen et al., 2010). According to whole-rock compositions Junttilanniemi intrusion is analogous to the Akanvaara and Koitelainen layered intrusions, northern Finland (Fig. 1, see e.g. Mutanen, 1997).

Exploration commenced in the Junttilanniemi area in 1974 when Rautaruukki Oy drilled three diamond drill holes into the magnetite gabbro unit and one drill hole into the southwestern part of the intrusion (Mäkelä, 1974). Bedrock mapping began in the area at the end of the 1980s, when GTK started to map the area (Kontinen and Meriläinen, 2004). During 1992–1993, the Department of Geology of the University of Oulu performed some field work in the area. In 2009–2010, GTK explored the intrusion area. The main target of the exploration was to work out the Ni-Cu-PGE ore potential of the Junttilanniemi layered intrusion and find the source of the PGE-rich (Cu 0.38 %, Ni 0.14 %, Co 0.009 %, S 0.7 %, Pd 6.83 ppm, Pt 1.56 ppm and Au 0.18 ppm) gabbronorite boulder found by layman from Näätävaara area, Nurmes. During the year 2010, GTK drilled a five (5) diamond drill hole profile (totaling 563.90 m) in the southern part of the Junttilanniemi layered intrusion on the ice cap of Oulujärvi (Karhusalmi area, see Fig. 2) and located a new reef-type PGE enrichment zone from the 2.44 Ga Fennoscandian layered intrusions (Halkoaho and Niskanen, 2011; 2013).

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2. Results

The stratigraphy of the lower part of the intrusion is completed by three ultramafic units. The border of the chromium richer and chromium poorer magma type was found between the MCU II and MCU III. Altogether five PGE enriched layers were found from the MCU I, MCU II and the lower part of MCU III, which all are associated with base metal sulfide disseminations. So high PGE-content (PGE+Au = 8.57 ppm) than contains the layman's boulder of Nurmes, was not found from the Junttilanniemi intrusion. The PGE richest drill hole sample (length 1 m) contains PGE+Au 0.83 ppm, Cu 0.45 %, Ni 0.064 %, Co 0.006 % and S 0.55 % (Halkoaho and Niskanen, 2011; 2013).

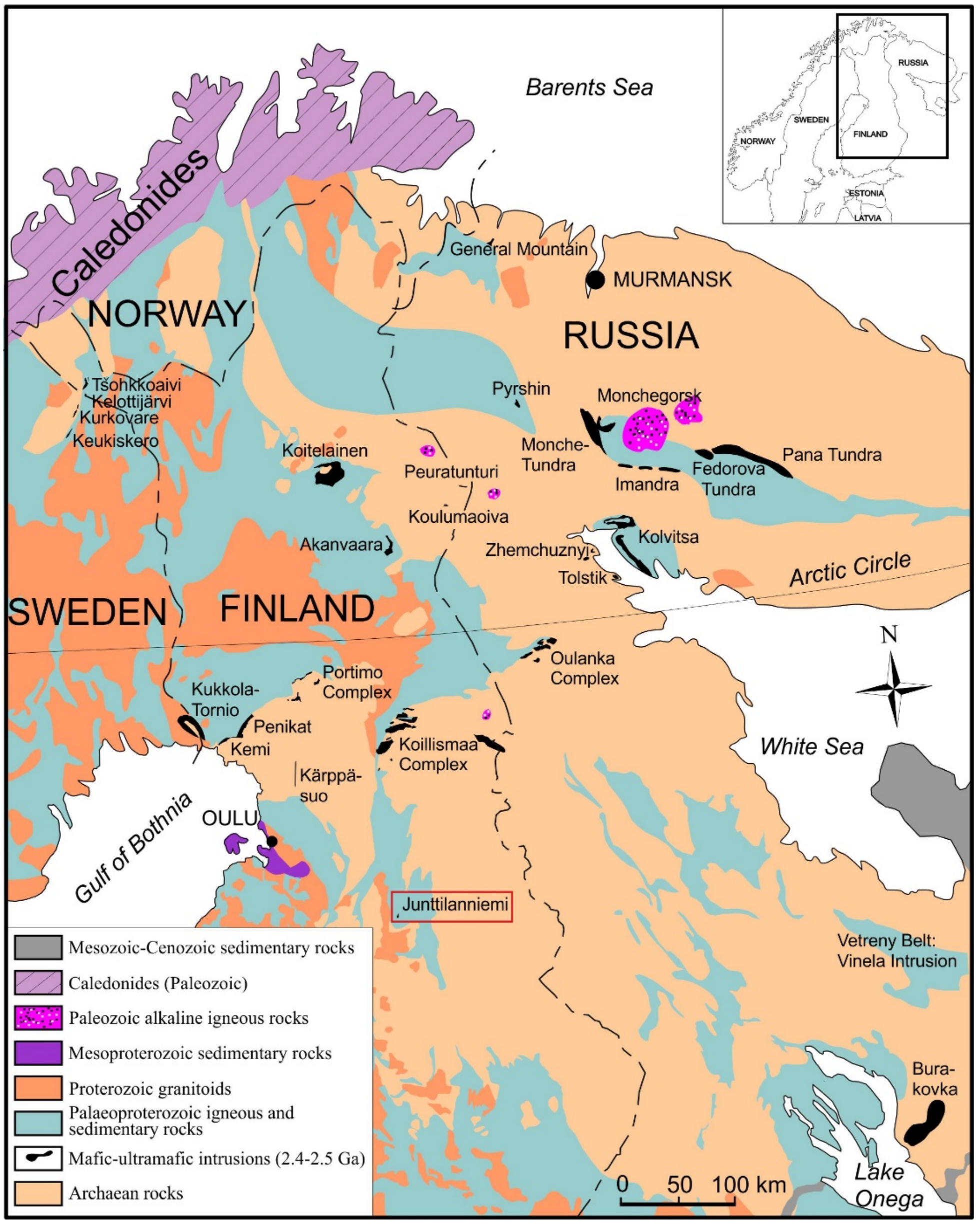

Figure 1. Simplified geological map from the part of Fennoscandian Shield, highlighting location of 2.44–2.5 Ga layered intrusions. Figure modified after Alapieti and Lahtinen (1989) and Maier et al. (2018).

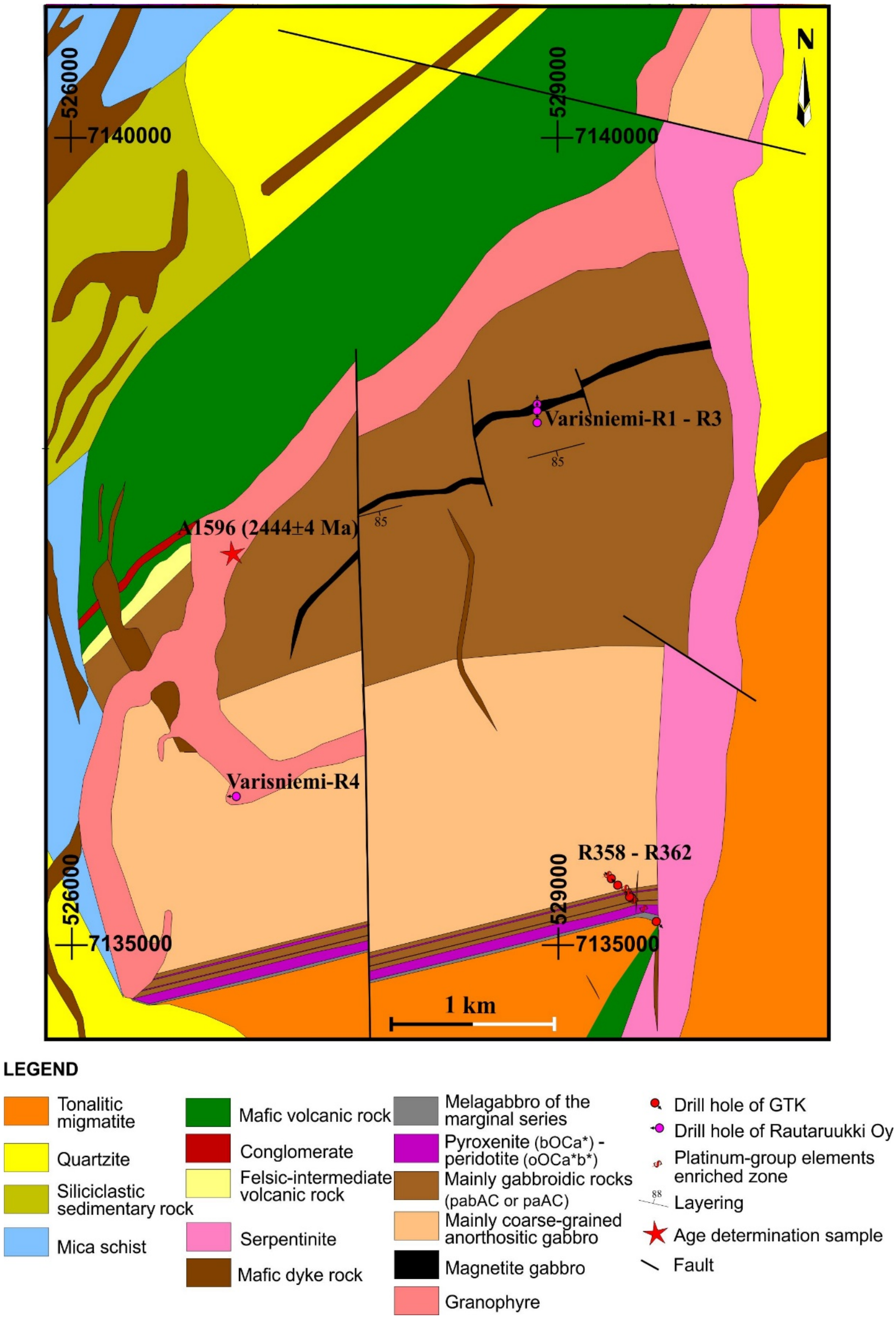

Figure 2. Geological map of the Junttilanniemi layered intrusion. Modified after Kontinen and Meriläinen (2004), Rasilainen et al. (2010), Halkoaho and Niskanen (2011), and Bedrock of Finland, DigiKP – Seamless bedrock map of Finland by GTK. bOCa* = poikilitic bronzite orthocumulate with intercumulus augite, oOCa*b* = poikilitic olivine orthocumulate with intercumulus augite and bronzite, pabAC = plagioclase augite bronzite adcumulate, paAC = plagioclase augite adcumulate and * = mineral is poikilitic.

3. Future prospects

Still, the layman's sample may originate from the Junttilanniemi layered intrusion, because only one cross-section of the PGE enriched zone has been made. The chromite-rich boulders found earlier from the north-northwest part of the intrusion indicate, that there is still, at least one, an undiscovered Palaeoproterozoic layered intrusion, which may also be the source of the PGE-rich layman's boulder. In the further study, a deep diamond drill hole from shore of the Oulujärvi is recommended. The distance from Ojaniemi to the lower contact of the intrusion is about 700 m and from Kuikkaniemi about 450 m (Halkoaho and Niskanen, 2011; 2013). In addition, exploration should be directed northwest side of the Junttilanniemi intrusion towards the municipality of Vaala, because the chromitite boulders found in the Junttilanniemi area do not originate from the Junttilanniemi layered intrusion.

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Next generation geoenvironmental deposit models – promoting sustainable utilisation of layered intrusions

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Summary Geoenvironmental mineral deposit models are based on the observation that different deposit types result in type-specific environmental impacts when mined. It is possible to predict the most likely mining and processing methods and, therefore, environmental impacts caused by each deposit type. This approach can be taken one step further by also considering the deposit location as this also affects both the environmental impacts and the regional opportunities of mining a certain type of deposit. Such a profiling can be carried out using publicly available spatial data sets. This presents possibilities also for layered intrusions research as models like this can be used to compare exploration targets for project portfolio and risk management, investment decisions, and transparent communication of exploration for the public.

1. Introduction

The demand for primary mineral resources by societies is in the increase globally. This change is driven by the increase in population and, importantly, the general standard of living in all parts of the world. In addition, an unprecedented shift in the demand for certain primary mineral-based raw materials is driven by the recent shift to green technologies in especially energy production and storage and in electric mobility (e.g., Xu et al. 2020). The latter shift in particular is based on sustainability and environmental arguments and promise. This requirement naturally extends also upstream in the value chain and the production of primary raw materials also needs to live up to the sustainability promise.

For primary mineral production to be sustainable, certain requirements need to be met (Kauppila, 2018). We will need to seek measures that promote a viable mining industry capable of solid environmental management investment. We will also need to maintain a high exploration activity to produce data, methods, and prospects to replace the deposits that we are mining for the benefit of the current generation. At all time, losses of natural capital other than the exhaustion of the deposit should be minimized in mining operations while local sustainable benefits are maximized.

All of these important facets of sustainability of mining projects are linked to one another and also to the public acceptance for mining projects, often called social license to operate. Public acceptance is crucial for high exploration activity and environmental issues are in the core of acceptance issues. Therefore, we need better tools to predict, mitigate, and communicate the risks of exploration and mining projects and to communicate all this to the public in an open and trustworthy manner.

Exploration projects typically lack public acceptance not because of the impacts of exploration as such but because of the anticipated impacts of the mining operation that might arise from successful exploration. This is the case even if most exploration projects never produce results that warrant a mine. Tools are therefore needed to systematically and transparently analyse the risks and opportunities related to exploration targets and to communicate the findings to the public. In addition, the industry needs tools to efficiently

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compare the properties of exploration targets for investment decisions, project portfolio management, and risk management.

