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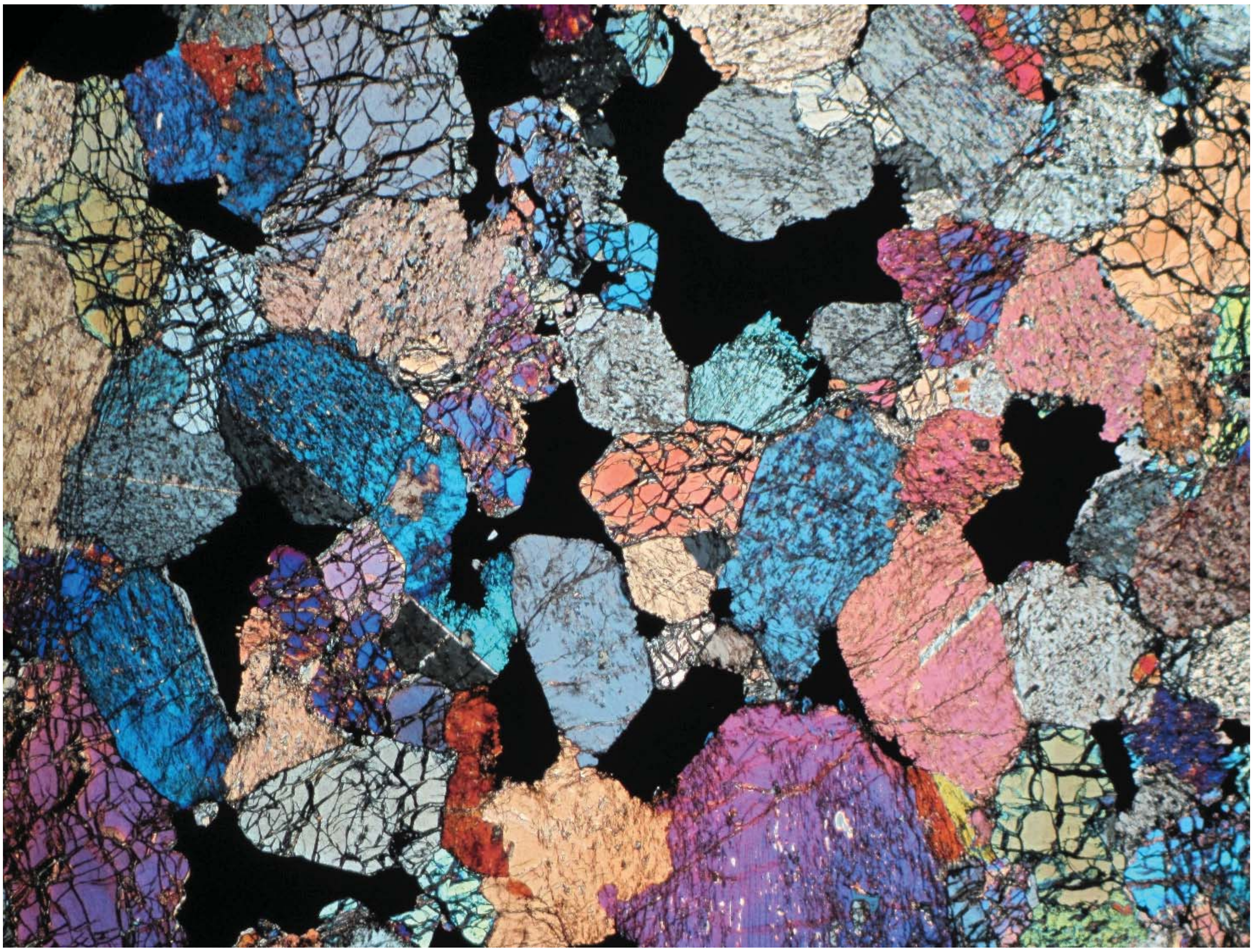

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Photomicrograph of Kevitsa olivine-pyroxene cumulate with interstitial Ni-Cu sulfides (opaque). Width of the photo 6.4mm.

KIRSI LUOLAVIRTA

MAGMATIC EVOLUTION OF THE KEVITSA IGNEOUS COMPLEX, NORTHERN FINLAND, AND ITS RELATION TO THE ASSOCIATED Ni-Cu-(PGE) MINERALIZATION

Academic dissertation to be presented with the assent of the Doctoral Training Committee of Technology and Natural Sciences of the University of Oulu for public defence in Auditorium L10, Linnanmaa, on 27 April 2018, at 12 noon

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Supervised by

Professor Eero Hanski
Oulu Mining School, University of Oulu

Professor Wolfgang Maier
The School of Earth and Ocean Sciences, Cardiff University, U.K.

Reviewed by

Docent Hannu Makkonen
Boliden FinnEx Oy

Research professor Yan Wang
Guangzhou Institute of Geochemistry, Chinese Academy of Sciences

Opponent

Professor Pertti Lamberg
Keliber Oy

Magmatic evolution of the Kevitsa igneous complex, northern Finland, and its relation to the associated Ni-Cu-(PGE) mineralization

Kirsi Luolavirta

University of Oulu Graduate School and Geoscience Research Unit
Faculty of Technology, University of Oulu
P.O. Box 3000, FI-90014 University of Oulu, Finland

ABSTRACT

Mafic-ultramafic intrusions are manifestations of magnesian mantle-derived melts emplaced into the Earth´s crust where they differentiate to composite cumulate rock successions. These intrusions are significant hosts for base and precious metal deposits primarily due to the high contents of these elements in their primary melts. A variety of magma chamber processes, notably crystal fractionation, magma recharge and mixing, contamination, liquid immiscibility and post-cumulus processes may operate upon emplacement, cooling and solidification of the intrusions. These processes and the interplay of these processes define the evolutionary histories of magmatic intrusive bodies and may be of significant importance in generation of ore deposits.

The ~2.06 Ga Kevitsa intrusion in central Finnish Lapland is part of a suite of relatively small mafic-ultramafic intrusions and volcanic rocks in the area and hosts a large disseminated Ni-Cu-(PGE) sulfide deposit. This PhD thesis examines the petrogenesis of the intrusion and its Ni-Cu-(PGE) sulfide ores by utilizing new and previous geological and geochemical data and new mineral compositional data and Sr and S isotope systematics. The main objective of the study is to constrain the internal stratigraphy of the intrusion and to study the magma chamber processes involved in the genesis of the intrusion and its mineralization. The PhD study was established in collaboration with the Kevitsa Mine to enhance understanding on magmatic architecture and emplacement history of the intrusion, which would potentially aid in defining further near mine exploration targets.

Detailed petrologic investigations reveal marked differences in lithological and whole-rock and mineral chemical stratigraphy in different parts of the Kevitsa intrusion. The ore-bearing domain is characterized by a complex internal architecture, presence of numerous inclusions and xenoliths and marked stratigraphic fluctuations in whole-rock, mineral and isotopic compositions. Cumulate succession around the ore domain, in contrast, show systematic lithological and compositional evolutionary tends and rather homogeneous Sr-isotopic signatures throughout the stratigraphy. The contrasting intrusive stratigraphy in the different parts of the intrusion is interpreted to reflect different emplacement histories. It is proposed that the Kevitsa magma chamber was initially filled by stable continuous flowage ("single" input) of basaltic magma followed by differentiation in an at least nearly closed system. In the following stage, magma pulses were repeatedly emplaced into the interior of the intrusion in a dynamic (open) system forming the sulfide ore bodies. Both Sr and S isotopic compositions obtained from the Kevitsa intrusive rocks record crustal signatures indicating the Kevitsa magmas assimilated materials from the country rocks. Heavy S isotopic compositions of the sulfide ores suggests external sulfur was important in triggering S-saturation. Ni-poor olivines in host rocks to pyrrhotite-dominated ore bodies indicate early-stage sulfur saturation of the Kevitsa magma, which may have produced proto-ores at some depth in the magma conduit. It is proposed that assimilation of these proto-ores by later magma inputs upgraded the metal tenors of the Kevitsa Ni-Cu-(PGE) ores.

Detailed petrological studies and characterization of the inclusions within the Kevitsa deposit proposes they are derived from the large dunitic cumulate body (Central Dunite) adjacent to the Kevitsa intrusion and from komatiitic country rocks. The mineralogy and compositional characteristics of the Central dunite suggest it to represent a conduit of picrite-basalt volcanic rocks in the area with temporal and genetic links to the Kevitsa olivine-pyroxene cumulates. The role of the abundant inclusions found from the deposit remains enigmatic. It is proposed that the entrapment of a high number of inclusions decreased the flow rate of the Kevitsa magma aiding settling of the sulfides.

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This thesis is a result of research conducted in collaboration with the Oulu Mining School (OMS, Faculty of Technology, University of Oulu) and First Quantum Minerals Ltd (FQM Ltd), the former operator of the Kevitsa Mine. I´m grateful for these parties for providing me the opportunity to work on this interesting, yet truly challenging research.

There are many people that I wish to thank for their contribution and support during the course of this project. The former Kevitsa mine and the exploration geologists, technicians and other staff, are kindly thanked for assistance, guidance and hospitality during my long visits at Sodankylä. Special thanks to Markku Lappalainen for establishing the research and for Frank Santaguida for putting his interest on this project. FQM Ltd is also acknowledged for providing their extensive data base to be utilized in this study.

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Oulu, April 2018
Kirsi Luolavirta

ORIGINAL PUBLICATIONS

This dissertation is based on the following four publications:

Paper I	Santaguida, F., Luolavirta, K., Lappalainen, M., Ylinen, J., Voipio, T., Jones, S. (2015) The Kevitsa Ni-Cu-PGE Deposit in the Central Lapland Greenstone Belt in Finland. In: Maier, W., Lahtinen, R., O´Brien, H. (ed.) Mineral Deposits of Finland, Elsevier, Amsterdam, p 195–210.
Paper II	Luolavirta, K., Hanski, E., Maier, W., Santaguida, F. (in press) Characterization and origin of dunitic rocks in the Ni-Cu-(PGE) sulfide ore-bearing Kevitsa intrusion, northern Finland: whole rock and mineral chemical constraints. Bulletin of the Geological Society of Finland.
Paper III	Luolavirta, K., Hanski, E., Maier, W., Santaguida, F. (2018) Whole-rock and mineral compositional constraints on the magmatic evolution of the Ni-Cu-(PGE) sulfide ore-bearing Kevitsa intrusion, northern Finland. Lithos 269–299, 37-53.
Paper IV	Luolavirta K., Hanski E., Maier W., Lahaye, Y., O´Brien, H., Santaguida F. (2018) *In-situ* strontium and sulfur isotope investigation of the Ni-Cu-(PGE) sulfide ore-bearing Kevitsa intrusion, northern Finland. Mineralium Deposita. https://doi.org/10.1007/s00126-018-0792-6

The geological and geochemical data utilized in the thesis were provided by the Kevitsa Mine. Papers II, III and IV were planned in collaboration with the Kevitsa Mine (Frank Santaguida, former FQM Ltd) and Kirsi Luolavirta, Wolfgang Maier and Eero Hanski. Kirsi Luolavirta is the corresponding author in these papers and responsible for the data collection and most of the data processing, interpretations and manuscript preparations. Eero Hanski and Wolfgang Maier contributed to data interpretations and writing, Frank Santaguida in figure preparations and Yann Lahaye and Hugh O´Brien in data analysis, processing and interpretations in paper IV. Kirsi Luolavirta is the second author in paper I and contributed to the manuscript and figure preparations and data interpretations.

CONTENTS

INTRODUCTION

Mafic-ultramafic intrusions form upon cooling and crystallization of mantle-derived magnesian magmas emplaced into the Earth´s crust. Many of these intrusions, notably the Bushveld in South Africa, Stillwater in USA, Sudbury and Voisey´s Bay in Canada, Jinchuan in China and Noril´sk and Pechenga in Russia, are hosts of significant PGE and Ni-Cu sulfide and Cr and Fe-Ti-V oxide deposits. This is primarily due to the sufficient metal contents of their parental magmas in addition to favorable ore-forming processes.