Geoenvironmental mineral deposit models are tools that seek to extend the ore deposit models to also predict the environmental pressures caused by the most likely mining operations that might be used to mine the deposit at hand (e.g., Seal & Foley, 2002). Such models could be used to analyze exploration projects at an early stage, provided that some predictions of the target deposit types (e.g. layered intrusions) are available. In addition, spatial data sets are increasingly available that could be used to also take into account the location-specific properties of the exploration area. These properties have a bearing on the vulnerability of the site surroundings for mining impacts and on the regional benefits that might be gained from a mining project. Such spatial data-based models can be termed next generation geoenvironmental deposit models as they take the approach further from the static, report-like format. This paper examines the possibilities of and approaches for next generation geoenvironmental mineral deposit models and the opportunities they provide for exploration targeting layered intrusions.

2. Research questions

Next generation geoenvironmental mineral deposit models are based on three assumptions: 1) deposit properties affect the properties of the mining operation and, therefore, the environmental impacts, 2) deposit location affects how vulnerable the site and its surroundings are to the mining-related stressors and how the region can benefit from the project, and 3) modern publicly available data sets can be used to analyze both of the points above to produce useful analyses that describe the components of risk and opportunities of the exploration targets.

2.1. Deposit properties affect environmental management challenges

Original geoenvironmental deposit models, and the modern ones as well, are based on the observation that deposit types affect the environmental management challenges encountered. Some mines are much easier to run with minimal environmental effects than others. The most common divisions are between metal mines and non-metal mines and between sulfidic and oxide metal mines. However, the issue is much more complex and requires that the properties of the country rock also is considered. This issue as well as things such as deposit geometry highlight the need for a model that is scalable. The model should be able to take into account data on deposit properties as it becomes available during exploration and the predictions should be updated accordingly. It is of great importance that the authorities are able to take the uniqueness of each deposit into account in making decisions on licensing and environmental permitting and models such as these can support authorities in facts-based decision making.

2.2. The effect of deposit manifests through process options and waste properties

The effects deposit properties have on the expected impacts of a mining operation are mainly based on two mechanisms: the properties of mining wastes (waste rock and tailings) and the methods selected to mine and process the ore. Current deposit models can be analysed and improved to provide reasonable estimates of also waste rock properties and useful predictions of tailings properties are also possible even though all deposits are unique in properties. For both waste types, predictions need to consider properties that are relevant for waste management, a feature not common in current deposit models.

A crucial feature in classical and modern geoenvironmental deposit models is the ability to predict the most likely mining and processing methods for the deposit types. This is, indeed, achievable with current expertise and with support from analysing current projects for similar deposits, if available. Scalability is of importance here and predictions should be updated as more information on the deposit is collected. Deposit properties affect not only the mining and processing methods but also the amounts of waste, types of emissions, hazards present, and the timing and duration of the expected impacts. Importantly, modern geoenvironmental models need to also take hazard and impact management measures into account. For instance, mining wastes should no longer only be seen as environmental hazards but also opportunities for beneficial uses such as backfilling. Similarly, the models should be able to handle brownfields sites as these are becoming increasingly common.

2.3. Deposit location affects framework conditions, risks and benefits

Because of the way classical geoenvironmental deposit models have been designed and presented, they typically do not take the environmental setting (location) of the exploration area or deposit into account. However, locations have a profound impact on both the environmental impacts of a project and the opportunities to generate sustainable benefits from mining. Not all deposit types produce similar impacts and some locations are riskier than others. Location also dictates many framework conditions for exploration and mining, such as protected areas, land ownership, or competing land uses.

Several features of the environment can have an effect on the impacts of mining-related emissions and other stressors at the site. Things such as topography, climate, hydrology, surface water bodies, surficial geology (e.g. aquifers), vegetation, other biota, rare and endangered species, specific habitats, background concentrations etc. all affect environmental risks. Similarly, factors such as human settlement, farming, fishing, sources of drinking water, other human food chain properties, and other exposure factors affect risks to human health. Properties of the surrounding society, in turn, have an effect on how sustainable benefits can be generated from the mining project.

2.4. Data sets and analysis methods

Next generation geoenvironmental deposit models not only utilize open spatial data sets to define the properties of the location surrounding the deposit but also information on the deposit types and mineral systems and modern methods of mining, processing, waste utilization, and environmental management. Current mineral systems thinking is at the core of the approach and allows extending the predictions to a larger area than deposit models alone. Modern deposit models, in turn, not only make predictions of deposit properties more accurate, but can be expanded to take environmental management-relevant properties of both the ore and its host rocks into account.

The next step in the analysis is then the unit process options available for each deposit type. These can extend upstream to the exploration phase and include mining methods, on-site mineral processing options, waste utilization and management, environmental management and emission abatement options, continuous progressive closure, final closure, and post closure land uses. Some of these processes are ones that generate emissions or pressures on the environment while others are used to reduce these emissions. The net result is thus a combination of the adopted process options.

With the deposit and project properties determined, the next step is profiling of the site with respect to vulnerability, impacts, and opportunities. This is based on spatial data sets that preferably are publicly available. The analysis targets ecological risks, health risks, spreading of contaminants, social impacts and opportunities, regional economic impacts, and framework conditions for exploration and mining. Each component of the analysis requires specific expertise on the question at hand and the final product must be a combination of all these various branches of assessment.

2.5. Profiling rather than scoring

For all steps and components listed above (deposit and mineral system properties, unit processes at an operating mine, and impacts and opportunities assessment), the aim is not to provide a deterministic scoring. Rather, the aim is to analyse and make visible the characteristics of each component that together describe the most likely operation that might be based on a certain deposit and the resulting impacts in that specific location. Therefore, the model provides a description, with ranges of uncertainty, of each component separately to produce an impact profiling of the exploration target. It can also offer the users the possibility to weight the components according to their specific needs. Furthermore, the system should be compatible with classifications such as the UNFC to be as useful as possible.

3. Opportunities for layered intrusions

To date, spatial data-based next generation geoenvironmental mineral deposit models capable of profiling and comparing exploration targets do not exist. However, the expertise to construct such systems is available for all the individual components required. As tools like this will promote acceptable exploration, exploration portfolio management, investment decisions, and risk management, there is an incentive for researchers in layered intrusions to promote their deposit types by developing the deposit and mineral systems part of such models. This may prove to be a competitive advantage in the future with a widespread adoption of such models in exploration management.

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

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Summary Kevitsa has been one of Europe's most important nickel mines. To enhance our understanding of the ore-forming and post-magmatic processes that occurred in the Kevitsa intrusion, we determined PGE concentrations of the main sulphide phases from the main ore types using laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS). Although the origin of the Ni-PGE ore remains ambiguous, it is clear that the formation was dominated by magmatic processes and hydrothermal redistribution of metal played an insignificant role.

1. Introduction and background to current research

The Kevitsa mafic-ultramafic intrusion is located in the Central Lapland Greenstone Belt, in Finnish Lapland, and hosts a large Ni-Cu-(PGE) sulphide deposit (Fig. 1a). The Kevitsa intrusion emplaced into the Savukoski volcanic sedimentary formation, and is composed of a lower ultramafic unit and an upper gabbroic unit (Fig. 1b). The Ni-Cu-(PGE) sulfide deposit occur in the middle of the ultramafic part (Fig. 1c). Kevitsa mine has been in operation since 2012, and it is one of Europe's most recent nickel mines and has an annual output in the range of 9000-10,000 t of nickel, 17,000-19,000 of copper and 22,000-24,000 oz each of platinum and palladium (Santaguida et al., 2015). Generally, multiple stage magmatic processes and intensive interaction between magma and sedimentary rocks are proposed to account for the complicated mineralization in Kevitsa (Yang et al., 2013; Luolavirta et al., 2018a, b). This work is a master thesis project aims to provide further constraints on the ore-formation processes at Kevitsa by studying the trace-element characteristics of the base metal sulfides at Kevitsa.

2. Research questions at hand

Though as by product, the Kevitsa deposit is an important producer of platinum group metals. However, the detailed mechanism for PGE enrichment is under debate. Base on texture of platinum group minerals, it is suggested that hydrothermal fluid process has played an important role in redistribution of PGEs, forming unusual PGE enrichment in some part of the intrusion (Gervilla and Kojonen, 2002). However, based on the good correlation between different PGEs and detailed textural study, it is suggested that the fluid redistribution of metals is not significant, except Cu and Au (Le Vaillant et al., 2016). In this study, in-situ trace element study of base metal sulfide has been conducted to further constrain the metal enrichment processes.

There are two main ore types that make up the economic resources, named normal ore and Ni-PGE ore (Mutanen, 1997). The normal ore is more continuous and comprises 90% of the volume, and Ni-PGE ore occurs as discontinuous lense like bodies. The normal ore has average Ni and Cu grades of 0.3 and 0.42 wt.% and the main sulfide minerals are pentlandite, chalcopyrite and pyrrhotite (Fig. 2a). The Ni-PGE ore consists predominantly of pentlandite, pyrite and millerite (Fig. 2b, c), with higher and more variable Ni grades, lower Cu grades (Ni/Cu 1.5-15) and high Ni tenors (generally >10%). The Ni-PGE ore also has a high PGE content ranging from >1 ppm, much higher than that of the normal ore (0.5 to1 ppm of

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combined Pt, Pd and Au). In addition, there is an uneconomic ore type, called false ore, which consists of pyrrhotite, with rare chalcopyrite and pentlandite, and generally has low Ni content of less than <0.1 wt.%.

To examine the ore-forming processes that occurred during the cooling and crystallisation of the Kevitsa magma chamber, and post-magmatic modification, in this study, trace-elements of the main sulphide minerals were analysed using laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS) (Fig. 3). Although Pd is found in all of the sulphide phases, pentlandite is the richest, with Pd contents ranging from 0.3 ppm in false ore to tens of ppm in the Ni-PGE ore. Pentlandite in the normal ore has Pd contents falling between the false and Ni-PGE ore type (Fig. 4a, b). Barnes et al. (2011) suggest millerite could form in a high Ni sulfide melt, though it is rare. More commonly, millerite occur as secondary alteration products (e.g., Vaara, Konnunaho et al., 2013). In Kevitsa, millerite and pyrite contain certain amount of both IPGEs and PPGEs, together with the well preserved primary texture, we confirm that these two phases are formed in magmatic stage (Fig. 4b). Pyrrhotite contains relatively high IPGEs, but lower PPGEs, and chalcopyrite contain the lowest amount PGEs, which is similar to the study on other deposits (Godel., et al., 2007). Pt contents are low in all the base metal sulphides, with the majority of analyses falling below the detection limit, indicating Pt bearing platinum group minerals are the main host.

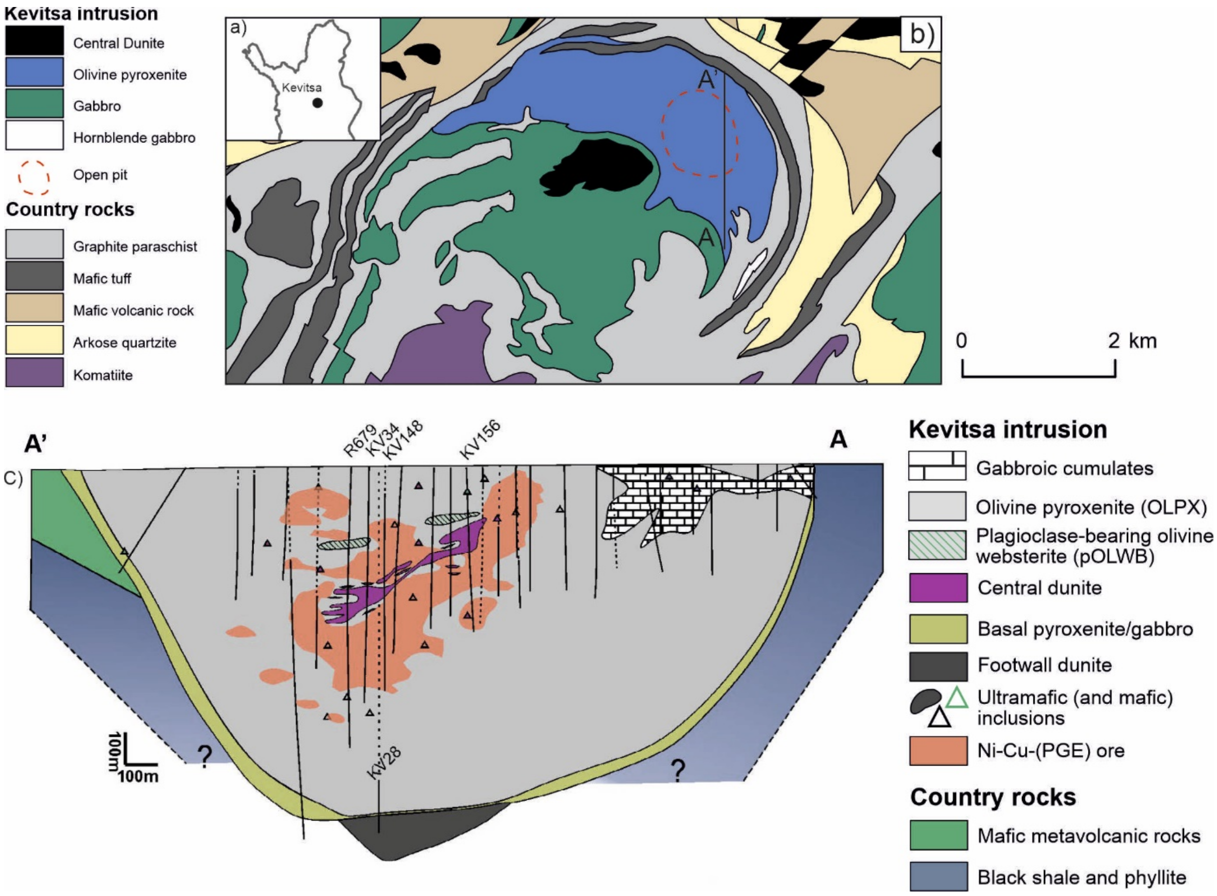

Figure 4. Geological map of the Kevitsa intrusion.

Generally, samples with higher PGE tenors show high PGE content in base metal sulfides (Fig. 4c). This indicates a magmatic origin for high metal tenors in the Ni-PGE ore, with a negligible effect of post-magmatic fluid enrichment. On the other hand, the false ores show very low metal contents for all chalcophile metals, indicating crystallization from a sulfide saturated magma, and an earlier stage of sulfide saturation may have occurred at depth (Fig. 4c).

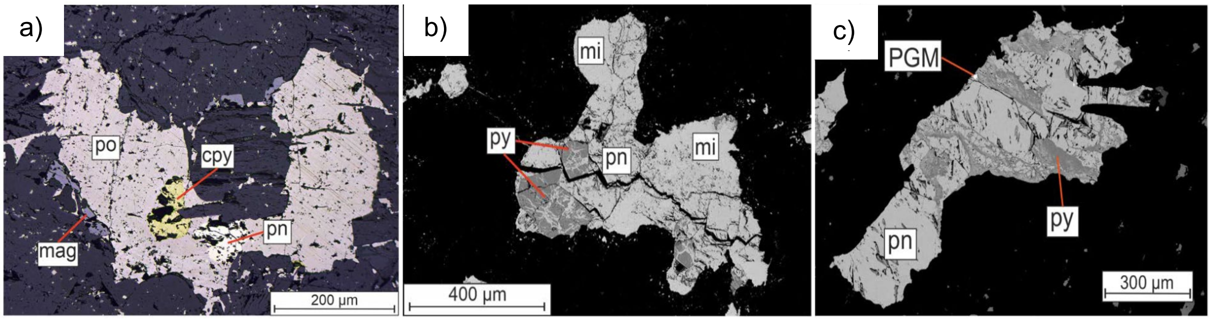

Figure 5. Base metal sulfide mineral texture of different ore types in Kevitsa. a) pyrrhotite (Po), pentlandite (Pn), and chalcopyrite (Cpy); b) Ni-PGE ores with well preserved association of millerite (Mi), Pn, and pyrite (Py); c) another Ni-PGE ore sample showing intergrowth of Pn and Py.

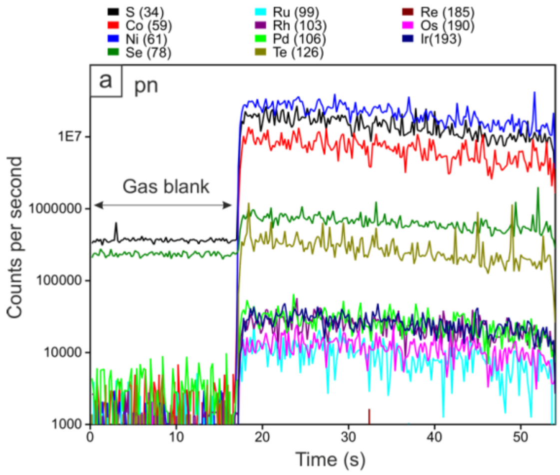

Figure 3. TRA spectra (counts per second vs. time in seconds) from laser ablation analyses of a pentlandite.

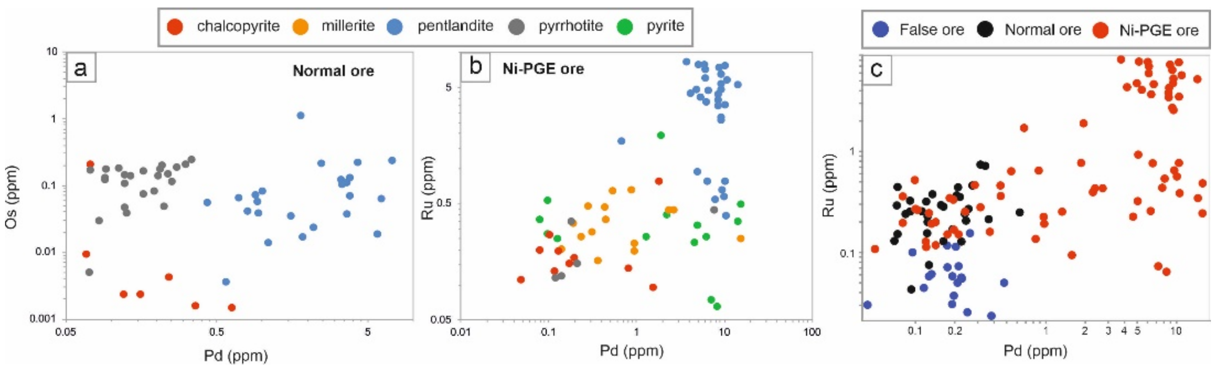

Figure 4. PGE content of base metal sulfide: a) Os and Pd content in different sulfide minerals (pyrrhotite, pentlandite and chalcopyrite) in normal ore; b) Ru and Pd content in different sulfide minerals in Ni-PGE ore; c) Ru and Pd in pentlandite in different types of ores.

3. Future research

We have done some preliminary mass balance study on the PGE budget in base metal sulfide compared with platinum group minerals. More detailed work could be conducted in the future.

In addition, the in-situ trace element study of sulfide minerals, and also arsenides, sulpharsenides could potentially be applied to other layered intrusions in Finland, to constrain the metal enrichment mechanisms.

Acknowledgements

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Sr isotope and trace-element characteristics of Finnish Layered intrusions; In-situ Sr isotope study of the Penikat intrusion, northern Finland

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Summary The Penikat layered intrusion belongs to the 2.44 -2.5 Ga mantle plume related magmatism, manifested by numerous large layered intrusions in Finnish Lapland and Kola. The Penikat intrusion comprise of five megacyclic units (MCU I to V (top)) with three major PGE reefs. The Sompujärvi reef (SJ) occurs at the base of the MCU IV, the Ala-Penikka reef (AP) within the MCU IV, and the Paasivaara reef (PV) at the upper-most part of the MCU IV. In-situ Sr-isotope compositions of plagioclase are analysed to constrain the petrogenesis of the Penikat intrusion and its PGE reefs. The results show a mild change in initial Sr isotope compositions at the lower part of the intrusion, upwards from MCU I to MCU IV. The MCU IV records the lowest most $Sr_{(i)}$ values within the Penikat intrusion, yet a transgressive shift towards more radiogenic signature is observed at the transition zone between MCU IV and V. The data indicates that different types of magmas have been involved in the Penikat intrusion, and magma mixing may have played a role in the formation of the PV reef in particular.

1. Introduction

There are many models for the origin of PGE reefs in layered intrusions; in brief, models that favour dynamic magma chamber processes as most relevant, and those that argue for fluid-induced PGE enrichment. The scope of this study is to utilize modern micro-analytical techniques to gather new data on Finnish layered intrusions and related reef-type PGE mineralisation to study the magma chamber processes related to the formation of PGE reefs.

The development of micro-analytical methods have made it possible to determine radiogenic isotope and trace-element compositions of minerals directly from thin sections (in-situ). Utilizing in-situ micro-analyses of plagioclase and apatite, this study aim to constrain both vertical and lateral Sr isotopic profiles of representative intrusive rock successions hosting PGE reefs (Penikat), in conjunction with the trace-element characteristics of these minerals. Such combination of analytical data allow detailed investigation of the nature of magmas, their emplacement history, magma mixing and contamination processes, and may also reveal the compositional characteristics of an involved fluid phase. A comparable study on representative layered intrusion(s) with PGE mineralization/showings (Koitelainen, Akanvaara) allow evaluation of the applicability of Sr and trace-element systematics in exploration of PGE mineralization. This presentation introduces the Sr isotope stratigraphy of the Penikat intrusion.

2. Preliminary studies and results

2.1. Penikat intrusion

The Penikat intrusion is one of the 2.44 Ga layered intrusions of the Tornio-Näränkävaara belt in northern Finland and host subeconomic reef-type PGE mineralization (Fig. 1). The pioneering geological discriptions and petrogenetic models of the Penikat intrusion and it´s PGE reefs are provided by Alapieti and Lahtinen (1986), Alapieti et al. (1990), Huhtelin et al.

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(1990), Halkoaho et al. (1990 a,b), Alapieti and Halkoaho (1995), and Iljina and Hanski (2005). More recently, the genesis of the Penikat intrusion and it´s PGE reefs is discussed by Maier et al. (2018).

The intrusion is divided into five megacyclic units (MCU I – MCU IV), each characterized by peridotitic/pyroxenitic rocks at the base and overlain by gabbroic successions. The thickness of the layered series is approximately 3 km. There are three major PGE reefs identified, namely the Sompujärvi reef (SJ), Ala-Penikka reef (AP), and Paasivaara reef (PV) (Alapieti et al., 1990). The PGE reefs are located close to the basal part of MCU IV (SJ), in the middle of MCU IV (AP) and in the upper-most part of the MCU IV (PV).

Previous studies indicate that different types of magmas may have been involved in the formation of the Penikat intrusion. It has been suggested that the magma of MCU I to III belongs to high siliceous magnesium basalt (SHMB, Cr-rich) and gabbronorite series, and the upper portion belongs to Cr-poor tholeiite series (Alapieti et al., 1990). Whereas Maier et al. (2018) suggest, that all cyclic units at Penikat belong to the SHMB and gabbronorite series, which may belong to one magma series with different degrees of fractionation.

In short, intrusions of new magma pulses and magma mixing, accompanied by fluid-induced processes have been proposed for the origin of the PGE reefs in Penikat (Huhtelin et al.1990; Halkoaho et al. 1990 a,b). The recent model by Maier et al. (2018) argues for magma recharge and hydrodynamic sorting of crystal slurries as a main mechanism for PGE-enrichment (SJ and AP reefs), while the PV reef represents residual liquid of the SJ reef, injected to its current stratigraphic level.

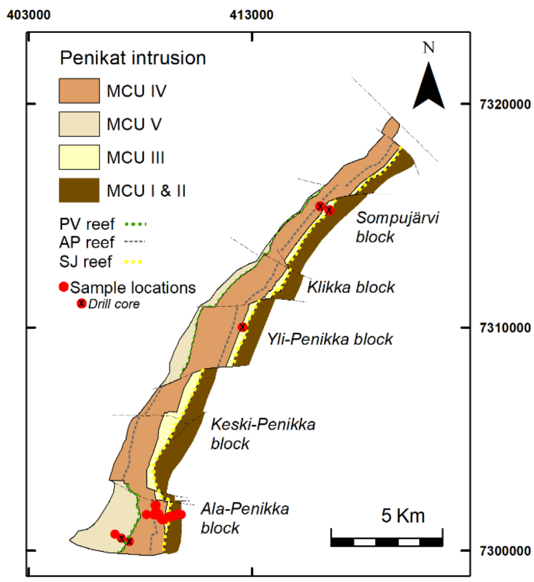

Figure 6. Geological map of the Penikat intrusion showing the sample sites. Modified after DigiKP, the digital map database of the Geological Survey of Finland, available at http://gtkdata.gtk.fi/Kalliopera/index.html and Halkoaho et al. 2005.

2.2 Sr isotope stratigraphy of the Penikat intrusion

A Sr isotope profile of the Penikat intrusion has been constructed to study the petrogenesis of the intrusion and the stratigraphic positions of the PGE reefs. Fresh plagioclase from 41 samples of the Ala-Penikka block were selected for in-situ Sr isotope analyses, covering ~1800 m of the stratigraphy (see Fig. 1). In addition, few samples from the Yli-Penikka and Sompujärvi blocks were analysed to test possible lateral variations of the SJ reef. Analyses were carried out by LA-

MC-ICP-MS at the Finnish Geosciences Research Laboratory at Geological Survey of Finland (GTK), Espoo. To have a statistical meaning, a large number of spots are analysed for each sample (generally >10, some >15). Major element compositions of the studied plagioclase grains are analysed by electron probe microanalyser (EPMA) at the Centre for Material Analysis, at the University of Oulu.

Overall, the Sr-isotope compositions of plagioclase are relatively homogeneous, with $Sr_{(i)}$ ranging from 0.7020 to 0.7040 (Fig. 2). Anorthite content of cumulus plagioclase grains varies from ~70–88 %. Despite the relatively homogeneous initial $Sr_{(i)}$ isotope compositions, some stratigraphic variation can be observed. Notably, the MCU IV records the lowest $Sr_{(i)}$ values with great majority of $Sr_{(i)}$ data falling to a range of 0.7020 to 0.7030. However, there is a marked gradual increase in $Sr_{(i)}$ at the contact zone between MCU IV and MCU V that coincides with an increase in plagioclase An content. The MCU V records the highest Sr isotopes of the Penikat intrusion, with $Sr_{(i)}$ generally around 0.7030–0.7035.

The dataset for MCU I-III is rather sparse, yet the MCU I record somewhat higher $Sr_{(i)}$ isotope compositions in comparison to MCU II-IV, and overall a smooth decrease in $Sr_{(i)}$ can be observed upwards from the footwall, a.k.a from MCU I to MCU IV. However, no apparent change in $Sr_{(i)}$ at the site of the SJ reef is observed, yet in-situ isotope analyses immediately below and above the SJ reef are complicated by severe alteration of the rocks.
Data collected from the Yli-Penikka and Sompujärvi blocks are similar to Ala-Penikka block (not shown). Isotopically, the host rocks to AP reef do not deviate from the other rocks of MCU IV.