The magmatic histories of mafic-ultramafic intrusive bodies may include complex periods of magma replenishment, mixing and mingling, crystal fractionation, crustal contamination, and post-cumulus processes (e.g., Irvine, 1980; DePaolo, 1985; Eales et al., 1986, 1990; Meyer & Wilson, 1999; Namur et al., 2010). For instance, in the case of the large and well-studied Bushveld Complex, all of these processes have been in operation at some stage during its growth, crystallization and solidification and are often linked to the generation of its sulfide and oxide mineralization (e.g., Barton et al., 1986; Naldrett & von Gruenewaldt 1989; Maier & Barnes, 1999; Harris & Chaumba, 2001). Presently, there exists comprehensive literature on various Ni-Cu-PGE ore deposits and their host rocks and certain features are found to be characteristic for the majority of these deposits. Consequently, several generalizations have been derived regarding the formation of magmatic Ni-Cu-PGE sulfide deposits and reviewed and discussed by various authors (e.g., Naldrett, 1997, 1999, 2004, 2010, 2011; Maier et al., 2001; Barnes & Lightfoot, 2005; Arndt et al., 2005; Lightfoot, 2007; Song et al., 2011; Maier & Groves, 2011).

The ~2.06 Ga Kevitsa intrusion, the target of this PhD study, is a relatively small mafic-ultramafic intrusive body that hosts a large disseminated Ni-Cu-PGE sulfide deposit (Mutanen, 1997; Mutanen & Huhma, 2001; Santaguida et al., 2015). The intrusion occurs together with a number of other Paleoproterozoic intrusive bodies and volcanic rocks in the Central Lapland greenstone belt, northern Finland (Fig. 1). In addition to the Kevitsa intrusion, the Sakatti Cu-Ni-PGE deposit (Brownscombe et al., 2015) and the komatiite-hosted Lomalampi PGE-(Ni-Cu) deposit (Törmänen et al., 2016) have been discovered in the volcano-sedimentary sequence assigned to the Savukoski Group (Lehtonen et al., 1998). Hence, the area seems to be highly prospective for magmatic Ni-Cu sulfide ore deposits.

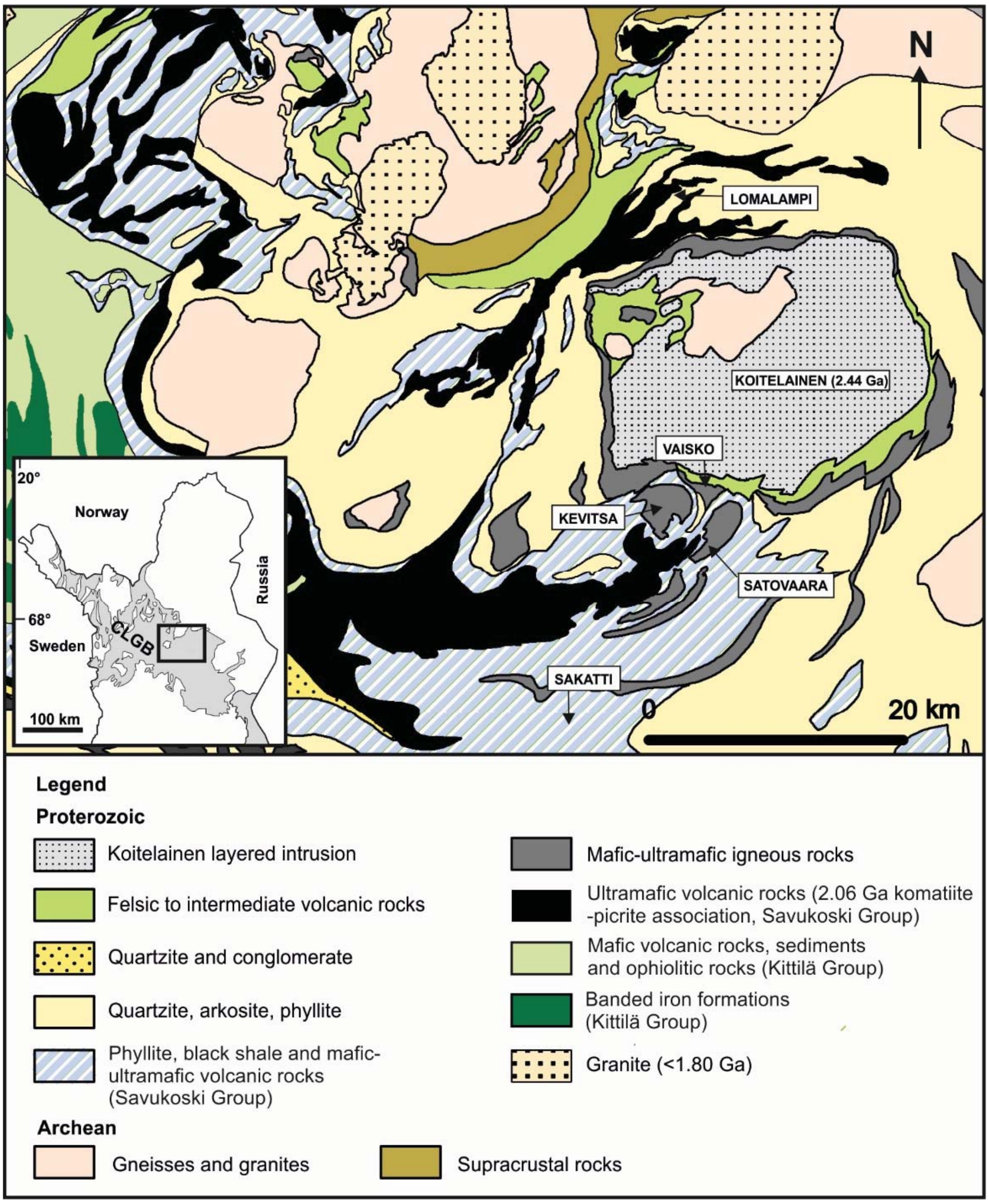


Fig. 1. Location of the Kevitsa intrusion in the Central Lapland greenstone belt (CLGB). The neighboring Koitelainen and Satovaara intrusions, Vaisko sill, and known magmatic sulfide deposits (Sakatti, Lomalampi) occurring in the Savukoski Group are also indicated. Modified after DigiKP, the digital map database of the Geological Survey of Finland, available at http://gtkdata.gtk.fi/Kalliopera/index.html.

The Kevitsa deposit is peculiar in that (i) it occurs in the central part of the ultramafic portion of the intrusion, which is exceptional as magmatic Ni-Cu sulfide segregations are more usually found at the basal parts of ore-bearing intrusions (e.g., Barnes & Lightfoot, 2005; Lightfoot, 2007), and (ii) the deposit is characterized by an unusually large variation in the metal contents of sulfides, showing a continuous range in Ni tenors from ~2 wt.% up to 40 wt.% (Mutanen, 1997; Yang et al., 2013a).

The first detailed geological description and petrogenetic model for the formation of the Kevitsa igneous rock suite and its mineralization were published by Mutanen (1997). He classified the Kevitsa ores based on the Ni tenor to several types: 1) false ore (Ni tenor 1-4 wt.%, uneconomic), 2) regular ore (Ni tenor 4-7 wt.%, the main economic mineralization), 3) Ni-PGE ore (high Ni tenor, generally >10 wt.%), and 4) transitional ore having an intermediate character between the regular and Ni-PGE ore. The preliminary model by Mutanen (1997) proposes that the Kevitsa intrusion represents differentiation of a single cast of basaltic magma and compositional heterogeneities of the ultramafic cumulates reflect variable degrees of in-situ contamination with pelitic and mafic-ultramafic volcanogenic materials. Since then, the research has been largely focused on specific features of the sulfide ore, such as the PGM (platinum-group minerals) mineralogy and chemistry (Gervilla & Kojonen, 2002), rare-earth element and isotopic characteristics (Hanski et al., 1997; Grinenko et al., 2003; Huhma et al., 2018) of the different ore types, the origin of the Ni-PGE ore type and related nickeliferous silicates (Yang et al., 2013a), and the effect of hydrothermal alteration on the metal contents (Le Vaillant et al., 2016). Recently, geophysical measurements were applied to access the geometry and internal structure of the Kevitsa intrusion (Koivisto et al., 2012, 2015), and Le Vaillant et al. (2017) used statistical methods to the large assay database of the mine to simplify the rather erratic tenor variations and construct a geological model for the deposit. The original model by Mutanen (1997) has been questioned and a new model involving multiple magma emplacements has been proposed for the Kevitsa deposit (Gregory et al., 2011; Koivisto et al., 2015). Despite all these previous studies, the internal architecture and the genesis of the whole intrusion have remained elusive.

The exploration and inventory drilling campaigns at Kevitsa have produced more than 100 km of drill core and a huge amount of geochemical data. These together with the largely well-preserved nature of the magmatic mineralogy of the intrusion provide a good base to study the magmatic evolution of the Kevitsa intrusive suite rocks, its sulfide ores and the ore-forming processes. This PhD project was initiated in collaboration with the FQM Ltd and the University of Oulu in order to study the petrogenesis of the Kevitsa intrusive suite rocks and potentially serve exploration to locate additional resources. This study utilizes the large database of the mine provided by the FQM Ltd, new mineral compositional data and in-situ Sr and S isotope measurements to constrain the internal magmatic architecture of the intrusion and to study the processes involved in the formation of the Kevitsa intrusion and related sulfide ores.

MAFIC–ULTRAMAFIC INTRUSIONS

Mafic-ultramafic intrusions are expressions of slowly-cooled, differentiated and crystallized mafic/ultramafic magmas emplaced into the Earth´s crust. These intrusions form a diverse group of igneous bodies recording variable parental magma compositions and a wide shape and size range from large layered intrusions and thinner sills to pipe-like conduits, chonolites or small irregular bodies. Moreover, mafic-ultramafic intrusions are observed to occur in various tectonic settings.

In terms of igneous petrology or mineral economics, the most significant expressions of mafic-ultramafic magmatism are large layered igneous bodies, such as the Bushveld Complex in South Africa, the Skaergaard intrusion in Greenland, and the Rum intrusion in Scotland, which have gained a lot of interest among researchers studying the evolution of rock series and processes taking place in magma chambers (e.g., Charlier et al., 2015). Fractional crystallization is the most fundamental process operating upon cooling in magma chambers. Crystallization of liquidus minerals and their successive accumulation on cooling surfaces (walls, roof and floor) produce progressive successions from ultramafic cumulates to mafic and eventually to felsic rocks. In addition to crystal fractionation, other processes can control the evolutionary histories of mafic-ultramafic intrusive bodies, including magma recharge, magma mixing (mingling), crustal contamination and liquid immiscibility (e.g., Irvine, 1980; DePaolo, 1985; Eales et al., 1990; Jensen et al., 1993, 2003; Meyer & Wilson, 1999; Tegner et al., 1999; McBirney & Creaser, 2003; Jakobsen et al., 2005; Namur et al., 2010). These processes constitute the broad concept of magmatic differentiation, i.e. the process by which magmas undergo bulk chemical change. Furthermore, various post-cumulus processes are likely to operate during slowly cooling intrusive bodies (e.g., Irvine, 1980; Tait et al., 1984; Barnes, 1986). The various magma chamber processes, which are discussed above and are illustrated in Fig. 2, together with their combinations give rise to a variety of rock types and have a potential to create economic concentrations of many valuable metals, such as Cr, Fe, Ti, V, PGE, Ni, Cu, Co and Au.