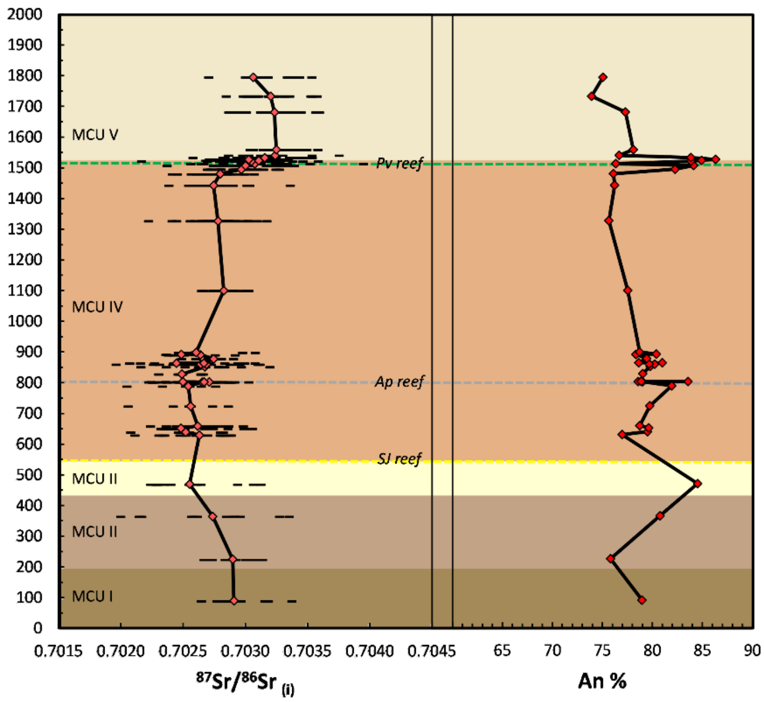

Figure 2. Compositional variations of $Sr_{(i)}$ isotope and An content of plagioclase with stratigraphic height (m). Data is expressed as median values for each sample, and for $Sr_{(i)}$ also the sample-scale variations are shown.

The results indicate that there are different types of magmas involved in the genesis of the Penikat intrusion; the MCU I-III, and particularly MCU IV and MCU V all record different Sr isotopic signatures. Hence, the parental magmas for the Penikat intrusion, is likely more diverse than previously thought. The Sr-isotope data, accompanied with lithological and chemical data from previous studies, indicate recharge of new magma at the sites of the SJ and PV reefs, and mixing of magmas with different isotopic composition, especially between MCU V and MCU V.

3. Future prospects

To further constrain the nature of the parental magmas in the Penikat intrusion, and to study the PGE-reef formation, in-situ trace-elements of plagioclase and apatite will be analysed. In addition, a similar analytical approach will be applied and tested on another 2.44 Ga Finnish layered intrusion with PGE showings (e.g. Akanvaara, Koitelainen).

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Origin of the gabbro-anorthosite-related Fe-Ti-V deposit at Otanmäki (central Finland): historical perspectives and topics of future research

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Summary The Otanmäki area in central Finland encompasses a gabbro-hosted Fe-Ti-V oxide deposit, which was mined between 1953–1985. The oxide ore occurs as semi-massive to massive magnetite-ilmenite lenses and discontinuous layers in a heterogenous zone consisting of gabbro and magnetite gabbro with fragments of anorthosite. Previous studies have proposed a magmatic origin for the Fe-Ti-V mineralization but details of the specific igneous processes, which resulted in the oxide ore bodies, remain poorly understood.

1. Introduction

The Otanmäki area in central Finland has been the subject of geological research since the discovery of gabbro-hosted magmatic Fe-Ti-V oxide deposits in the area in the 1930s (Paarma, 1954; Pääkkönen 1956; Kerkkonen, 1979; Lindholm and Anttonen, 1980; Nykänen, 1995; Huhma et al., 2018; Mäkisalo, 2019). The largest of the oxide deposits, the Otanmäki deposit, was an important global producer of vanadium during its operation between 1953–1985. In total, 30 Mt of magnetite-ilmenite ore was mined, grading 32–34% Fe, 5.5–7.6% Ti, and 0.26% V. According to the Otanmäki Mine Oy company's interim mineral resource estimate (Hokka and Lepistö, 2019), the remaining resources at Otanmäki are classified to the inferred category and estimated to be about 24 Mt @ 28% Fe, 10% Ti, 0.21% V.

Despite the long history of geological investigation, considerable uncertainty on many aspects of the geology and origin of the Otanmäki Fe-Ti-V oxide mineralization still prevail. In previous studies, the origin of the oxide ore has been related to primary magmatic crystallization plus textural modification during regional metamorphism. The metamorphic overprinting was important economically as recrystallization of magmatic ilmenomagnetite (magnetite with micro-intergrowths of ilmenite) produced separate grains of ilmenite and magnetite, which allowed their effective separation in the beneficiation of the ore (Kerkkonen, 1979). However, the specific igneous differentiation processes, which led to the extreme Fe-Ti-V enrichment in the Otanmäki magma chamber, have remained poorly understood.

In this study, based on our recently obtained field, petrographical and whole-rock major and trace element and available previous data, we propose a revised model of the internal structure of the Otanmäki intrusion and discuss the processes which resulted in the Fe-Ti-V mineralization.

2. Geology of the Otanmäki intrusion

The ca. 2.06 Ga Otanmäki mafic intrusion is hosted in Archean TTG-series (tonalite-trondhjemite-granodiorite) gneisses (Fig. 1). The intrusive body was foliated and metamorphosed under amphibolite facies conditions during the Svecofennian orogeny (1.9–1.8 Ga). It is divided into three major blocks, which have mostly fault contacts against the

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surrounding Archean TTG gneisses and ca. 2.05 Ga A-type granites and intermediate igneous rocks (Fig. 1). Each block bears laterally continuous oxide ore zones, which are remarkably voluminous in relation to the small size of the whole gabbroic body (Fig. 1).

Based on our field and petrographic observations, the Otanmäki intrusion can be divided into three major units, the Lower Zone, the Ore Zone, and the Upper Zone (Figs. 1 and 2). The rocks in the Lower Zone have relatively well-preserved magmatic mineral compositions and textures, but in the Ore Zone and Upper Zone, the rocks are foliated and show metamorphic mineral assemblages.

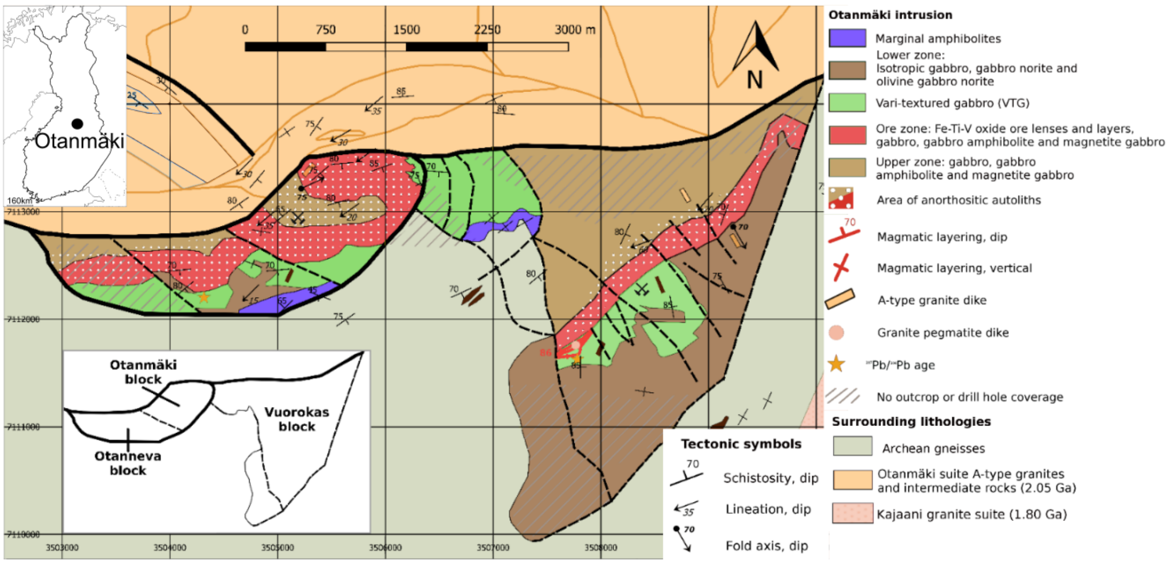

Figure 1. Geological map of the Otanmäki intrusion (Mäkisalo, 2019).

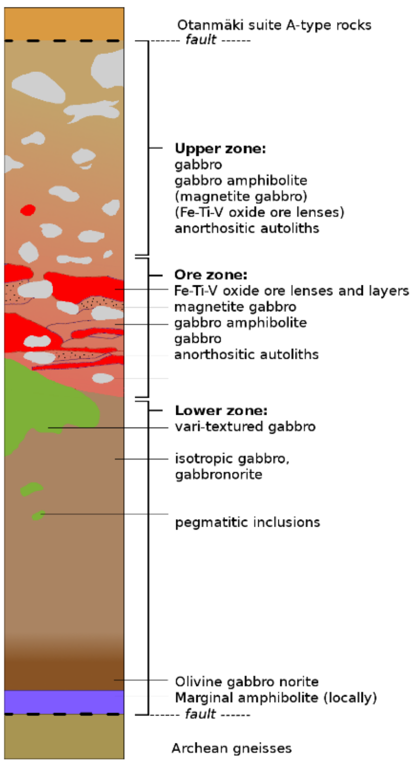

Figure 2. Schematic magmatic stratigraphy of the Otanmäki intrusion (not to scale) (Mäkisalo, 2019).

The Lower Zone consists mostly of medium- to coarse-grained isotropic gabbro and gabbronorite, which are associated with variably-sized and irregularly shaped bodies (1- to 500-m in diameter) of pegmatoidal varitextured gabbro (VTG) (Figs. 1 and 2). The VTGs show a large variation in the grain size (2 to 50 cm) and color index on an outcrop scale, ranging in composition from gabbronorite to anorthosite. They have both gradational and irregular contacts to isotropic gabbro–gabbronorites.

The Lower Zone rocks show a sharp transition to the Ore Zone, which comprises semi-massive to massive oxide ore lenses and layers, gabbro, magnetite gabbro and gabbro amphibolite. The oxide ore is distributed in numerous semi-massive to massive magnetite-ilmenite lenses, or, more rarely, discontinuous layers, which are 3–50 m wide and up to 200 m long (Fig. 3). The Ore Zone rock assemblage changes gradually into the Upper Zone, where isotropic gabbro dominates and oxide ore is no longer present. Both the Ore and Upper Zone gabbros portray occasional modal layering, but it is not a prevailing feature. In addition, countless, angular to subrounded anorthositic autoliths of 1–30 meters in diameter are met throughout the Ore and Upper Zones (Figs. 1–3). An interesting feature is that some of the autoliths are fully enclosed within oxide ore, suggesting that the solidification of the high-density oxide ore postdated the emplacement of some of the anorthositic autoliths.

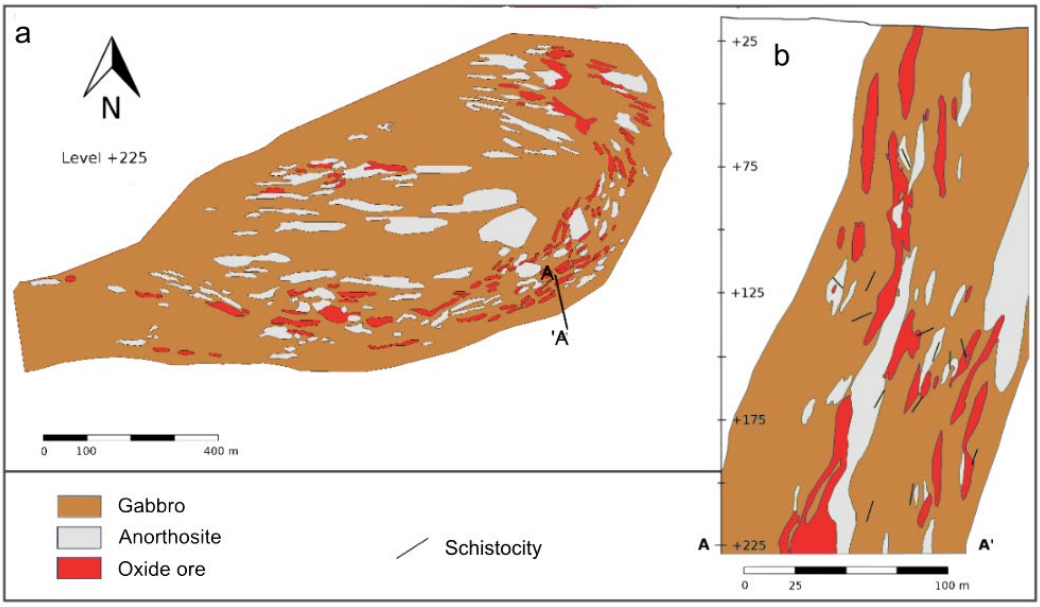

Figure 3. a) Geological map of the +225 level of the Otanmäki Ore Zone. b) Cross section of the ore zone at A–A’ in a. Modified after Lindholm and Anttonen (1980).

3. Previous models of oxide ore genesis and topics of future research

The first investigators, Paarma (1954) and Pääkkönen (1956), recognized that the wall rocks of the oxide ore are metamorphosed gabbroic rocks and ore resembles many other titaniferous iron ores of magmatic origin known at the time. According to Paarma (1954), the ore was formed by direct crystallization from a Fe-Ti-rich magma. However, the generally strongly deformed nature of the ore bodies and their wall rocks made Pääkkönen (1956) to propose that the accumulation of oxide minerals and formation of the ore bodies were related to metamorphic segregation of primary (magmatic) disseminated oxide minerals from the gabbroic wall rocks.