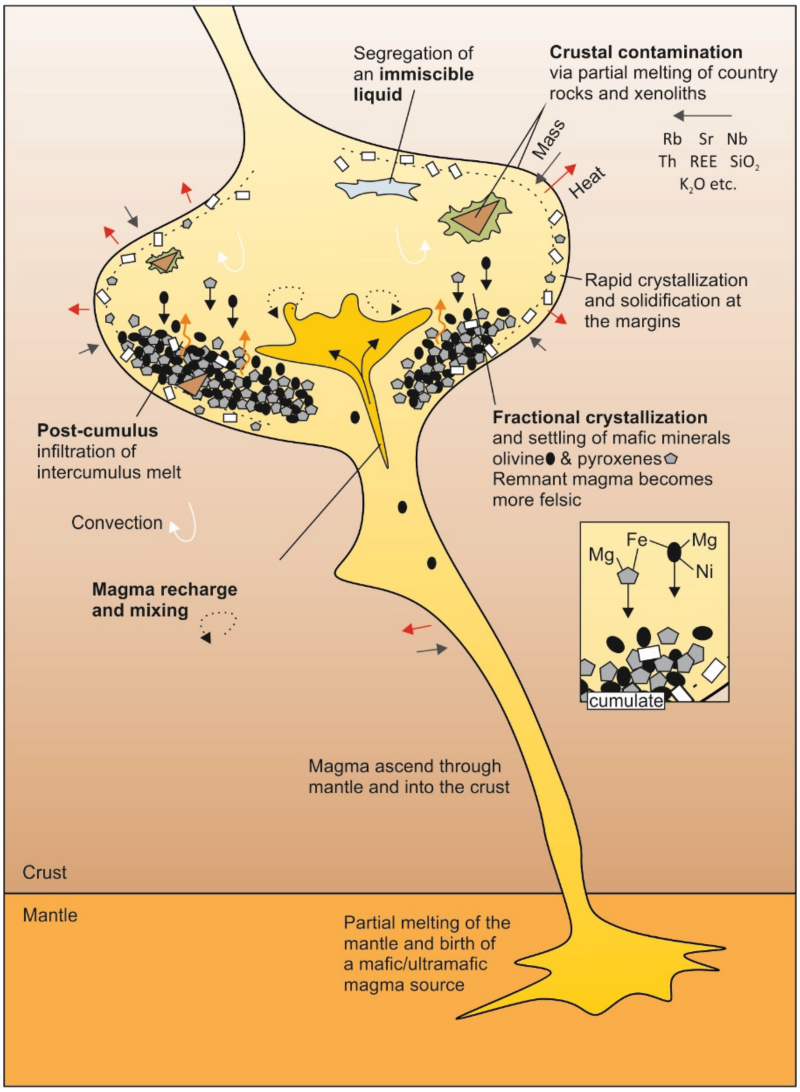


Fig. 2 *Simplified* sketch showing the general features of a magma chamber and related processes.

MECHANISMS OF MAGMA EVOLUTION

Crystal fractionation

Aside from partial melting of mantle, crystal fractionation is the dominant process generating different magma compositions. Upon cooling of magma in magma conduits or chambers, or at the Earth´s surface, magma crystallizes minerals according to the temperature of crystallization of its liquidus minerals. The crystallization sequence of a typical basaltic magma undergoing fractional crystallization (FC) was established by Bowen (1928) and is known as the Bowen´s reaction series. In the case of magnesian mantle-derived melts, the major early crystallizing phases are olivine and pyroxenes. As these minerals are removed from the magma by crystal settling, the concentrations of elements compatible to these minerals (e.g., Mg, Ni) decrease in the magma while those of incompatible elements (e.g., Ti, Zr) increase. In mantle-derived magmas undergoing differentiation principally by a process of fractional crystallization (FC), accumulation of crystals, e.g., by gravity settling, produces predictable cumulate successions, in which the mineral phases and their compositions vary as the magma progressively evolves. Hence, a classical approach in studies of genetically related intrusive rocks as well as their potential volcanic equivalents is utilization of variation diagrams involving whole-rock and mineral major and trace-element compositions (e.g., Revillon et al., 2000; Luo et al., 2012; Wang et al., 2014; Luolavirta et al., *in press*).

The fractional crystallization path of silicate melts may be complex because in addition to the parental magma composition, the conditions of crystallization can significantly affect the order of the appearance of the liquidus phases as well as their compositions. The effects of pressure, volatile content (e.g., H_2O) and oxygen fugacity (fO_2) on the phase relations in basaltic systems have been studied and discussed in numerous experimental studies (e.g., Berndt et al., 2005; Feig et al., 2006, 2010; Hamada & Fujii, 2008; Freise et al., 2009; Husen et al., 2016). Because fO_2 controls the Fe^{2+}/Fe^{3+} ratio in the magma, changes in fO_2 influences significantly the stability and composition of iron-bearing oxide and silicate minerals and for instance, the stability field of olivine increases with decreasing fO_2, likely due to preferred partitioning of Fe^{2+} in olivine and high Fe^{2+}/Fe^{3+} in the magma, whereas under oxidizing conditions, the Fe^{2+}/Mg in the magma is lower and higher Fo contents of olivine are expected (e.g., Berndt et al., 2005; Hamada & Fujii, 2008; Freise et al., 2009;). The effects of H_2O addition are well known; it decreases the liquidus temperature, suppresses plagioclase crystallization and expands the stability field of olivine (Kushiro, 1975; Bernt et al., 2005; Feig et al., 2006).

The crystallization of minerals is thought to take place along the cooling surfaces of magma chambers, that is at their margins, but mainly the cumulus minerals accumulate on the floor of the chamber and record the variations in melt composition, temperature, oxygen fugacity and isotopic ratios during the evolution of magma chamber. In open magmatic systems, the course of crystallization may change as the composition of the fractionating magma or conditions of crystallization are affected by incorporation of crustal material or addition of new magma into the magma chamber. Presently, various petrological software programs, such as MELTS (Ghiorso & Sack 1995**;** Ghiorso et al., 2002), PETROLOG (Danyushevsky & Plechov, 2011) and COMAGMAT (Ariskin et al., 1993), are available, which have been designed to compute equilibrium phase relations for igneous systems under a variety of thermodynamic constraints (pressure, temperature, oxidation state, and H_2O content), facilitating simulation of crystallization processes of silicate liquids.

Crustal contamination

When transported and emplaced in the crust, the high-temperature mantle-derived magmas are likely to melt and assimilate its country rocks with low melting temperatures. In doing so, they lose heat promoting crystallization of the minerals that were already crystallizing from the magma. The capacity of a magma to assimilate country rocks depends on, and is limited, by the thermal energy of the magma (i.e. latent heat of crystallization). The interplay of simultaneous assimilation (A) and fractional crystallization (FC) (AFC-processes) in crustal magmas chambers was already envisaged by Bowen (1928), and several mathematical formulations have been generated to quantify contamination effects and predict the composition of hybrid magmas undergoing this process under various circumstances (see e.g. DePaolo, 1981; Aitcheson & Forrest, 1994; Spera & Bohrson, 2001, 2004; Thompson et al., 2002; Guzmán et al., 2014).

Evidence for crustal contamination can be inferred from the occurrence of partially digested country rock xenoliths, hybrid rocks, disequilibrium in mineral assemblages or compositions, or it can be revealed by crustal geochemical signatures in intrusive rocks produced by a mantle-derived magma. The geochemical features of crustal rocks are well expressed in certain trace element ratios, such as elevated La/Sm, Ce/Yb, Zr/Y, Zr/Th, La/Nb and Th/Yb and hence, high ratios of these elements in magmatic rocks are widely used as evidence for crustal contamination (e.g., Lightfoot et al., 1991; Vlastélic et al., 2005).

Radiogenic (e.g., Rb-Sr, Sm-Nd, Lu-Hf, Re-Os) and stable (e.g., S, O) isotope systems are sensitive tracers of contamination processes. The advantage in the use of isotopes is that they remain largely unaffected by closed-system fractionation processes but may change significantly due to crustal contamination or injection of magmas with different isotopic characteristics into the magma chamber.

The Rb-Sr method is based on the decay of radiogenic ^{87}Rb to ^{87}Sr (e.g. Jäger, 1979). The half-life ($t_{1/2}$) is 49.6×10^9 years and the decay constant (λ) 1.3968×10^{-11} y^{-1} (Rotenberg et al., 2012). By measuring the present-day ratios of ^{87}Sr/^{86}Sr and ^{87}Rb/^{86}Sr with a mass spectrometer, the initial (^{87}Sr/^{86}Sr)$_i$ at the time of the closure of the isotope system can be obtained from the isochron equation:

$$^{87}\mathrm{Sr}/^{86}\mathrm{Sr} = (^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i + (^{87}\mathrm{Rb}/^{86}\mathrm{Sr})(e^{\lambda t}-1) \qquad (1)$$

^{86}Sr is a stable isotope, with its abundance remaining constant through time. The preferential partitioning of Rb into the crust relative to Sr has resulted in high ^{87}Rb/^{86}Sr ratios in crustal rocks and over time much higher $^{87}Sr/^{86}Sr$ ratios than observed in mantle rocks. Hence, if a mantle-derived magma assimilates old crustal material, elevated $(^{87}Sr/^{86}Sr)_i$ values are to be expected.

Isotopes can be determined on whole-rock samples or mineral samples using mineral separation, microdrilling, or in-situ analysis. Grain-scale analyses allow tracing isotopic changes in magma during crystallization of a given mineral grain or may reveal isotopic disequilibrium among co-existing phases. Hence, isotopic measurements of individual minerals allow evaluation of contamination processes operating in magma chambers in a detailed scale. For instance, Tepley & Davidson (2003) observed an upwards increase in $^{87}Sr/^{86}Sr$ in plagioclase towards an upper contact of macro-rhythmic units 9 and 10 in the Rum layered intrusions. This was accompanied by isotopic disequilibrium between cores and rims of some plagioclase grains as well as between plagioclase and clinopyroxene. The authors interpreted the isotopic disequilibrium to reflect initial crystallization of plagioclase in a close proximity to wall rocks, where contamination is expected to be more efficient, and later crystallization of the plagioclase rims and clinopyroxene from a less contaminated magma.

After the development of the micro-analytical techniques (LA-MC-ICP-MS), an increasing number of research utilize in-situ measurements of $^{87}Sr/^{86}Sr$ in plagioclase directly from thin sections by LA-MC-ICP-MS (Davidson et al., 2001, 2008; Yang et al., 2013b; Liu et al., 2014; Gao et al., 2015; Mangwegape et al., 2016; Wilson et al., 2017; Luolavirta et al., 2018b). The relatively high concentrations of Sr in plagioclase, its resistance to post-crystallization compositional modifications and prevalence of plagioclase in various types of igneous rocks make this mineral useful to Sr isotope studies. In-situ analyses allow fast determination of isotope compositions of rocks and can be used to study detailed core-to-rim isotopic variations in individual mineral grains. Aside from contamination, isotopic analyses can track down other open-system magma chamber processes, such as injection of new magma with a different isotopic composition into the magma chamber.

Magma replenishment and mixing

Cooling and crystallization of magma chambers is in many cases interrupted by invasion(s) of new undifferentiated magma into the magma chamber. The growth and evolution of large mafic-ultramafic intrusion, such as the Bushveld Complex (e.g. Cawthorn & Walraven, 1998; Nex et al., 2002; Tanner et al., 2014), the Bjerkreim-Sokndal intrusion (Jensen et al., 1993, 2003; Nielsen et al., 1996), and the Stillwater Complex (McCallum, 1996), are linked to such recharge events. Injections of new magma pulses into the magma chamber can be revealed by major changes in liquidus mineral assemblages, changes in mineral compositions or trace element ratios that are distinct from what is expected by fractional crystallization, or sudden or sustained shifts in isotope compositions (e.g., Cox & Hawkesworth, 1985; Eales et al., 1986, 1990; Bédard et al., 1988; Cawthorn et al., 1991; Kruger, 1994; Meyer & Wilson, 1999; Pang et al., 2009; Nex et al., 2002; Namur et al., 2010; Liu et al., 2014; Luolavirta et al., 2018b).

The fresh invading magma can interact and mix in various ways with the resident magma or solids. The intensity of mixing is dependent on the rheology contrast between the mingling magmas and on the momentum of the invading melt (e.g., Poli et al., 1996). In other words, intensive mixing can take place between magmas with little difference in composition and temperature (density). If the fresh undifferentiated invading melt is roughly similar in composition to the resident magma in the chamber or if the density contrast between the magmas is decreased, for instance, via fractionation processes, mixing is expected to lead into gradational reversals in mineral or trace element compositions and smooth shifts in isotopic compositions (e.g., Kruger & Marsh, 1985; Eales et al., 1986; Lee & Butcher, 1990; Jensen et al., 1993; Tepley et al., 1999).

In contrast to complex multi-stage evolution, some classic layered intrusions, such as the Skaergaard intrusion (McBirney, 1996) and numerous sill-like intrusions (Latypov, 2003), are considered to result from differentiation of a single batch of magnesian magma. As pointed out by Latypov (2003) and Pang et al. (2009), a “single” magma input can be understood as an influx of magma of a constant composition within a timespan that is much shorter than that of solidification and hence during the course of magma emplacement, the course of crystallization in the main magma body does not significantly change. Even in magma chambers considered to originate by emplacement of a single magma input, heterogenities in minerals and rock successions may develop, e.g., due to convective fractionation, diffusion, supercooling, compaction and percolation of residual liquids and contamination (Maaløe, 1976; Stewart & DePaolo, 1990; McBirney, 1995, 1996; Mutanen, 1997; Humphreys, 2009). An alternative method to evaluate open- and closed-system magma chamber processes is to apply a mass balance approach (e.g., McBirney, 1996; Pang et al., 2009; Liu et al., 2014). For instance, in the Skaergaard intrusion, low Zr contents in low-lying cumulates are balanced by an enrichment higher in the stratigraphy (McBirney 1996). Hence, imbalance either in the major or trace element budget of a cognate suite of rocks may imply that part of residual liquids escaped during the growth of the intrusion.