Kerkkonen (1979) and Nykänen (1995) proposed that crystallization of pyroxenes, plagioclase and olivine from a Fe-Ti-rich tholeiitic parental magma under highly reducing and relatively high-pressure conditions (~7 kbar) resulted in Fe-Ti-V enrichment in the residual melt and abundant crystallization of oxide minerals in the Otanmäki magma chamber. Kerkkonen (1979) described that the rocks of the least deformed parts of the Ore Zone display magmatic cumulus textures, flow lamination and turbulence structures around anorthosite autoliths. He suggested that two mechanisms were important in the Otanmäki magma chamber: 1) flotation and accumulation of plagioclase in the roof part of the magma chamber, particularly in the early stages of magmatic evolution, and 2) magmatic flow that enhanced density-driven differentiation resulting in high-density floor cumulates, and caused brecciation, entrapment and transport of the earlier formed plagioclase-rich roof cumulates to deposit as autoliths on the floor of the magma chamber. Based on the complex spatial association of the irregular-shaped oxide ore bodies with anorthositic autoliths and gabbroic wall rocks, Kerkkonen (1979) also suggested that turbulent magmatic flow on earlier formed basal cumulates, and around autoliths deposited on them, may have locally produced small-scale physicochemical heterogeneities in the magma, which promoted selective in-situ crystallization of magnetite only.

The previous views on the origin of Otanmäki Fe-Ti-V deposit are largely conceptual and lacking strong supporting evidence, and many basic issues of the magmatic evolution of the Otanmäki magma chamber have not yet been addressed. For example, it remains to be answered whether the magma chamber evolved in open- or closed-system conditions. In this respect, it would be highly interesting to model how much Fe-tholeiitic parental magma is required to produce the mass of each component in the Otanmäki intrusion, including the Fe-Ti-V oxide ores. Compared to typical oxide ores in layered intrusions, one distinct feature of the Ore Zone in Otanmäki is the distribution of ore in numerous discontinuous, lens-like oxide-rich bodies (Fig. 2). How this situation arouse is a big research question. It also remains unresolved how the pegmatoidal VTG bodies just beneath the Ore Zone rocks were formed and whether their origin was linked to the Fe-Ti-V mineralization processes. Detailed petrological modelling on the crystallization processes, especially the changing of magma density during magma evolution, would be critical to decipher these issues. In addition, modeling would require additional detailed geological and geochemical mapping to accurately demonstrate the map to outcrop-scale distribution of different components within the intrusion.

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Thermodynamic and geochemical modeling of assimilation in primitive magma systems

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Summary During few recent decades, a surge in thermodynamically controlled geochemical models for igneous systems has occurred. These provide considerable potential to study the evolution of economically important primitive open magma systems, including layered intrusions. Here we provide an overview of the recent findings of the PALIN-research project based at the University of Helsinki that utilizes such tools for studying various magmatic settings. The findings indicate that assimilation of wall-rocks, often crucial to ore formation, is a complex and selective process and can have unforeseen consequences related to geochemical evolution of primitive magmas. We further consider future challenges related to modeling and understanding of intrusive open systems.

1. Introduction and background to current research

In order to understand and constrain the geochemical evolution of an igneous open system, knowledge on the thermodynamic properties and constraints of the system and its phases are required. The traditional binary mixing and assimilation-fractional crystallization (AFC; DePaolo, 1981) models overlook many aspects of the assimilation processes that are critical to ore formation processes. Recent advancements in harnessing the information gathered from experimental petrology (e.g., Ariskin et al., 1993, 2018; Ghiorso and Sack, 1995; Gualda et al., 2012; Bohrson et al., 2014, 2020; Heinonen et al., 2020) have resulted in the generation of modeling tools that can be used to provide such information and constraints (Fig. 1). Using such tools, in turn, leads to more refined models and better control on the geochemical signatures that may be the result of assimilation processes potentially relevant for ore deposition.

2. Research questions at hand

The current research of our group is funded by the Academy of Finland from September 2016 to August 2021 and is named "Partial melting processes in the contact zones of layered intrusions (PALIN); https://blogs.helsinki.fi/jsheinon/". The project focuses on two research areas: 1) the development and application of thermodynamic models to layered – and other mafic and also more siliceous – intrusions and 2) partial melting experiments on wall-rocks of layered intrusions (namely black shale; see Virtanen and Heinonen, this volume, for more information).

The focus area 1 is managed in collaboration with the Colorado School of Mines (USA) and the University of California Santa Barbara (USA) and relies on a freely available modeling tool called Magma Chamber Simulator (MCS; Bohrson et al., 2014, 2020; Heinonen et al., 2020; Fig. 1; https://mcs.geol.ucsb.edu/). The MCS utilizes the experimentally calibrated MELTS-family of algorithms (rhyolite-MELTS or pMELTS; REFS). It uses these algorithms (MELTS-engines) to study the phase equilibria and geochemical evolution of the crystallizing resident magma, wall-rock that is heated and potentially melted and assimilated by the magma either as stoped blocks of batches of partial melt, and possible recharge magmas (R_nAS_nFC system; Fig. 1; see Bohrson et al., 2020). The evolution of the modeled system is controlled by

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user-input parameters that can then be varied to find the best and most fitting models for the studied natural system (forward modeling). These best-fit models have potential to reveal evolutionary scenarios and provide thermodynamic and geochemical constraints that would have otherwise remained hidden.

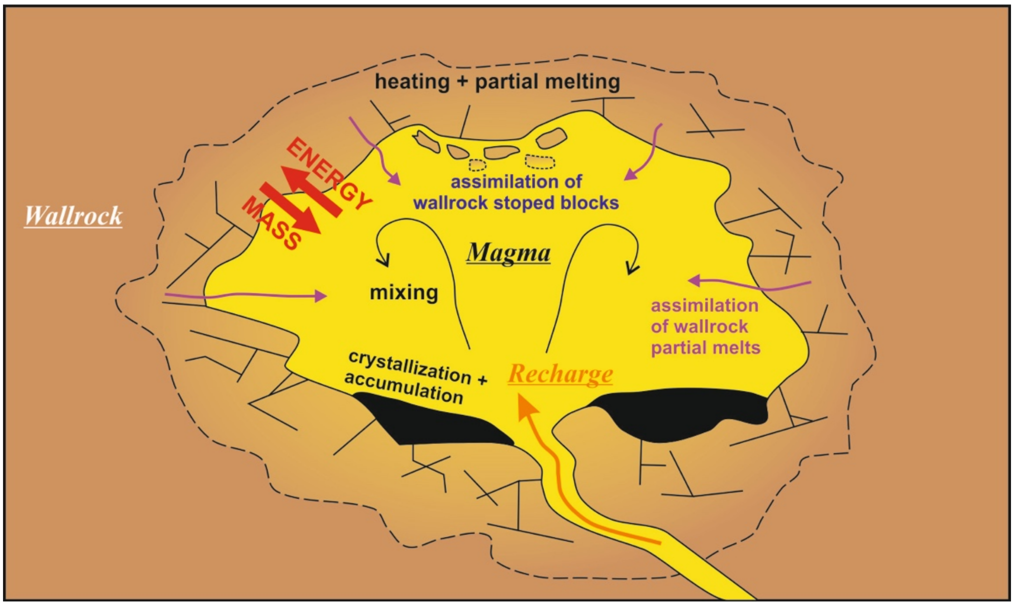

Figure 7. The processes that Magma Chamber Simulator handles using thermodynamic and compositional constraints. Three subsystems (resident magma, wall-rock, and recharge magma) are underlined.

Our research has and is revealing several important aspects of primitive magmatism and assimilation. In the context of ore formation and prospecting, the assimilation capacity of parental magmas, the onset and span of assimilation, and resulting geochemical signatures are key parameters. For example, primitive igneous systems have considerable thermodynamic potential to assimilate crustal rocks, even basalts (Heinonen et al., in press). Very recent modeling with MCS suggests that some komatiitic melts have thermodynamic potential to assimilate even more than their own weight of partial melts of silicate crust. This can have important implications for the generation of, for example, siliceous high-Mg basalts in the Proterozoic (Fig. 2). Assimilation is not only limited to assimilating partial melts of the wall-rocks, but hot magmas can also dissolve notable amounts of wall-rock, including more primitive floor cumulate layers of the cogenetic magmatic system (Latypov et al., 2021, see also Yao et al., 2021). On the other hand, even minor assimilation of partial melts of felsic crustal wall-rocks, considerably enriched in incompatible trace elements, by primitive magmas may have notable effects on their geochemistry (Heinonen et al., 2019). Assimilation of "barren" wall-rocks may also dilute the magma from economically important components and thus prohibit ore formation (Virtanen et al., 2021). In addition to these examples, the ongoing research tries to find a parental magma candidate for the 2.5−2.4 Ga layered intrusions of Fennoscandia and constrain their deep crustal evolution before emplacement to upper crustal levels.

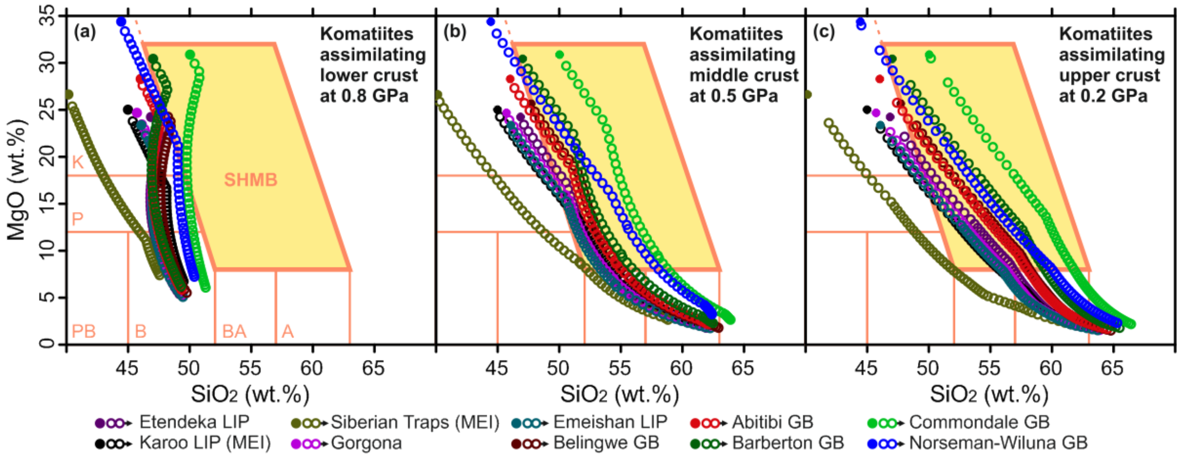

Figure 2. The results of the Magma Chamber Simulator AFC models for various komatiitic melts shown in SiO_2 vs. MgO diagrams overlain with relevant portions of boninite classification of Pearce and Reagan (2019). Parental melt is marked with a closed symbol – every open symbol marks an assimilation step of wall-rock (a = lower crust, b = middle crust, c = upper crust) partial melt in the thermodynamically controlled assimilation model. Abbreviations of the classification shown in a: K = komatiite, P = picrite, PB = picrobasalt, B = basalt, BA = basaltic andesite, A = andesite, SHMB = siliceous high-Mg basalt (highlighted).

3. Future prospects

Something that is missing from the thermodynamic models, are kinetic constraints. In the future, we also need to better consider and combine such information with the thermodynamic and geochemical modeling. There is increasing amount of evidence that many magma systems parental to layered intrusions were dynamic and composed of complex sill and magma mush systems instead of being "box-like" magma chambers in the traditional sense (for recent studies related to Bushveld Igneous Complex, South Africa, by Scoates et al. (in press) and Yao et al. (2021)). In such magmatic environments, the dynamics and the kinetics – not just thermodynamics – of the system become critical for its evolution.

Even given these limitations, thermodynamically constrained geochemical models of open igneous systems are a significant leap forward from the traditional binary mixing and AFC modeling. In addition, they provide good approximations on the overall effects of assimilation processes, regardless of local variations in magma dynamics and kinetic factors. Our and other groups' findings have generated an emerging view of magmatic systems that have potential to assimilate significant amount of wall-rock and, on the other hand, be considerably influenced by only small-additions of wall-rock or associated fluids and melts. These results call for reconsiderations on the potential geochemical tracers of assimilation processes that are often critical for ore formation. The mass balance of the parental magma and the different phases of assimilated wall-rock is central for this question. For example, some economically promising intrusive candidates showing signs of assimilation of crust by having, for example, high SiO_2 and LREE/MREE, could be "barren" due to 1) only minor input of selectively enriched crustal partial melts or 2) wholesale assimilation of large amounts of crust, which could dilute concentrations of elements that have potential for ore formation. The thermodynamic tools have potential to respond to such issues and help in constraining crystallization and assimilation processes in igneous systems. Such tools have been underused in studies of Fennoscandian intrusive systems (for a recent example, see Järvinen et al. 2020).

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Assimilation of sulphur-bearing black shale and its effects on the formation of magmatic Cu-Ni deposits – the essential role of devolatilization fluids

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We have conducted heating experiments, Raman spectroscopy, and thermodynamic modelling on black shale wallrock related to the 1.1 Ga Duluth Complex, United States, to examine how contact metamorphism and partial melting mobilize S and Cu in black shales and affect Cu-Ni deposit formation in layered intrusions. Our results show that S and Cu are effectively mobilized via devolatilization fluids, which we suggest as the main medium for S and Cu transport from black shale to magma. In addition, assimilation of black shale partial melt lowers magmas capacity to dissolve S, which further increases the degree of sulphide saturation.