Some caution needs to be exercised when applying multi-phase histories to a suite of rocks. Magma mixing can take place between layers in compositionally stratified magma chambers, which can lead to a similar outcome as in the case of magma recharge, such as unpredictable mineral assemblages and reverse mineral compositions (Tegner et al., 2006). As been discussed above, changes in pressure, oxygen fugacity or water content during the course of crystallization can significantly change the liquidus minerals and their proportions and compositions. Also, the mineral composition may change due to reaction with percolating melt/fluid or trapped liquid (e.g., Irvine, 1980; Barnes, 1986; Cawthorn, 1996).

Isotopic analyses provide a powerful tool for revealing influxes of isotopically distinct magmas into the magma chamber (e.g., Nielsen et al., 1996; Liu et al., 2014). Furthermore, grain-scale studies, in particular, allow tracking mineral disequilibrium within individual grains or among silicate minerals, aiding in the recognition of i) mixing/mingling of magmas with different isotopic signatures (e.g., Davidson & Tepley, 1997; Tepley et al., 2000; Gao et al., 2015), ii) intrusions of variably contaminated crystal mushes into the magma chamber (Roelofse & Ashwal, 2012; Roelofse et al., 2015), or iii) mixing of co-existing but isotopically distinct crystal mushes (Prevec et al., 2005; Seabrook et al., 2005; Yang et al., 2013b). Yet, isotope compositions may change and crystal disequilibrium can develop in a crystallizing magma undergoing contamination (Tepley & Davidson, 2003), in cumulates affected by late-stage percolating melts/fluids with a different isotopic composition (Chutas et al., 2012; Yang et al., 2013b), and late-stage metasomatic replacement processes (McBirney & Creaser, 2003).

Liquid immiscibility

Silicate liquid immiscibility refers to the separation of silicate magma into two compositionally different liquids that coexist in equilibrium with each other (Roedder, 1979). Silicate liquid immiscibility is considered a rather rare process in natural magmas but, for instance, immiscibility between Fe-rich and silica-rich liquids may occur during differentiation of tholeiitic basalts (Jakobsen et al., 2005; Namur et al., 2012) and be important in the genesis of some granitic magmas (Charlier et al., 2011). Segregation of sulfide liquid from silicate magma (discussed further below) is an example of liquid immiscibility and essential in the formation of magmatic sulfide deposits.

POST-CUMULUS PROCESSES

After development of the initial framework of cumulus minerals, the textural, mineralogical and chemical characteristics of both the cumulate and its minerals can be affected by a variety of post-cumulus processes (for a review, see Sparks et al., 1985). These processes largely comprise the interplay between the solids and melt taking place at the boundary between the accumulated solids and the magma reservoir or deeper in the cumulus pile. Adcumulus growth is one significant phenomenon in cumulate rocks, which is generally considered to take place during late-stage of crystallization via compositional convection, whereby a boyant solute is replaced by undepleted melt from the overlying magma column (Morse, 1986; Tait et al., 1984), or via compaction/cementation of the cumulate pile and expulsion of the intercumulus liquid (Irvine, 1980; McKenzie, 1984; Richter & McKenzie, 1984).

Infiltration metasomatosis is a process where migrating pore magma (or vapor) is expelled from the underlying porous cumulate pile (Irvine, 1980; Boudreau & McCallum, 1992; Mathez, 1995), magma is emplaced later into partially solidified cumulates (Bédard et al., 1988; Tegner & Robins, 1996; Holness et al., 2007), or a fluid phase (chlorite solution, Schiffries, 1982) reacts with the surrounding crystals and modifies their compositions and/or texture and/or mode. In the most spectacular case of crystal-melt reactions, the modal mineralogy of a rock is changed due to displacement and partial melting and resorption of the pre-existing minerals and precipitation of others, leading to replacive cumulates (Irvine, 1982).

The outcome of crystal-melt reactions evidently depends on the volume, composition and nature of the reactant melt. Replacive lithologies are generally recognized as irregular masses, which may transgress magmatic layering, or by juxtaposition of minerals out of chemical equilibrium (Irvine, 1980; Boudreau & McCallum, 1992; Tegner & Robins, 1996). Reaction between trapped liquid and solids or percolation of differentiated intercumulus melts within the cumulate framework will result to post-cumulus overgrowth of the pre-existing minerals, changing their composition to more evolved ones (Irvine, 1980; Barnes, 1986; Cawthorn, 1996) or, as discussed above, isotopic disequilibrium may develop if the reactant melt has a different isotopic composition (Chutas et al., 2012). Because post-cumulus processes may modify the rock in a number of ways, they are important to consider when interpreting lithological, chemical or isotopic data or assessing the evolution and differentiation history of slowly cooled magma chambers.

MAGMATIC Ni-Cu-PGE SULFIDE DEPOSITS

A large proportion of the world´s nickel is produced from magmatic (Fe-Ni-Cu) sulfides associated with mafic and ultramafic intrusions and volcanic rocks. The magmatic sulfide deposits fall naturally into two major groups according to their deposit style: those that are valuable primarily because of Ni and Cu and to those where PGEs are the primary products (Naldrett, 2004; Maier et al. 2001). In addition, other metals, such as Co, Au, can be economically important. The PGE deposits predominantly occur as stratiform ore bodies in large layered intrusions (e.g., the Bushveld and Stillwater Complexes) and tend to be sulfide poor. The Ni-Cu deposits, in contrast, exhibit more complex geometries, are generally sulfide rich and occur in relatively small mafic-ultramafic intrusions (e.g., Norils´k, Pechenga, Jinchuan, Voisey´s Bay, Uitkomst, Kabanga), which are in several cases related to magma conduit systems (Naldrett, 2004; Li et al., 2001; Maier et al., 2001; Arndt et al., 2005; Song et al., 2011). In addition, significant Ni-Cu deposits are found at the base of komatiitic lava flows (e.g., Lesher & Keyes, 2002; Barnes, 2006).

The Ni-Cu-(PGE) deposits are related to different, yet magnesian (komatiite, picrite, basalt) parental magma compositions, giving one basis for the classification of Ni-Cu-(PGE) deposits (Naldrett 2004; Barnes & Lightfoot 2005). The Sudbury ores (Canada) are an exception among the Ni-Cu-PGE deposits, as they are considered to be related to an asteroid impact (Naldrett, 2004). Most of the significant magmatic sulfide deposits appear to related to rift magmatism (e.g., Norils´k, Pechenga, Thompson, Voisey´s Bay, Kabanga, Jinchuan, Duluth Complex) in an intracontinental tectonic setting (Naldrett, 2004; Begg et al., 2010). Convergent tectonic settings have generally been thought unfavorable for the formation of reasonable sized (economic) sulfide deposits. However, the Ni-Cu deposits in the Palaeoproterozoic Kotalahti and Vammala nickel belts in central and southern Finland are clear manifestations of mineralization related to orogenic magmatism (Makkonen, 2015 and references therein). In addition, other notable deposits have been recognized in orogenic provinces, such as Aguablanca (Spain) (Casquet et al., 2001; Tornos et al., 2001; Piña et al., 2006) and Huangshandong (among many others) in the Central Asian Orogenic Belt (e.g., Gao et al., 2013). Hence, attention towards Ni-Cu±PGE occurrences in orogenic terrains has been increasing.

PROCESSES CONTRIBUTING TO THE FARMATION OF MAGMATIC Ni-Cu-PGE SULFIDE DEPOSITS

Extensive studies of Ni-Cu-PGE deposits have revealed certain features that are characteristic of the majority of the deposits. These features and the theoretical aspects related to the formation of magmatic Ni-Cu-PGE deposits are reviewed and discussed by various authors (e.g., Naldrett, 1997; 1999; 2004; 2009; 2010; 2011; Barnes & Lightfoot, 2005; Arndt et al. 2005; Song et al. 2011; Maier et al. 2001; Lightfoot 2007; Maier & Groves, 2011). Briefly, the key factors are: 1) a reasonably high degree of mantle melting generating a parental mafic-ultramafic magma with adequate concentrations of metals, 2) efficient transport of the magma into or onto the crust with minimum prior fractionation of olivine or sulfides, 3) contamination of the magma with crustal materials, aiding sulfide saturation, 4) interaction of sulfides with a large volume of magma resulting in enrichment of the sulfides in metals and 5) mechanical concentration of sulfides to economic levels (see Fig. 3 for summary). Although, these processes broadly apply to both PGE and Ni-Cu ore genesis, the focus herein is on Ni-Cu ores hosted by mafic-ultramafic intrusive bodies.

Magma generation and ascent

In order to form an economic Ni-Cu-PGE deposit, the primary magma must contain adequate amounts of ore metals. Such metal-rich mafic-ultramafic magmas are generated in the mantle having an average Ni content of approximately 2000 ppm and a total PGE content of 24 ppb (McDonough & Sun, 1995). Olivine is the major mineral of the mantle (~70%), incorporating most of the mantle nickel in its crystal lattice. Hence, when olivine melts, Ni is released to the melt, with the Ni content of the melt increasing as a function of the degree of melting (Fig. 4a). Copper and PGEs in the mantle are mainly hosted by the sulfide phase and hence their contents in the melt during mantle melting depend on the amount of dissolved sulfur. The solubility of sulfur in most mafic and ultramafic magmas is fairly low (~500 to 1000 ppm Mavrogenes & O'Neill, 1999) at high pressures, and according to the model calculations, approximately 18% (Naldrett, 2009, Fig. 2a) to 20-40% (Barnes & Lightfoot, 2005) of melting is required to dissolve all the sulfide in the mantle. At that point, Cu and PGEs reach their maximum concentrations in the melt but will be diluted with further melting whereas Ni continues to progressively increase in the melt, resulting in an increase in the Ni/Cu ratio of the melt. The Ni/Cu ratio of a deposit reflects the silicate magma composition from which it crystallized; for komatiite- and picrite-hosted deposits, Ni/Cu is generally higher than 3, reaching 20 in deposits generated from highly magnesian komatiites, and <2 in deposits linked to more evolved magma compositions (Barnes

& Lightfoot, 2005). The estimated MgO contents of the parental magmas for most of the Ni-Cu-PGE deposits are >8 wt.% (Naldrett 2010), which is broadly in line with the above theoretical consideration according to which a relatively high degree of partial melting is required for the magma to obtain high concentrations of Ni, Cu and PGE. Generation of large volumes of high-degree partial melts is generally linked to mantle plume events (e.g., Campbell, 2005).

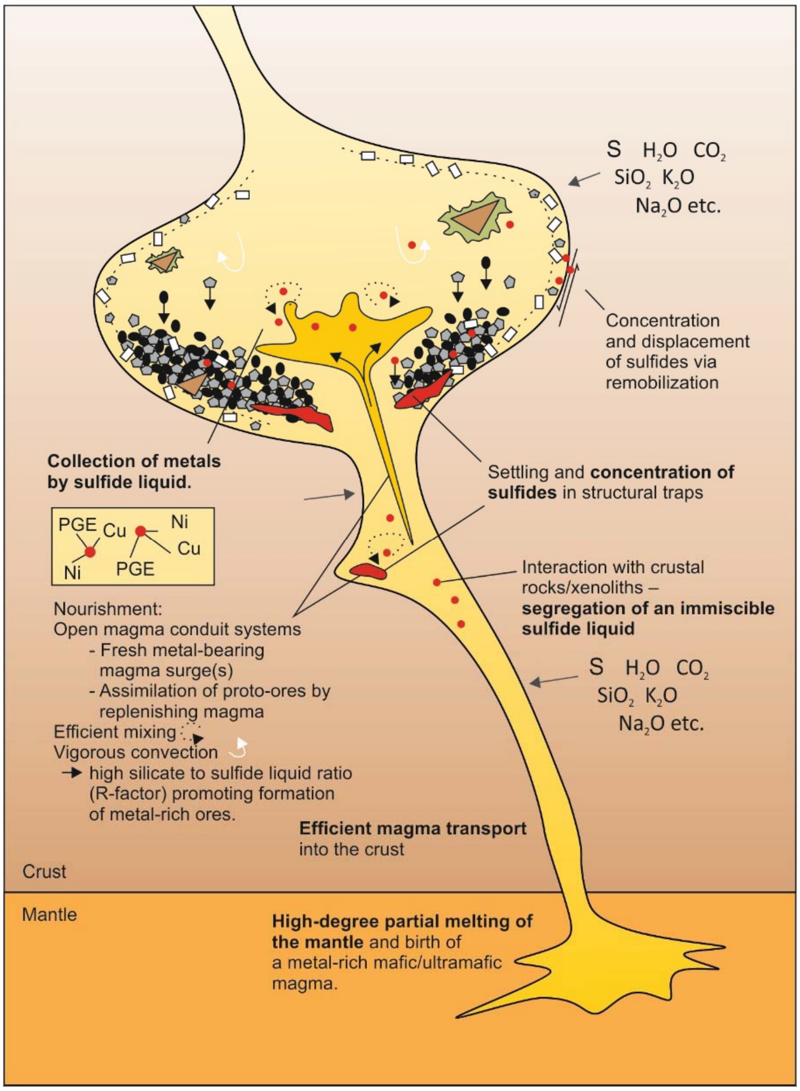


Fig. 3 Simplified sketch showing the development of magmatic Ni-Cu sulfide deposits.