1. Introduction and background to current research

Assimilation of crustal wallrocks effectively modifies the thermal state and compositional identity of the interacting mantle-derived magmas. As a consequence, anomalous rock formations, such as economically important ore deposits, may arise. Assimilation has been identified as the decisive process that lead to formation of many magmatic base (and noble) metal sulphide deposits hosted by layered intrusions and komatiitic lava flows. A few notable examples include the Ni-Cu(-PGE) deposits of the Duluth Complex in the USA, Noril´sk in Russia, Kambalda in Australia, as well as Kevitsa and Sakatti in Finland (e.g., Naldrett, 1999, Maier and Hanski, 2017).

In nature, assimilation rarely is a simple mixing of two compositionally fixed chemical entities (magma and wallrock), but a complex process, where the composition of the assimilated material is governed by the thermal state and the continuously evolving wallrock phase equilibrium. In order to pinpoint the possible trigger mechanisms for the sulphide deposit formation, it is essential to understand how the wallrock reacts upon contact metamorphism and partial melting.

Partial melting processes at the contact zones of layered intrusions (PALIN) is an Academy of Finland funded research project aiming to shed knowledge on the wallrock-magma interactions. The project is involved in co-developing and utilizing the freely available Magma Chamber Simulator (MCS; Bohrson et al., 2014; https://mcs.geol.ucsb.edu/) – a thermodynamically constrained geochemical modelling software – to unravel the fundamental phenomena occurring in open magmatic systems. The unique feature in the MCS is that it can track the simultaneous phase equilibria within magma, wallrock, recharge magma batches, and stoped wallrock blocks. In the presented subproject managed by the first author, contact metamorphic and partial melting processes in natural black shale wallrock samples are studied and MCS is used to test how selective wallrock assimilation affects sulphide saturation in magmas. The project started in 2016 and ends in August 2021.

2. Research questions at hand

The case study for our research is the 1.1 Ga Duluth Complex, Minnesota, where mafic magmas assimilated sulphur-bearing black shales of the adjacent 1.9 Ga Virginia Formation.

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The assimilation triggered the genesis of one of the largest known Cu-Ni(-PGE) deposit clusters in the world (e.g., Miller et al., 2002). Utilizing heating experiments and Raman spectroscopy, we aim to identify the key contact metamorphic and partial melting processes mobilizing S and Cu in the black shale wallrock. In addition, we use thermodynamic modelling to test how selective black shale assimilation affects sulphide saturation in the Duluth magmas.

2.1. Black shale heating experiments

Both xenoliths and the devolatilized and partially molten footwall of the Virginia Formation black shale have been suggested as the main source of S in the Duluth Complex Cu-Ni(-PGE) deposits. We study the relative importance of fluids and melts as the transport medium for S and Cu during assimilation.

We conducted a series of heating experiments (2 kbar, 700–1000°C) on a natural black shale sample from the Virginia Formation (Fig. 1a) at the experimental petrology laboratory at ETH, Zürich. These experiments showed that a carbon-oxygen-hydrogen-sulphur (COHS) fluid mobilizes ~45% of the S and ~60% of the Cu in the black shale already upon subsolidus devolatilization (Fig. 1b and d), which provides a mechanism for effective S and Cu transport to the magma. Further S and Cu assimilation can occur at 1000°C, when the silicate partial melt becomes the volumetrically dominant phase. At the same temperature, monosulphide solid solution and Cu-rich sulphide melt attach to the devolatilization fluid bubbles (Fig. 1c and e) promoting buoyant transportation to the magma.

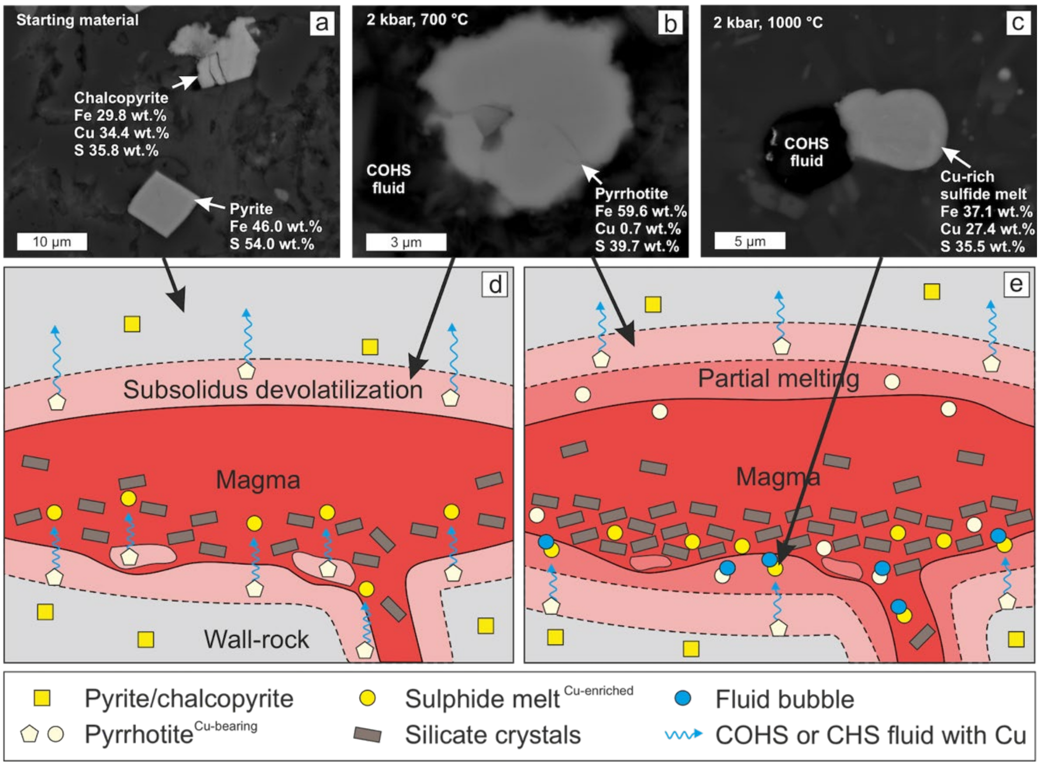

Figure 8. Back-scattered electron images of sulphide phases present in a. natural pristine black shale starting material (thin section) as well as in the experiments at b. 700°C and c. 1000 °C. The compositions were measured semiquantitatively with energy dispersive detector of field emission scanning electron microscope. Cu-bearing monosulphide solid solution is the main sulphide phase at 1000 °C (not shown). The schematic model for black shale assimilation shows how S and Cu could be transported to the magma at d. subsolidus devolatilization conditions and e. during partial melting.

2.2. Raman spectroscopy of organic carbon speciation in the contact aureole

Kerogen (a hydrocarbon compound) observed in pristine Virginia Formation samples has transformed into graphite at the proximity of the Duluth Complex (Fig. 2). Graphitization of kerogen is associated with release of hydrocarbons, which potentially mobilize sulphur as H_2S by reducing pyrite to pyrrhotite at early stage of contact metamorphism (Fig. 2).

Raman spectroscopy can be used to determine the structure of the organic carbon species. We aim to characterize the graphitization process with a set of natural samples from outside and inside the Virginia Formation contact aureole (Fig. 2) and determine if a hydrocarbon-bearing fluid could have mobilized S or not. We expect this study to provide insight into the role of fluids in the assimilation of S and Cu.

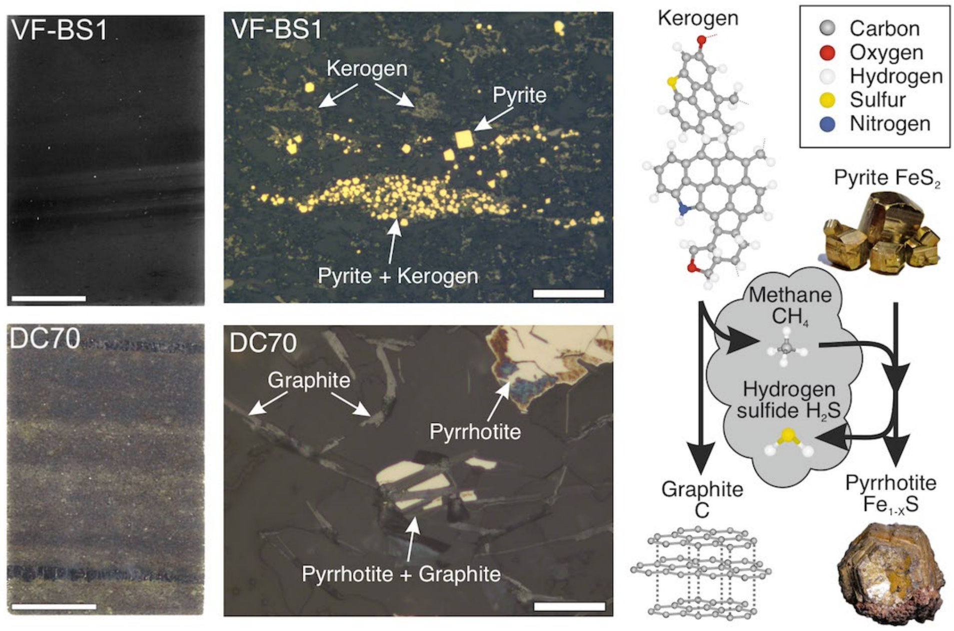

Figure 9. On the left, thin sections of pristine (VF-BS1) and contact metamorphosed (DC70) black shale from the Virginia Formation. In the middle, reflected light photomicrographs of the same samples showing the main organic carbon and sulphide species. On the right, a schematic model of the proposed contact metamorphic reaction where graphitization of kerogen releases methane, which reduces pyrite to pyrrhotite, while releasing hydrogen sulphide.

2.2. Magma Chamber Simulator modelling

Assimilation of sulphur-bearing wallrock is known to increase the degree of sulphide saturation in magma, but the lack of thermodynamic modelling tools for open magmatic systems has hampered the detailed description of the process. The effect of continuous assimilation of wallrock partial melt to the S budget and SCSS in the magma has not been tested before.

We used the MCS to examine how assimilation of the Virginia Formation black shale affected the formation of the magmatic Cu-Ni deposits of the Duluth Complex. We tentatively modelled S as a trace element to give insight into its mobility during black shale partial melting. The models show how the assimilation of thermodynamically constrained wallrock partial melt changes the major element composition of the magma promoting sulphide saturation (Fig. 3). The trace element models, where $restite^{wallrock}/partial\ melt^{wallrock}$ partition coefficient for S are ≤1 (Fig. 3), are compatible with the pre-existing S isotopic data (Ripley 1981) and with our heating experiments, where subsolidus devolatilization effectively mobilizes S.

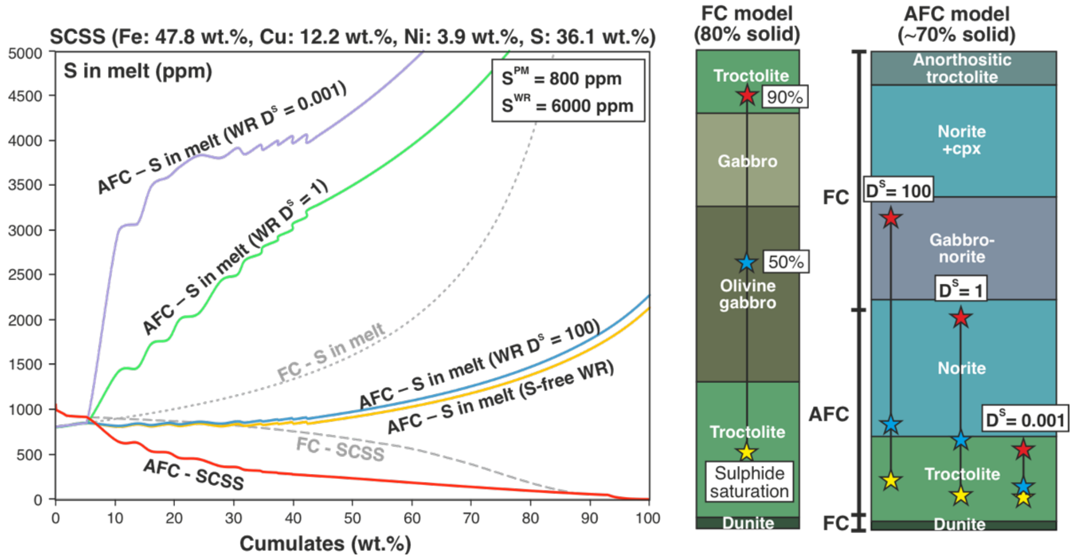

Figure 10. The sulphur content at sulphide saturation (SCSS) and S contents for fractional crystallization (FC) and assimilation-fractional crystallization (AFC) models conducted with the Magma Chamber Simulator. The initial S content of the parental melt is 800 ppm and of the wallrock 6000 ppm. The D^S indicates $restite^{wallrock}$/partial $melt^{wallrock}$ partition coefficients for S in the AFC models. SCSS is calculated according to Smythe et al. (2017). The modelled cumulate stratigraphies for the same models. The stars indicate sulphide saturation (yellow) as well as 50% (blue) and 90% (red) sulphide precipitation (of total precipitated according to the model).

3. Future prospects

We intend to utilize the aforementioned methodology to other sulphide-rich magmatic systems that were susceptible to wallrock assimilation. Especially attractive prospects are the Ni-Cu(-PGE) deposit-hosting layered intrusions in Fennoscandia, such as Kevitsa and Sakatti, of which many show signs of wallrock assimilation (Maier and Hanski, 2017).