Many of the large Ni-Cu-PGE deposits occur in a close proximity to major crustal lineaments (e.g., Norils´k, Jinchuan, Voisey´s Bay, Duluth) representing major faults, rifts or shear zones, denoting the importance of prominent crustal structures for efficient magma transport into (or onto) the crust (Barnes & Lightfoot, 2005; Begg et al., 2010; Maier & Groves, 2011). Rapid transport of magma prevents significant segregation of olivine and/or sulfides and resulting decrease in the metal budget of the magma (Fig. 4b).

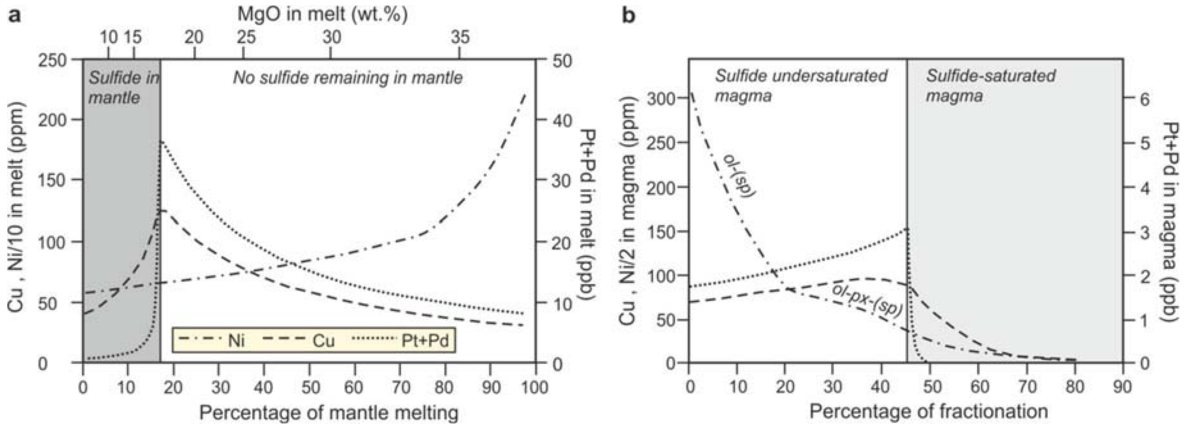


Fig. 4 Concentrations of Ni, Cu and Pt+Pd in the magma a) with increasing degree of partial melting of mantle peridotite (increasing MgO content of the partial melt) and b) as a function of crystal fractionation of a high- Mg basaltic magma (14 wt.% MgO) attaining S saturation after 45% of crystallization. Modified after Naldrett (2009).

Attainment of sulfide saturation

Several experimental studies have demonstrated that the solubility of sulfur in mafic magmas is controlled by a variety factors, notably the pressure, temperature, oxygen fugacity, and magma composition including its water content (e.g., Haughton et al., 1974; Carroll & Rutherford, 1985; Mavrogenes & O'Neill, 1999; O'Neill & Mavrogenes, 2002; Liu et al., 2007; Fortin et al., 2015). It is well documented that the solubility of sulfide in a mafic magma increases with falling pressure while falling temperature has an opposite, yet less notable effect (e.g., Mavrogenes & O'Neill, 1999). The effect of oxygen fugacity to the sulfur solubility become considerable under redox conditions above the Ni-NiO buffer (NNO +1.5) when the sulfide (S^{2-}) in the melt is transitioned into sulfate (S^{6+}), increasing the magma´s ability to dissolve sulfur (e.g., Carroll & Rutherford, 1985). Magma composition, particularly its ferrous iron (Fe^{2+}) content, has a strong influence on the sulfur solubility due to the favorable bonding of Fe^{2+} and S^{2-}, resulting in positive correlation between the iron content and sulfur solubility in the melt (Haughton et al., 1974; Carroll & Rutherford, 1985; O'Neill & Mavrogenes, 2002). However, it has been recognized that bonding of S with cations (Mg, Ca, Fe, Na, K) other than Fe is also feasible (e.g., O'Neill & Mavrogenes, 2002). Fortin et al. (2015) also showed that the sulfur solubility increases in magmas with higher concentrations of water. The sulfur solubility in silicate melts is generally expressed as the sulfur concentration at sulfide saturation (SCSS), which represent the maximum amount of sulfur a melt can dissolve before sulfide phases segregate. Presently, there are various empirical equations based on the major element composition of the silicate melt to calculate SCSS (see e.g. Fortin et al., 2015).

As mentioned above, the ability of the magma to dissolve sulfur increases with falling pressure. Consequently, regardless of whether the magma was saturated with sulfur or not upon leaving its source, it is likely to be S-undersaturated when approaching the surface. Hence, at a reasonably shallow crustal level, an additional process is required to bring the magma to sulfide saturation. These processes are reviewed e.g. by Ripley & Li (2013). In the simplest case, fractional crystallization of silicates increases the S concentration in the melt and eventually sulfide melt segregates in a "cotectic" proportion from the silicate melt. Model calculations suggest that for most primitive melts, sulfide saturation occurs after ~20-45% of crystallization (Barnes & Lightfoot, 2005; Naldrett, 2009; Ripley & Li, 2013) at a stage when most of the Ni has been partitioned into the silicates (olivine) (Fig. 2b). Therefore, generation of significant amounts of Ni-bearing sulfides as a result of crystal fractionation is generally considered improbable, yet ores rich in PGE and Cu may form.

In the case of magmatic Ni-Cu deposits, the sulfide immiscibility is in most cases related to interaction of the magma with crustal rocks. This interaction may lead to a decrease in magma´s ability to dissolve sulfur due to changes in its chemical composition and/or assimilation of external sulfur in the magma from sulfide-bearing country rocks. The contamination processes affecting the sulfur solubility may involve assimilation of volatiles (H_2O, CO_2, CH_4, H_2S) and addition of silica and alkalies from siliceous country rocks (Ripley & Li, 2013).

There is general consensus that the most efficient way to induce sulfur saturation in mafic/ultramafic magmas is to increase the S concentration in the melt. A great number of Ni-Cu deposits are associated with S-bearing country rocks providing a potential source of external sulfur. These include Kabanga (Maier at al., 2010), Pechenga (Barnes et al., 2001; Hanski et al., 2011), Voisey´s Bay (Li & Naldrett, 1999), and Noril´sk (Ripley et al., 2003) and in Finnish Central Lapland, Kevitsa (Mutanen, 1997), Sakatti (Brownscombe et al., 2015), and Lomalampi (Törmänen et al., 2016) deposits. Sulfur isotope analyses are widely applied to determine the source of sulfur in magmatic systems. The S isotopic composition ($\delta^{34}S$) is reported as $^{34}S/^{32}S$ in ‰ relative to the ratio in the V-CDT (Vienna Canyon Diablo Troilite) standard, expressed as

$$\delta^{34}S = \frac{^{34}S/^{32}S_{\text{sample}}}{^{34}S/^{32}S_{\text{V-CDT}}} \times 1000 \tag{2}$$

Sulfur in the mantle generally shows $\delta^{34}S$ values in the range of -2 to +2‰ (Ripley and Li 2003), and isotopic compositions distinct from the predicted mantle values (either heavier or lighter) indicate the presence of external sulfur. Sulfur isotopic data from most economic Ni-Cu deposit suggest that sulfur is at least partly derived from crustal sources (Fig. 5). There are only few magmatic Ni-Cu-(PGE) sulfide deposits that lack the association of sulfidic country rocks or definite crustal S isotopic signatures, notably Nabo-Babel (Seat et al., 2009) and Jinchuan (Ripley et al., 2005; Lehmann et al., 2007). In the case of the Nebo-Babel ore deposits, addition of silica is proposed as the primary cause of sulfide saturation (Seat et al., 2009). Lehmann et al. (2007) suggested that assimilation of carbonate-rich fluids increased the oxygen fugacity of the Jinchuan magma, resulting in the formation of the sulfide ores. However, a small number of S isotope data on Jinchuan ores show heavy $\delta^{34}S$ values (Ripley et al., 2005) and the application of the more recently developed multiple sulfur isotope analysis has revealed anomalous $\Delta^{33}S$ values (Duan et al., 2016). This implies that the sulfur in Jinchuan ores is at least in parts derived from crustal sources. Regardless of the mechanism promoting sulfur saturation, the amount of sulfide liquid produced without external sulfur (mantle-sulfur only) is expected to be small (~1.5%) (Barnes, 2007; Ripley & Li, 2013) and formation of a significant high-tonnage Ni-Cu-PGE deposit would require a highly efficient sulfide collection mechanism from a large volume of metal-bearing magma (discussed further below).

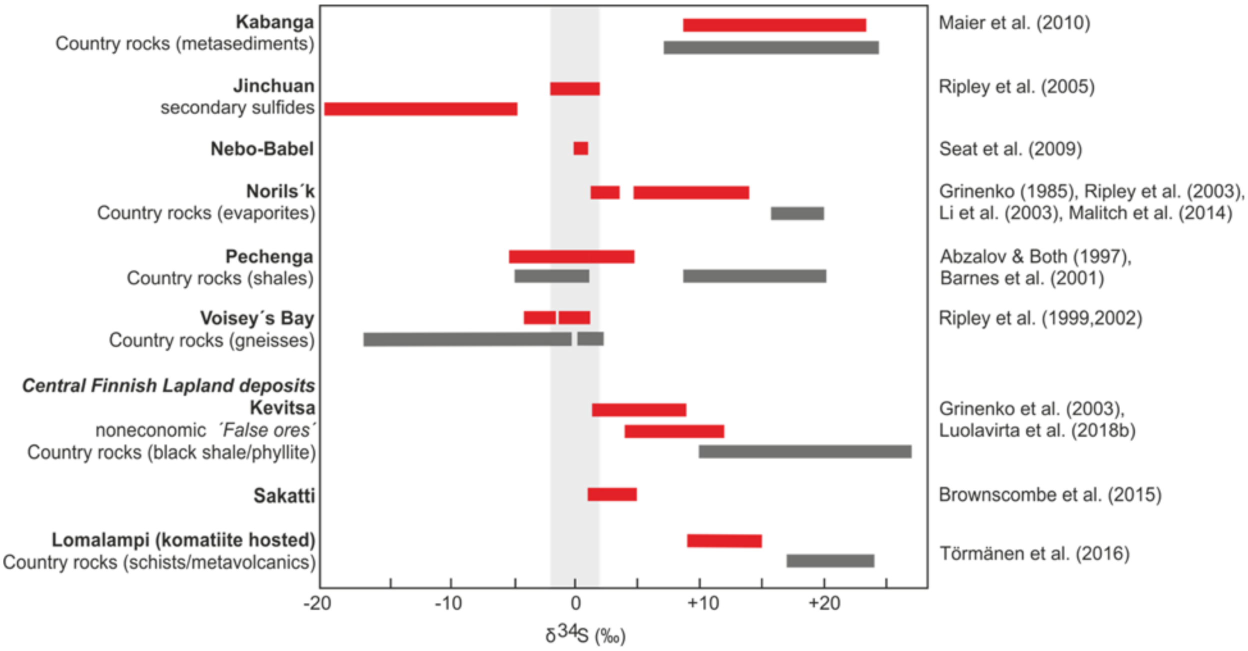


Fig. 5 Examples of sulfur isotope compositions in magmatic Ni-Cu±PGE sulfide deposits and their country rocks. The gray vertical column indicates the range of isotope values of typical mantle sulfur.

Collection of metals by sulfides

When immiscible sulfide liquid segregates from the silicate magma, chalcophile elements partition preferably into the sulfide melt. The concentration of these elements in the sulfide melt depends on i) their concentration in the silicate melt, ii) the sulfide melt-silicate melt partition coefficients of the elements (D), and iii) the so-called R-factor, which expresses the silicate melt/sulfide melt mass ratio, i.e. the amount of silicate liquid with which the sulfide melt equilibrated (Campbell & Naldrett, 1979). In brief, a high volume of silicate magma relative to that of the sulfide liquid (high R-factor) is required to generate ore-grade sulfides. The effects of R-factor depend on the D values, being more pronounced for elements, which have high sulfide liquid/silicate liquids partition coefficients, particularly PGE. For further information and utilization of the R-factor, the reader is referred to Naldrett (2004) and Barnes & Lightfoot (2005), for example.

The contents of Ni, Cu and PGE in many sulfide ores are higher than what would be expected for sulfide that had separated from the volume of magma equivalent to the size of their host intrusions (Campbell & Naldrett 1979; Naldrett et al., 1992). Therefore, the sulfide liquid must have collected metals from a much larger volume of silicate magma. Such upgrading processes are likely to take place in open magma conduit systems where sulfides can interact and equilibrate with repeated new (undepleted) magma pulses (e.g., Naldrett et al., 1996; Maier et al., 2001). For some deposits, it has been proposed that they formed by assimilation of earlier-formed proto-ores that had accumulated in a conduit system or staging magma chamber. For example, Voisey´s Bay (Li & Naldrett, 1999) and Kabanga (Maier & Barnes, 2010) deposits and the unusually high PGE grades at Noril´sk (Naldrett, 2004) are attributed to such processes.

One widely adopted approach to assess the sulfide segregation history of igneous bodies is to study the nickel-Fo relationship of olivine (Li & Naldrett, 1999; Li et al., 2002, 2003, 2004, 2007, 2013; Thakurta et al., 2008; Luolavirta at al., 2018b). Nickel is compatible in olivine (partitioning coefficient $D^{Ni}_{olivine/melt}$ ~4.5─25; Hart & Davis, 1978; Kinzler et al., 1990; Gaetani & Grove, 1997) and decreases in olivine together with its Fo content during olivine fractionation (Fig. 4b and 6). However, Ni behaves as a chalcophile element when sulfur is available. Empirical and experimental determinations of $D^{Ni}_{sulf/sil}$ vary from 100 in high-MgO komatiitic melts (Lesher and Campbell, 1993) to ~1000 in basaltic melts (Peach et al., 1990; Patten et al., 2013). If sulfide saturation occurs with or without olivine precipitation, Ni readily partitions into the sulfide phase. Consequently, the magma´s Ni content decreases rapidly and olivine crystallizing from that magma will have a nickel content that is lower than that predicted by "normal" crystal fractionation under sulfur-undersaturated conditions (Fig. 6). Alternatively, chalcophile element ratios, such as Cu/Pt or Cu/Pd, can be applied to evaluate the sulfide saturation history of magmas (e.g., Li et al., 2001; Maier et al., 1998; Song et al., 2009; Yang et al., 2012). The PGEs have much higher D values than that of Cu ($D^{Cu}_{sulf/sil}$ ~250–1400: Francis 1990; Gaetani and Grove 1997; $D^{PGE}_{sulf/sil}$ ~10^4–10^5: Peach et al. 1990; Fleet et al. 1991; Ballhaus et al. 1994) and therefore after precipitation of even a small amount of sulfide, the PGE content of the magma will decrease much more rapidly than that of Cu, causing the Cu/Pt or Cu/Pd ratios to increase in the evolving magma.

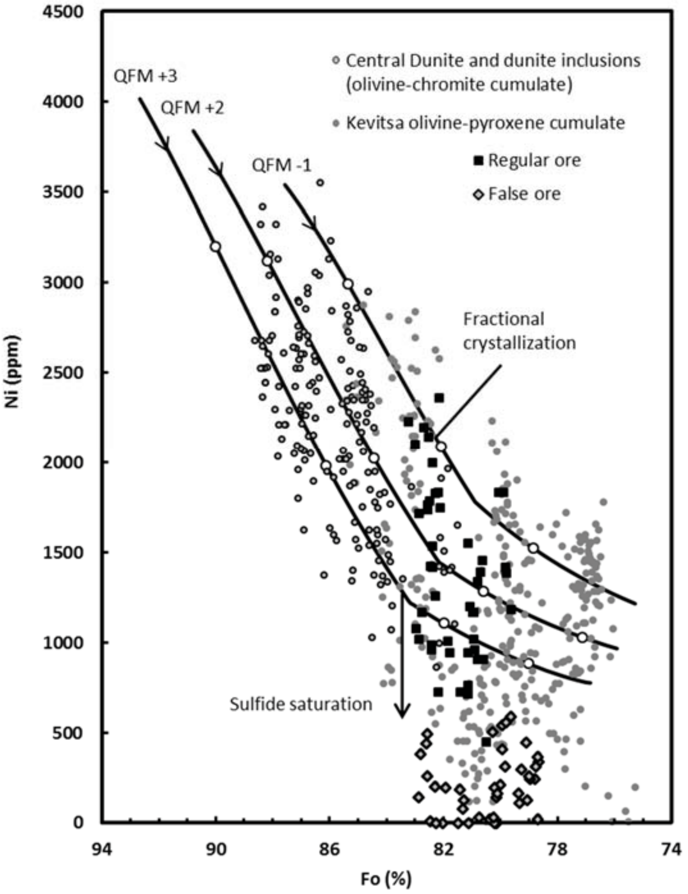


Fig. 6 Plot of nickel vs. forsterite (Fo%) contents of olivine in Kevitsa intrusive suite rocks compared with theoretical olivine compositional trends calculated at QFM+3, QFM+2 and QFM-1 for a picritic parental magma containing 700 ppm Ni. White dots in model curves refer to 10, 20, 30 and 40 percentages of fractional crystallization. Separation of sulfide liquid results in decrease the Ni content of the silicate magma and crystallization of olivine with depleted Ni concentrations. Figure is from Luolavirta et al. (2018b).

Concentration of sulfides

To form an economically viable sulfide deposit, the sulfide droplets need to be collected and concentrated in a restricted locality within the magmatic system (conduit, intrusion, lava channel), as otherwise, the rocks may contain widespread disseminated sulfides with an insufficient grade to be regarded as an ore. Being denser than the silicates, sulfide droplets tend to migrate downwards by gravity and accumulate towards the base of their host intrusion or lava flow. Sulfides are efficiently collected in structural traps (e.g., Barnes & Lightfoot, 2005), such as embayments in the footwall (Noril´sk-Talnakh; Diakov et al., 2002) or sites where a feeder conduit spreads or enters the intrusion (Voisey´s Bay; Li & Naldrett, 1999). At such localities, the flow rate of the magma is reduced, which decreases its capacity to carry dense sulfide droplets, leading to gravitational settlement of the droplets from the magma. The physical properties and mechanisms of collection of immiscible sulfide liquid and the constraints of percolation of sulfides within the framework of silicate minerals are discussed in detail by Mungall & Su (2005), Barnes et al. (2008), and Chung & Mungall (2009), for example.

Deformation and metamorphism may play a role in further concentration of sulfides and modifying their mineralogical and chemical composition (Barnes & Lightfoot, 2005). Post-magmatic modification and oxidative upgrading of the metal content of sulfides appear particularly important in some komatiite-hosted deposits (Barnes & Hill, 2000; Barnes et al., 2009; Konnunaho et al., 2013).

PREVIOUS STUDIES OF THE KEVITSA INTRUSION AND RELATED Ni-Cu-(PGE) MINERALIZATION

The Kevitsa deposit was discovered in 1987 by the Geological Survey of Finland (GTK), which was followed by extensive exploration campaigns over the following 20 years. A mine decision was made in 2009 by First Quantum Minerals Limited (FQM Ltd) and metal production started in 2012. The exploration and development history of the Kevitsa mine is summarized by Santaguida et al. (2015). During the course of this study in 2016, the ownership of the Kevitsa mine was shifted from FQM Ltd to Boliden AB.

The first detailed description of the geology of the Kevitsa intrusion was published by Mutanen (1997) who also classified the Kevitsa ore types to regular, Ni-PGE, false and contact type mainly based on the Ni-tenor (see Table 1). The chemical and mineralogical evidence for crustal contamination, including the REE data, was discussed in detail and a magmatic model involving differentiation of a single cast of basaltic magma and in-situ assimilation with sulfide-rich pelites, black shale and komatiitic rocks was proposed as an explanation to the lithological and compositional variations within the ultramafic cumulates. Accordingly, the ore formation was attributed to various sources of contaminants, resulting in a continuous range of ore compositions from low Ni-tenor ore (false ore) via regular ore to high Ni-tenor type (Ni-PGE ore) reflecting incorporation of components from the sedimentary and komatiitic end members.

Gervilla & Kojonen (2002) conducted a study of platinum-group minerals (PGM) in sulfide-bearing rocks at Kevitsa and noted that the PGMs were compositionally highly variable and tend to occur included in secondary hydrous silicates. The authors concluded that hydrothermal mobilization of PGE, possibly by chlorine-bearing fluids, resulted in modification of the primary magmatic concentrations of these elements and formation of PGE-rich ores (Ni-PGE ore type). Le Vaillant et al. (2016) studied the effects of hydrothermal alteration on the distribution of base and noble metals within the Kevitsa deposit and, in contrast to Gervilla & Kojonen (2002), argued that no significant mobilization of Ni or PGEs has occurred but Cu (and Au) may have been mobile. Although Le Vaillant et al. (2016) observed some decoupling between Pt, Pd and IPGE (iridium-group platinum-group elements) in the Ni-PGE ore type, which could be attributed to hydrothermal alteration and addition of Pd and Pt to the ore type, the undisturbed magmatic correlation between Pt and Pd argue against any large-scale redistribution.

Grinenko et al. (2003) conducted the first comprehensive stable isotope study involving S and C isotope analyses of the Kevitsa cumulates and country rocks. They obtained heavy S-isotopic compositions for both “barren” rocks (δ^{34}S up to 9.3‰ on average) and ores, with the regular, Ni-PGE and false ore types yielding average δ^{34}S values of +3.8‰, +6.1‰, and +8.2‰, respectively. These data indicate substantial derivation of sulfur in the ore from crustal sources. The contents of low-temperature and high-temperature carbon and δ^{13}C values were similar in barren and ore-bearing ultramafic cumulates. The reported isotope compositions of the sedimentary country rocks hosting the Kevitsa intrusion show an average δ^{34}S value of +18‰. The authors marked decoupling in S and C isotope compositions and C contents between the Kevitsa ores and sediments directly enclosing the intrusion and concluded that these sedimentary rocks could not act as the main source of sulfur and that the magma assimilated a sedimentary source at depth and during its ascent into the Kevitsa magma chamber.

Table 1 summarizes typical chemical, isotopic and mineral compositional properties of the different ore types at Kevitsa. REE characteristics together with preliminary Nd, Os and S isotopic compositions of the Kevitsa ores were given by Hanski et al. (1997), and new Nd isotope data on the Kevitsa ores are provided by Huhma et al. (2018). The host rocks to the Ni-PGE ore type reveal to be markedly different in comparison to the host rocks to the regular and false ores by their highly negative ε_{Nd} value and notable LREE enrichment. Also, the olivine in the Ni-PGE ore type is characterized by relatively high Fo contents and shows extremely high Ni contents (Mutanen, 1997; Yang et al. 2013a). Yang et al. (2013a) proposed a model for the Ni-PGE ore, involving assimilation of Ni sulfide-bearing komatiitic inclusions and crystallization of silicates from a Ni-enriched magma. This model is in line with considerations by Lamberg et al. (2005) who applied Ni# and Co# to the Kevitsa ores and suggested that the composition of the Ni-PGE ores reflect mixing of tholeiitic and komatiitic materials.

Table 1 Characteristics of the Kevitsa Ni-Cu-(PGE) sulfide ores and their host rocks.