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Geology of the Precambrian mafic-ultramafic Näränkävaara intrusion – Review of recent results

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Summary The Precambrian Näränkävaara intrusion comprises a 1.3 km thick layered series (dated at 2436 Ma), and a 1.5–2 km thick 'basal dunite' series (not dated). The layered series contains an ultramafic zone (harzburgite-websterite) and a mafic zone (gabbronorite-diorite) with typical igneous layering, and two reversals back to peridotitic compositions caused by influx of less-fractionated mafic magma. The basal dunite is dominated by low-porosity olivine adcumulates, and exhibits open-system lithological features (e.g., bimodal olivine, poikilitic chromite, and varying Mg#'s with height); it is also compositionally layered. Contact relationships between the two series are ambiguous, but Sm-Nd systematics strongly suggest a comagmatic origin (ε_{Nd} from −1.7 to –3.5 at 2.44 Ga). Furthermore, estimated parental magma compositions for both series are similar and represent LREE-enriched high-Mg basalts with 13–18 wt% MgO. The layered series hosts an uneconomic 20–85 m thick offset-type PGE-reef with Pd+Pt+Au of 50–500 ppb and Pd/Pt of ~3. The basal dunite series exhibits varying Ni-contents at a similar Mg# – the Ni-depletion in some sections could hypothetically be caused by S-saturation, however any significant sulfides have not been found in the basal dunite series. Petrogenetically, it is hypothesized that the basal dunite represents an earlier part of magmatism with slightly higher MgO and Ni parental magma, and possibly (at least partly) an open system feeder channel environment, which then evolved into a more static magma chamber environment forming the layered series.

1. Introduction and background to current research

Several mafic layered intrusions were emplaced in the NE Fennoscandian shield during long-lived mantle plume magmatism at 2.5−2.4 Ga, with many of these intrusions hosting Ni-Cu-PGE mineralization (Bayanova et al. 2009). Parental magmas of these intrusions can be classified as komatiitic or High-Mg basalts contaminated with Archean crust (average ε_{Nd} approximately −2, MgO 9–18 wt%; Kulikov et al. 2010). The Näränkävaara intrusion is the easternmost member of the Tonio-Näränväkaara belt of intrusions, which have an average age of ~2.44 Ga. Näränkävaara is included in the Koillismaa-Näränkävaara Layered Intrusion Complex (KLIC), comprising the Western Intrusions of the Koillismaa Complex in the west, and Näränkävaara intrusion in the east, with the two connected by a large-scale geophysical anomaly dubbed the 'hidden dyke' (see map in Fig. 1) speculated to represent a feeder channel (Alapieti 1982).

The Näränkävaara intrusion (Fig. 1) comprises 1) a layered series (dated at 2436 Ma; Alapieti 1982), and 2) a basal dunite series (not dated). The 1300 m thick layered series is almost unaltered and contains an ultramafic zone composed of peridotites-pyroxenites and a mafic zone composed of gabbronorite-quartz diorite. Typical magmatic layering is found in both series with cumulus-phases appearing in order olivine+chromite-orthopyroxene-clinopyroxene-plagioclase-magnetite; two reversals back to peridotitic compositions are found, one in each zone, with both related to influxes of new relatively unfractionated magma. An uneconomic 20–85 m thick offset-type PGE-reef ("SL reef") with 50–500 ppb of Pd+Pt+Au and an average Pd/Pt of 3 of is found at the border of the ultramafic and mafic

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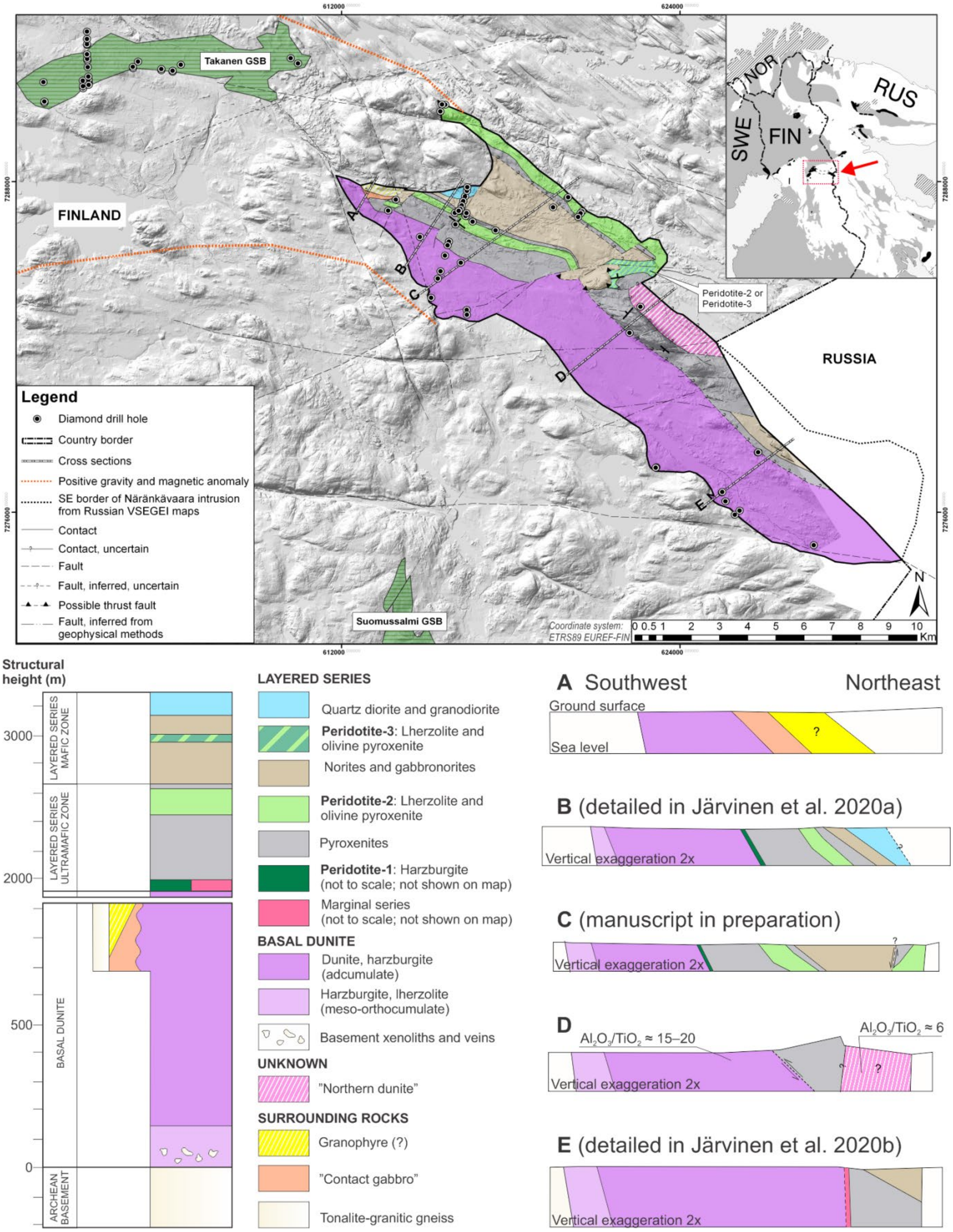

Figure 11. Simplified geological map, magmatic stratigraphy, and relevant cross-sections of the Precambrian mafic-ultramafic Näränkävaara intrusion. Map overlain on hill-shaded topography. Inset shows 2.5-2.4 Ga mafic intrusions in Fennoscandia (black) with Näränkävaara and KLIC pointed out.

zones – apparently the reef began to form before the first lithological reversal but reef-formation was halted by the influx of new magma, and resumed soon after disappearance of olivine from the liquidus (Järvinen et al 2020a). The ~1500-2000 m thick basal dunite series is thoroughly serpentinized and dominated by low-porosity olivine adcumulates with minor orthocumulates and (ortho)pyroxenites. Whole-rock geochemistry can be used to separate the body into 10 subzones (layers) with Mg#'s decreasing from south to north towards the layered series (Fig. 1), however with several reversals to more primitive compositions (Järvinen et al. 2020b).

In addition, a ~20 m thick marginal series gabbronorite separates these two series (in the SE-block of the intrusion, see Fig. 1), grading into pyroxenites of the layered series and with a tectonic contact to the basal dunite. The current location of the marginal series suggests a hiatus in magmatism between the two series, but it may also be the result of post-magmatic faulting.

2. Research questions at hand

This is a 4-year PhD project in which we aim to update the geology, petrogenesis, and Ni-Cu-Co-PGE mineral potential of the Näränkävaara intrusion, based on the wealth of new sample materials that have become available since the last major study (Alapieti 1982).

The primary interest is related to the origin and Ni-criticality of the basal dunite series. It exhibits several lithological features typically described from open-system komatiitic cumulates, e.g. abundance of 'extreme' olivine adcumulates, back-and-forth variation in Mg# with stratigraphic height, bimodal olivine, and poikilitic chromite. Among other things, this led to the hypothesis that the basal dunite might in-fact represent an Archean komatiitic wall-rock to the Paleoproterozoic layered series magmatism. However, two major results contradict this hypothesis, and rather argue for a ~2.44 Ga related intrusive origin. First, the parental magmas of both series were determined by 1) direct analysis of the marginal series, 2) weighted average calculation of the layered series, and 3) modelled from the southern margin olivine orthocumulate of the basal dunite (inferred to represent olivine-melt mixes) (Järvinen et al. 2020a & 2020b) – all three parental magmas show similar LREE-enriched high-MgO basaltic compositions with 13–18 wt% MgO (Fig. 2A), similar to other 2.5-2.4 Ga intrusions. Second, whole-rock Sm-Nd isotope systematics of both series are compatible with a crustally contaminated Paleoproterozoic plume origin (Fig. 2B), and similar to other intrusions of the same age (εNd -1.7–-3.5 at 2.44 Ga; Järvinen et al. 2021). We speculate that the basal dunite represents an earlier part of KLIC magmatism with a slightly higher MgO parental magma (15–18 wt%), and possibly (at least partly) an open system feeder channel environment; evolving into a more static magma chamber environment forming the layered series, with two late influxes of relatively unfractionated magma of similar composition (13–15 wt% MgO).

A distinct Ni-depletion is found in the basal dunite, both in whole-rock analyses with varying Ni at a similar Mg# (Fig. 3C), and in mineral analyses of chromite and olivine (3200–2150 ppm Ni in olivine at $Fo_{87.5}$). It is possible that this depletion is related to sulfide saturation depleting the residual magma in Ni, and as such the basal dunite is thought to have potential for internal or marginal/offset Ni-sulfide mineralization.

The layered series hosts an uneconomic PGE-reef which is homogeneous along a strike length of 5 km. It is unlikely that this reef would contain significantly higher quantities of PGE along undrilled profiles. However, all parental magma determinations show "fertile" magma compositions in that the magmas contain close to primitive mantle quantities of Ni-Cu-PGE, and as such there is potential for e.g. marginal sulfide deposits.

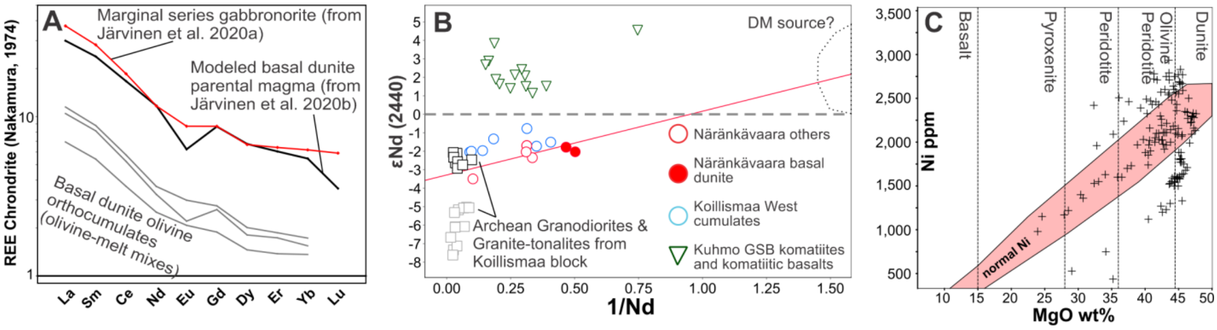

Figure 2. Whole-rock geochemical diagrams from the Näränkävaara intrusion **A** REE-diagram comparing parental magma compositions of the layered series and the basal dunite **B** ε_{Nd} vs 1/Nd diagram illustrating comagmatic plume-related origin of layered series and basal dunite (mix of depleted mantle plume source(?) and Archean crustal contaminant) **C** Ni vs. MgO diagram of basal dunite olivine cumulates illustrating Ni-depletion (variable Ni at similar MgO).

3. Future prospects

The geological framework of the KLIC is still poorly known: we speculate that the basal dunite is at least partly a feeder channel cumulate, having fed the layered intrusion(s), and is possibly related to the 'hidden dyke' previously speculated to represent a feeder channel as well (Alapieti 1982).

The possibility of Ni-sulfide saturation in the basal dunite warrants further investigation by, e.g., low-detection limit whole-rock PGE analyses and in-situ chromite trace-element analyses to investigate possible PGE-depletion that could have been caused by sulfide saturation. The 'hidden dyke' also forms an interesting target for Ni-Cu-PGE sulfide exploration, as it overlaps with a small Archean greenstone belt with abundant volcanosedimentary sulfides which could have provided a sulfur-rich wall-rock contaminant for the Paleoproterozoic magmas.

Another open question is the formation process of extrusive komatiite-like cumulus textures in intrusive systems – especially of the poikilitic chromite which is generally only described from primitive high-temperature high-volume komatiite flows (Godel et al. 2013).

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Chromite as a lithochemical tracer mineral in Finnish mafic-ultramafic host lithologies

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Summary This research project targets the utilization of chromite as a lithochemical tracer to identify Ni-Cu-PGE deposits in mafic-ultramafic lithologies. We use detailed *in-situ* geochemical methods to constrain the trace element and PGE distribution in Finnish greenstone belt and ophiolite chromites, which have crystallized in different sulfide saturation conditions, and have been subjected to metamorphism to varying degrees. Our preliminary results reveal that the chromite cores have maintained the original magma composition at least partially, while the crystal rims generally reflect post-magmatic processes. Our findings suggest that with careful consideration, chromite can be used as a lithochemical tracer of magmatic processes even in highly metamorphosed terrains.