	Regular ore	**Ni-PGE ore**	**False ore**	**Reference**
Ni tenor	4–7%	6–60%	<4%	Mutanen (1997), Yang et al. (2013a), Santaguida et al. (2015)
Ce_N/Yb_N (avg)	2.0–2.2	7	2.0–2.2	Hanski et al. (1997), Luolavirta et al. (2018a)
ε_{Nd} (avg)	-3.4	-6.4	-3.4	Huhma et al. (2018)
$\delta^{34}S$ ‰ (avg)†	+3.8	+6.1	+8.2	Grinenko et al. (2003)
$\delta^{34}S$ ‰ (avg)*	+4.1	+2.7	+6.6	Luolavirta et al. (2018b)
Fo% olivine	77–84	84–90	76.5–83	Mutanen (1997), Yang et al. (2013a), Luolavirta et al. (2018a)
Ni (ppm) in olivine	700–2500	3000–14 000	<1000	Mutanen (1997); Yang et al. (2013a); Luolavirta et al. (2018a,b)

* in-situ, † whole-rock

The geometry of the Kevitsa intrusion and its internal lithological contacts and structures have been accessed by reflection seismic measurements conducted by Koivisto et al. (2012, 2015). These geophysical investigations have revealed a deep southern continuation of the intrusion. Later drilling has confirmed the existence of previously unknown cumulate successions to a depth beyond 1.7 km but given the timing of these recent findings, they are not included in this study. Also internal seismic reflections were observed within the ultramafic cumulate succession and inferred as boundaries of differentiated magma pulses.

Recently, Le Vaillant et al. (2017) applied mathematical techniques (i.e. continuous wavelet transform and tessellation) to the large assay data base of the Kevitsa mine. The authors used Ni and Pd tenor variations and utilized the tessellation method to reduce the number of units in drill holes and constructed a simplified geological model for the deposit. Based on this modelling, an inwards-dipping cryptic layering in sulfide composition and an overall increase in metal tenors from the bottom upwards were observed. The authors interpreted this to reflect a progressive increase in silicate-sulfide mixing efficiency during the evolution of the Kevitsa intrusion from a sill-like complex into a widened convecting magma chamber.

REVIEW OF THE ORIGINAL ARTICLES

Paper I: Santaguida, F., Luolavirta, K., M. Lappalainen, M., Ylinen, J., Voipio, T., Jones, S. (2015) The Kevitsa Ni-Cu-PGE Deposit in the Central Lapland Greenstone Belt in Finland. In: Maier, W., Lahtinen, R., O´Brien, H. (ed.) Mineral Deposits of Finland, Elsevier, Amsterdam, p. 195–210.

The first paper is part of the book Mineral Deposits of Finland and describes the general features of the Kevitsa Ni-Cu-PGE sulfide deposit and its host rocks. The Kevitsa Mine is based on a magmatic Ni-Cu-PGE sulfide deposit hosted by a composite ultramafic-mafic intrusion within the Central Lapland greenstone belt. The deposit was discovered in 1987 by GTK and the mining was started by First Quantum Mineral Ltd in 2012. The expected life time of the mine is more than 20 years, with an annual output in the range of 17 000–19 000 t for copper, 9000–10 000 t for nickel, 12 000–13 000 oz for gold, and 22 000–24 000 oz for both platinum and palladium.

The Kevitsa Ni-Cu-PGE mineralization is concentrated in the center of the intrusion as an irregular shaped sulfide ore body. The mineralization is predominantly composed of disseminated pentlandite and chalcopyrite occurring together with pyrrhotite and magnetite showing a generally well preserved magmatic texture. The mineralization show variation in terms of Ni, Cu and PGE contents and according to Mutanen (1997) four distinct ore types are recognized, namely regular ore, Ni-PGE ore, transitional ore and false ore. In mine modeling the regular ore has Ni tenor of 4–7%, Cu/Ni >1 and PGE contents less than 1 g/t and the Ni-PGE ore is characterized by Ni tenor >10. Drilling and resource modeling indicate the transitional ore is not a true ore type but represents a low grade Ni-PGE ore. Besides different ore types Ni-Cu variability can be high on a local scale (20m x 20m) but overall Ni-rich mineralization (Ni-PGE ore) is prominent at depth and in the southern proportion of the ore body and Cu-rich type (regular ore) typically occur in the central parts. The regular ore comprises 95% of the resources. False ore is dominated by pyrrhotite and show low Ni tenor (2–3%). Low Ni-tenor sulfides are also encountered immediately above the base of the intrusion, called contact ore.

Olivine websterite is the dominant rock type of the ultramafic lower part of the intrusion (~1km thick) and host rock for the sulfide mineralization. Compositional variations within the ultramafic cumulates are minor but discrete lithological units of pyroxenite, plagioclase-bearing (olivine) websterite and basal pyroxenite-gabbro can be mapped. Amphibole and serpentine-chlorite alteration is prevalent throughout the intrusion and locally obscures recognition of primary rock types. The most intense alteration appears to be associated with late mafic veins and dykes and overall does not impact the distribution of metals at the deposit-scale.

Paper II: Luolavirta, K., Hanski, E., Maier, W., Santaguida, F (*in press*) Characterization and origin of dunitic rocks in the Ni-Cu-(PGE) sulfide ore-bearing Kevitsa intrusion, northern Finland: whole rock and mineral chemical constraints. Bulletin of the Geological Society of Finland.

This paper focuses on constraining the origin of dunitic rocks in the Ni-Cu-(PGE) sulfide-bearing Kevitsa intrusion, which occur as numerous inclusions within the Kevitsa olivine-pyroxene cumulates and as a separate dunite body (termed Central Dunite) in a close spatial association with the Kevitsa intrusion. In particular, the possible genetic link between the Central Dunite and Kevitsa intrusive successions is addressed. Furthermore, the inclusions are of special interest because they appear to be most abundant within the ore domain, implying a potential relationship between the presence of the inclusions to the sulfide ore genesis.

Textural characterization reveals two distinct types of inclusions: i) cumulate-textured (termed Kevitsa Dunite) and ii) recrystallized ultramafic inclusions. The latter are further divided into two subgroups (Group 1 and Group 2) based on the mineralogy, whole-rock chemistry and spatial distribution within the Kevitsa intrusion. The Central Dunite and Kevitsa Dunite are texturally and mineralogically similar olivine-chromite cumulates and show similar whole-rock and mineral compositions, suggesting that they are cogenetic. Evidence for a magmatic rather than replacement origin of the dunitic cumulates is given by their more primitive mineral composition compared to Kevitsa olivine pyroxenites, as well as mineral compositional trends involving Fo, MnO and Ni in olivine and Mg# and Cr_2O_3 in clinopyroxene, which are consistent with magmatic fractionation. The whole-rock major and trace element compositions and mineral differentiation indices of the dunitic cumulates and Kevitsa olivine pyroxenites fall on the same linear trends and both record similar REE characteristics indicating a genetic link between these two. A two-stage magmatic origin is proposed to explain the field characteristics and compositional trends of the dunitic cumulates and Kevitsa ultramafic successions. The parental magmas for the dunitic cumulates were probably picritic and relate to the picritic basalt volcanic rocks that occur in the vicinity of Kevitsa intrusion. The observed high Fo content of olivine (~89 mol.%) is consistent with a high-Mg parental melt.

The recrystallized ultramafic inclusions are fine grained and show a granoblastic texture indicative for thermal textural readjustment. Group 1 recrystallized inclusions show a chemical affinity towards the dunitic cumulates and are interpreted as their recrystallized clasts. Group 2 recrystallized inclusions are compositionally comparable to the immediate mafic-ultramafic volcanogenic country rocks of the Kevitsa intrusion as well as to the komatiitic volcanic rocks in the CLGB and are interpreted as dehydrated metavolcanic country rock xenoliths.

The increased viscosity and decrease in the flow rate of the Kevitsa magmas due to entrapment of a high number of inclusions is proposed as a mechanism to promote settling of sulfides, contributing to the formation of the Ni-Cu-PGE sulfide deposit.

Paper III: Luolavirta, K., Hanski, E., Maier, W., Santaguida, F. (2018) Whole-rock and mineral compositional constraints on the magmatic evolution of the Ni-Cu-(PGE) sulfide ore-bearing Kevitsa intrusion, northern Finland. Lithos 296–299, 37–53.

The third paper utilizes the large data base of the Kevitsa mine and aims to improve the understanding of the internal architecture of the Kevitsa intrusion and petrology of its constituent rocks and host rocks to the sulfide ore. Mineral compositional profiles were constructed on selected representative drill cores, which together with whole-rock compositional profiles were utilized to evaluate the emplacement of the Kevitsa magmas (open vs. closed system).

In the studied drill cores located few hundred meters outside the current resource domain, the ultramafic cumulate successions record a simple lithological stratigraphy, which includes from the base upwards a basal pyroxenite-gabbro, olivine pyroxenite, pyroxenite, and gabbro (gabbro is intersected in one of the studied drill cores). Also the variations in whole-rock and mineral compositions (olivine and pyroxenes) are modest and predictable. The deposit area, in contrast, is characterized by a complex internal architecture manifested by lithological variations, numerous dunitic inclusions and xenoliths, and pronounced cryptic variations in whole-rock and mineral compositions. The contrasting lithological and compositional stratigraphy obtained from the different parts of the intrusion likely reflects different emplacement histories. It is proposed that the Kevitsa magma chamber was initially filled by stable continuous flow ("single" input) of basaltic magma followed by differentiation in at least nearly closed system. In the following stage, magmas were repeatedly emplaced into the interior of the intrusion in a dynamic (open) system forming the sulfide ore bodies.

The olivine pyroxenites are mainly composed of cumulus olivine (Fo_{77-89}) and clinopyroxene ($Mg\#_{81-92}$) with variable amounts of oikocrystic orthopyroxene ($Mg\#_{79-84}$). They comprise the bulk of the ultramafic cumulates and are the dominant host rocks to the sulfide ore. The host rocks to the regular and false ore type mineralization are mineralogically and compositionally similar ($Fo_{\sim 80-83}$, mostly) and show mildly LREE-enriched REE patterns (Ce_N/Yb_N ~2), characteristic of the bulk of the Kevitsa ultramafic cumulates. The abundance of orthopyroxene and magnetite is lowest in the host rocks to the Ni-PGE ore type, being in line with the mineral compositions of the silicates, which are the most primitive found in the intrusion. However, it contradicts with the LREE-enriched nature of the ore type (Ce_N/Yb_N ~7), which indicates a significant component of crustal material in the magma. To gain the peculiar compositional and mineralogical characteristics of the host rocks to the Ni-PGE ore type, the parental magma probably interacted with different country rocks en route to the Kevitsa magma chamber.

Paper IV: Luolavirta, K., Hanski, E., Maier, W., Lahaye, Y., O´Brien, H., Santaguida., F. (2018) *In-situ* strontium and sulfur isotope investigation of the Ni-Cu-(PGE) sulfide ore-bearing Kevitsa intrusion, northern Finland. Mineralium Deposita

The fourth paper reports *in-situ* Sr and S isotopic compositions of the Kevitsa ultramafic cumulates in order to investigate the isotopic variation across the cumulate stratigraphy and the potential existence of isotopically distinct magmas and the relationship of contamination and ore-forming processes. The Sr isotope compositions of intercumulus plagioclase and S isotope compositions of pyrrhotite (and pyrite) were analyzed by LA-MC-ICP-MS at the Geological Survey of Finland.

This study shows that the $^{87}Sr/^{86}Sr_{(i)}$ values of the Kevitsa ultramafic cumulates are highly radiogenic (>0.7045) in comparison to the estimated depleted-mantle Sr isotope ratio of ~0.702 at 2.06 Ga, implying strong involvement of crustal material in their genesis. The $^{87}Sr/^{86}Sr_{(i)}$ values obtained from the ore-bearing part of the intrusion show stratigraphic variations and exceed 0.705 with the maximum value reaching up to 0.711. In contrast, in rocks around the ore body, the initial Sr isotope compositions remain relative constant (0.705-0.706) throughout the intrusive stratigraphy. Also marked differences in $^{87}Sr/^{86}Sr_{(i)}$ between different ore types are observed; the regular and false ore have $^{87}Sr/^{86}Sr_{(i)}$ values of 0.705-0.707, while the Ni-PGE ore type shows much higher values of 0.709-0.711. These Sr isotope compositions are in line with the ε_{Nd} values of -6.4 obtained for Ni-PGE ore and -3.4 for regular and false ore types (Huhma et al., 2018).