1. Introduction and background to current research

The chromite mineral group commonly occurs in mantle derived mafic-ultramafic lithologies and its composition yields insights into Ni-Cu-PGE ore-forming processes. Recently, attention has been focused to the contents of the platinum group elements (PGEs; Rh, Ru, Ir, Os, Pd, Pt) in chromite. Previous studies suggest that the Ru content of chromite can fingerprint sulfide saturation processes of the host magma in mafic-ultramafic systems (Fiorentini et al. 2008, Locmelis et al. 2018). In sulfide-saturated conditions, chalcophile PGEs partition strongly into the immiscible sulfide phase, but in sulfide-undersaturated conditions Ru-rich chromite can crystallize (Fiorentini et al. 2008, Brenan et al. 2012). However, post-magmatic processes can overprint the magmatic geochemical signatures (including PGEs), which makes it challenging to discriminate primary compositions from secondary compositions, especially in dominantly metamorphosed terrains such as Fennoscandia. In addition, studies covering systematic mineral-scale variations in trace element (Ti, V, Mn, Co, Ni, Zn) and PGE concentrations in altered and unaltered chromites are rare (e.g., Mukherjee et al. 2015).

We study the distribution of major and trace elements and PGEs of some Finnish chromites from mineralized (S-saturated) and barren (S-undersaturated) greenstone belt and ophiolite lithologies. We perform *in-situ* core to rim analyses on altered and unaltered chromite grains to monitor whether the chromite mineral chemistry reflects the changes in sulfide saturation conditions of a system in crystal to regional scale, and to what extent metamorphism has overprinted the magmatic signatures.

2. Results and discussion

The preliminary LA-ICP-MS results of the greenstone belt and ophiolite chromites (n = 58) show distinct chromite chemistries between the two lithologies and between the mineral cores and rims. The ophiolite chromites have distinctly higher Mg# [Mg/(Mg+Fe)] and lower Cr# [Cr/(Cr+Al)], Zn/Al, Ru/Al, and Mn/Al (Fig. 1, 2) compared to the greenstone belt chromites. Generally, the greenstone chromites show systematic core to rim increase in Cr#, Mn/Al, V/Al, Zn/Al, and Ru/Al (Fig. 1, 2). Our preliminary dataset is not yet standardized with external major element data, but the elemental ratios still yield crucial information on the elemental distribution.

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The core to rim enrichment of fluid mobile elements relative to the Al concentrations (Zn/Al, Mn/Al, V/Al) implies a progressing elemental exchange with fluids at the crystal rims. We note here that the distinct lithologies display different ratios of fluid mobile/immobile elements suggesting that they reflect different fluid compositions. The chromite cores have instead retained the primary magmatic composition, at least moderately. Hence, the preliminary results indicate that even in the highly metamorphosed Finnish terrains, the chromite core composition can be used to trace primary igneous processes while the chromite rim compositions may give insights to post-magmatic processes, such as fluid activity and composition.

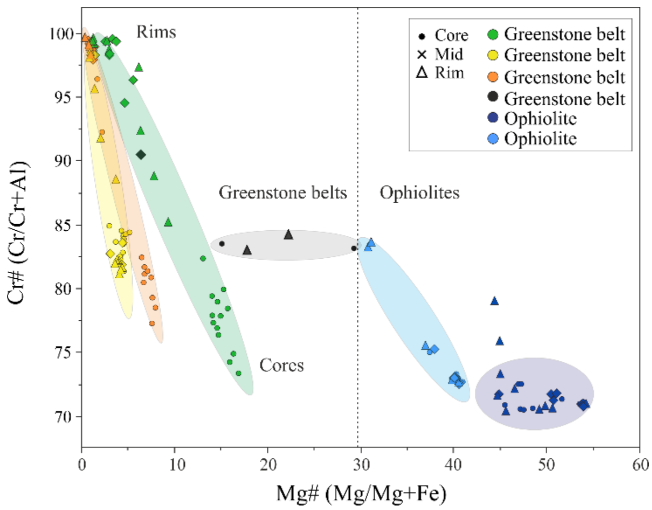

Figure 12. The preliminary core to rim results of the Finnish greenstone belt and ophiolite chromites. Mg# = [Mg/(Mg+Fe)] and Cr# = [Cr/(Cr+Al)]. The dataset is not yet standardized with external major element data.

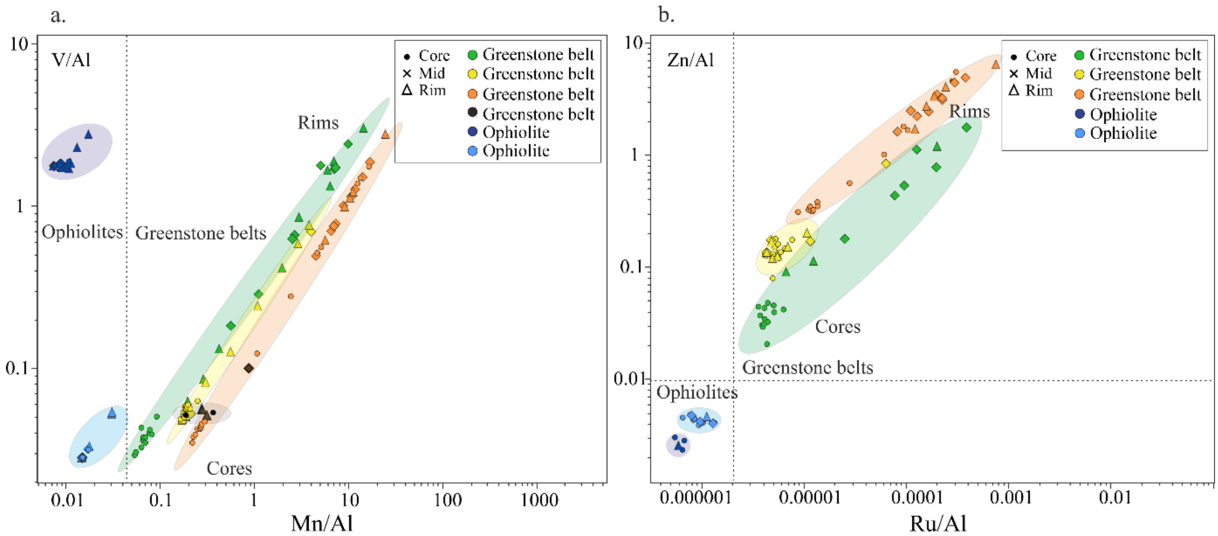

Figure 2. The preliminary core to rim results of the Finnish greenstone belt and ophiolite chromites. Mn/Al vs. V/Al (a.) and Ru/Al vs. Zn/Al (b.) of the analysed chromites expressed in logarithmic scale. The dataset is not yet standardized with external major element data.

3. Future prospects

The sample set will be extended to cover chromites from other Finnish lithologies and from the Macquarie Island (Southwestern Pacific) and the Troodos ophiolites (Cyprus). The aim is to establish a comprehensive chromite composition database covering various sulphide-bearing and barren lithologies. The database will provide information on the magmatic, metamorphic, and hydrothermal evolution involved in the ore-forming processes and will help to identify potential Ni-Cu-PGE ore bodies. The ultimate goal of our project is to evaluate the potential of chromite as a lithochemical tracer mineral establishing a global database, in addition to identifying the variables that influence the mineral chemistry of chromites.

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Apatite as a tracer for magmatic-hydrothermal ore-forming processes

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Summary This project focuses on the trace element chemistry of igneous apatite in various magmatic systems with the use of *in situ* analytical techniques. The composition of apatite may possibly be used as a tracer for various magmatic-hydrothermal processes due to the breadth of chemical substitutions possible within the structure. Apatite is found in many mineralized layered intrusions as a minor phase. Apatite may be utilized in the tracking of metasomatic fluids in layered intrusions or in geochronological studies in the absence of other commonly used phases i.e. zircon. Apatite accumulations can be exploited economically for phosphorus and possibly for rare earth elements as well.

1. Introduction and background to current research

This contribution outlines a PhD project that investigates the trace element chemistry of igneous apatite. The project comprises three subprojects, each of which concentrates on a different type of magmatic system: 1) carbonatites, 2) massif-type anorthosites and layered intrusions, and 3) rapakivi granites. The aim of the study is to gain new insight into the substitution mechanisms of trace elements in these chemically different magmatic environments and to compile a chemical database of apatite compositions. The main analytical methods utilized are electron microprobe (EPMA) and laser ablation inductively coupled plasma mass spectrometer (LA-ICP-MS) aided with cathodoluminescence (CL) and scanning electron microscopy (SEM) imaging techniques. These *in situ* methods allow the quantification of compositional differences (e.g. growth zonation, alteration) between and within individual grains of apatite in a single sample. The current stage of the project concentrates on the carbonatite subproject, in which the apatite compositions of the Archean Siilinjärvi glimmerite-carbonatite rocks are being studied. The sub-project on layered intrusions and massif-type anorthosites is planned to be launched during 2021.

2. Research questions at hand

The apparent compositional variability and geological ubiquity makes apatite a potential versatile tracer of numerous geochemical processes. Calcium-phosphate apatite minerals [$Ca_{10}(PO_4)_6(F,OH,Cl)_2$] are the most common phosphate minerals in the Earth's crust and present as accessory or trace phases in most magmatic, metamorphic, and sedimentary rocks (e.g. Piccoli and Candela 2002, Hughes and Rakovan 2015). Magmatic apatite is typically fluorapatite in composition, with a varying hydroxyl component (Piccoli and Candela 2002). Chlorapatite is found in some mafic-ultramafic intrusions (e.g. Boudreau et al. 1986, discussed below) and in metasomatically altered rocks (Kusebauch et al. 2015). Bromine, I, S, C, and structural water can also be incorporated into the apatite structure to some extent. Sulphur is compatible in the apatite structure in many oxidation states ranging from reduced (S^{2-}) to oxidized (S^{4+}) (Konecke et al. 2017). The $S^{6+}/\Sigma S$ ratio can be used as an oxybarometer (Konecke et al. 2019).

The apatite structure can incorporate a range of elements to cation and anion sites, often with coupled substitutions to balance charges (Pan and Fleet 2002). Trace elements, such as

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rare earth elements (REE) are strongly partitioned into apatite, with a preference of middle REE over heavy REE (e.g. Hughes et al. 1991, Pan and Fleet 2002). This enrichment in REE may lead to apatite accumulations being a potential source for REE (Emsbo et al. 2015). Economic apatite accumulations are typically exploited as raw material for phosphate fertilizers, with phosphorites (chemical sediments, Filippeli 2008) being the most voluminous rock type. Magmatic deposits are also exploited e.g. the Siilinjärvi glimmerite-carbonatite complex (O'Brien et al. 2015), which may be potentially be utilized for REE as well (Decrée et al. 2020). Besides alkali rock types and carbonatites, iron-oxide-apatite cumulates (Kiruna-type, nelsonites or oxide-apatite-gabbronorites) are also exploited.

3. Future prospects

3.1. Chlorapatite in layered intrusions

Chlorine-bearing apatite is present in or near platinum group element (PGE) mineralized strata in many layered mafic-ultramafic intrusions, (e.g. Bushveld; JM and Merensky Reef; Boudreau, 1993; Great Dyke; Boudreau et al., 1986; Munni Munni; Boudreau et al., 1993; Stillwater; Boudreau and McCallum, 1989; Penikat; Halkoaho, 1994; Näränkävaara, Järvinen et al., 2020; Duluth Complex; Bathtub Intrusion; Raič et al., 2018; Norilsk; Serova and Spiridonov, 2018). The role of chlorine-bearing fluids in the metallogenesis of PGE reefs is controversial (cf. Godel 2015 and references therein). There are proponents of both orthomagmatic (Campbell et al. 1983) and magmatic-hydrothermal genetic models (Boudreau et al. 1986). Apatite compositions, textures, and inclusions (monazite, xenotime) can provide evidence of metasomatic events and the type of metasomatic fluid(s) involved in them (Harlov et al. 2002, Harlov and Förster 2003).

3.2. Apatite geochronology

Apatite can also be used in geochronological studies as uranium and thorium can be incorporated into the structure (Chew et al. 2011). Another suitable method for dating of mafic-ultramafic intrusions is the ^{176}Lu-^{176}Hf isotope system (Chew and Spikings 2015, Scoates and Wall 2015). Apatite is a suitable mineral for this as well because Lu is readily incorporated (Kd >>1) into the apatite structure whereas Hf is not (Kd < 1).

3.3 Fennoscandian Fe-Ti(-V)-P mafic-ultramafic intrusions

In Finland, there are Paleoproterozoic (~1.88 Ga) Fe-Ti(-V)-P enriched mafic intrusions. These intrusions are typically composed of more fractionated mafic rocks than the Ni-Cu mineralized mafic-ultramafic Vammala and Kotalahti type intrusions of similar age (e.g. Makkonen 2017). These Fe-Ti(-V)-P intrusions are located within but near the periphery of the Central Finland Granitoid Complex, situated into two major areas with several small, gabbroic intrusions – Kauhajärvi (Kärkkäinen and Appleqvist 1999) and Koivusaarenneva (Kärkkäinen and Bornhorst 2003). The Kauhajärvi intrusion hosts Fe-Ti oxide (magnetite, ilmenite) and apatite rich layers which vary in thickness from 2 to 30 meters. The Koivusaarenneva gabbro has ilmenite and vanadiniferous magnetite layers (Kärkkäinen and Bornhorst 2003). The composition of apatite in these localities has not been investigated in detail. The trace element and halogen concentrations could possibly provide additional information about the conditions in which the mineralizations formed.

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