In-situ sulfur isotope measurements reveal that both the ore-bearing samples and "barren" rocks are similar in their sulfur isotope compositions, with $\delta^{34}S$ being generally >2‰, suggesting that the Kevitsa magma assimilated sulfur from country rocks. The regular and Ni-PGE ore record median $\delta^{34}S$ values of +4‰ and +2.6‰, respectively. The heaviest S isotopic compositions are measured from the false ore with median $\delta^{34}S$ of +6.5‰. The non-mantle like S-isotope compositions indicate external sulfur played an important role in triggering sulfide saturation. No correlation is observed between the strontium and sulfur isotope compositions, indicating that the contamination of the silicate magma and assimilation of sulfide were at least partly separate processes.

The obtained isotope data from different locations of the intrusion are well in line with the whole-rock and mineral compositional profiles recording relatively homogeneous compositions in rocks around the ore body but marked variation within the deposit domain (Luolavirta et al., 2018a). This indicates that the ore-bearing domain represents a dynamic site with multiple injections of variably contaminated magma whereas the surrounding intrusion experienced a less vigorous emplacement history.

The low level of metals in pyrrhotite-dominated sulfide ores ("false ore") and the Ni-depleted nature of its olivine suggest that some sulfides may have precipitated and deposited in the feeder conduit during the initial stage of magma emplacement. Assimilation of early-formed sulfides by later magma injections may have been important in the formation of the main mineralization.

DISCUSSION AND CONCLUDING REMARKS

The main objective of this PhD study was to formulate a geologic model for the formation of the Kevitsa intrusive suite rocks and its ore deposit. The large lithogeochemical database of the mine, comprehensive drill core logging and sampling, and mineral chemical and Sr isotopic analyses from various parts of the intrusion allowed construction of the internal architecture and stratigraphy of the intrusion and examination of the processes operating during filling and crystallization of the Kevitsa magma chamber. This petrological data together with new in-situ S isotope data are further utilized in the discussion of the sulfide ore-forming processes. In addition, attention was paid to a separate dunite body that is associated with the Kevitsa intrusion and numerous ultramafic inclusions and xenoliths within the Kevitsa intrusion. The inclusions are particularly common within the ore domain of the intrusion, indicating a possible linkage to the sulfide ore genesis.

There are several lines of evidence for operation of open magma chamber processes (magma recharge and mixing) during evolution of igneous rock suites, including unexpected shifts in the order of appearance of fractionating mineral phases or their modes (Kruger, 2005; Namur et al., 2010), stratigraphic variations and reversals in mineral (Cawthorn et al., 1991, Pang et al., 2009;

Namur et al., 2010) and whole-rock compositions (Eales et al., 1990) that do not follow simple crystal fractionation trends, and changes in isotopic profiles (DePaolo et al., 1985; Jensen et al., 1993 Kruger, 1994). In contrast, closed system crystal fractionation of a "single" batch of magma will produce systematic mineral evolutionary trends following the liquid line of descent.

As shown by Luolavirta et al. (2018a, b), the lithological, whole-rock and mineral compositional as well as isotopic profiles obtained from different parts of the Kevitsa intrusion turned out to be markedly different. In drill cores located few hundred meters outside the ore-bearing domain, the ultramafic cumulate successions record a simple lithological stratigraphy, which includes, from the base upwards, a basal pyroxenite-gabbro, olivine pyroxenite (OLPX), pyroxenite and gabbro (Fig. 7a). Also the variations in whole-rock and mineral compositions (olivine and pyroxenes) are modest and predictable and the initial Sr isotope compositions remain fairly constant throughout the intrusive stratigraphy (Fig. 8). On the contrary, the ore domain of the intrusion is characterized by a complex internal architecture manifested by the presence of discontinuous zones of plagioclase-bearing (olivine) websterites (pOLWB), numerous ultramafic inclusions and xenoliths (Fig. 7b), and cryptic variations in whole-rock and mineral compositions and $^{87}Sr/^{86}Sr_{(i)}$ values (Fig. 9). The compositional fluctuations as well as the presence of abundant inclusions and xenoliths in the ore domain are best explained by multiple turbulent magma emplacements of variably contaminated silicate magma and sulfide liquid. The emplacement of the surrounding intrusion, in contrast, can be potentially explained by crystallization of a "single" cast of magma in at least nearly closed system.

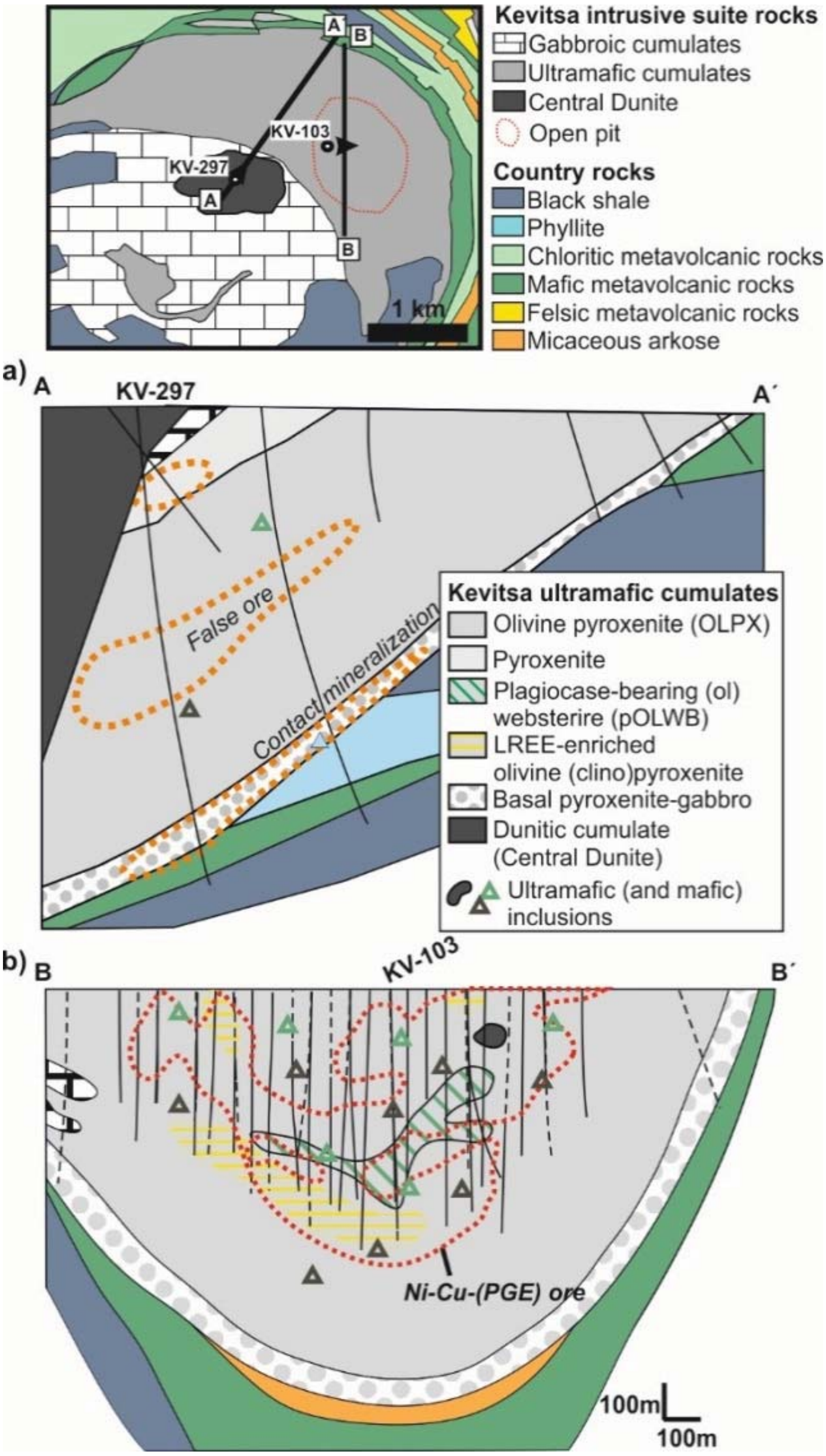


Fig. 7 a) SW-NE- (A-A´) and b) S-N-trending (B-B´) cross sections of the Kevitsa intrusion.

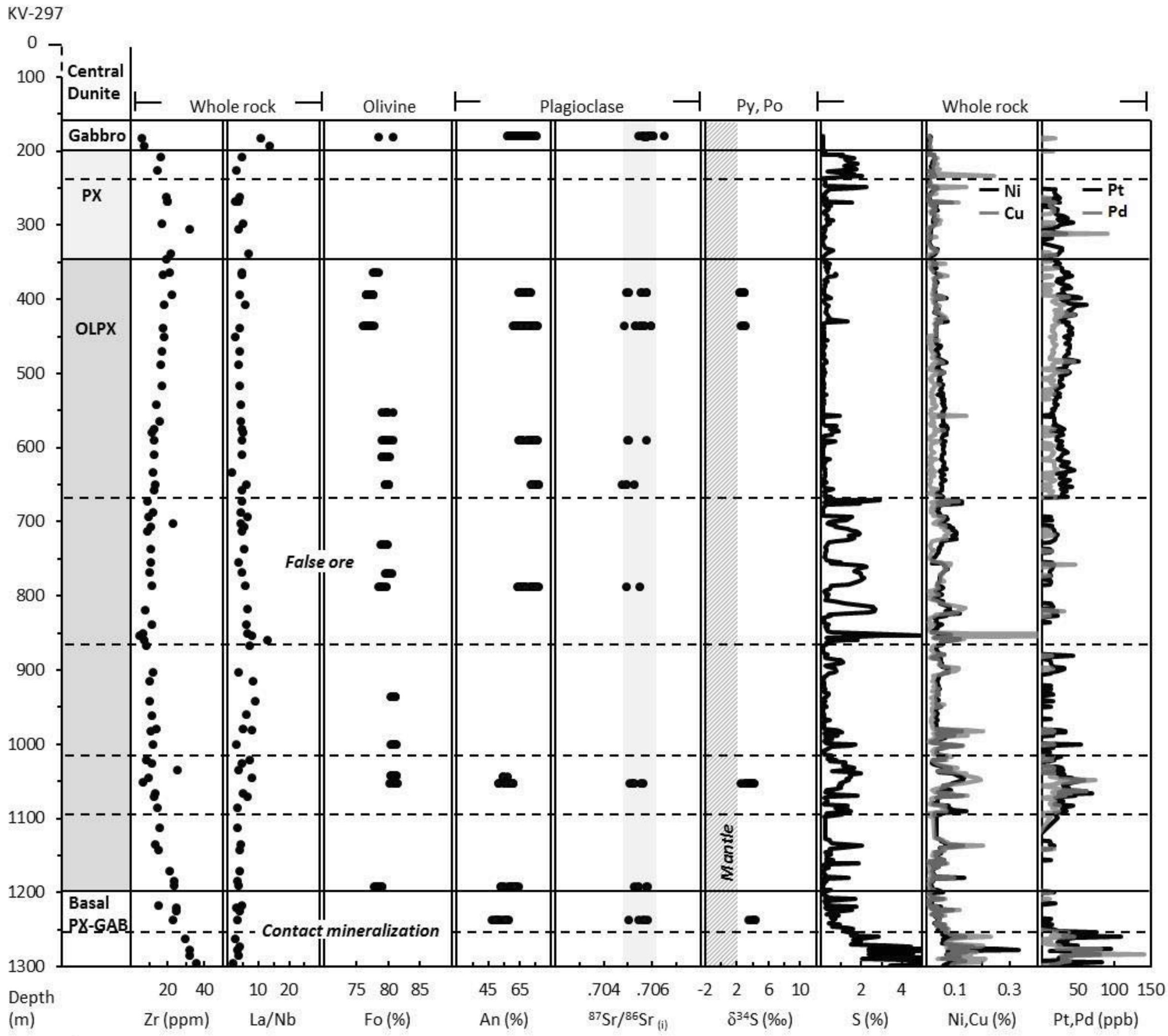


Fig. 8 Stratigraphic variations of whole-rock Zr, S, Ni, Cu, Pt and Pd contents and La/Nb ratio, Fo content of olivine, Sr isotope composition and An content of plagioclase, and S isotope compositions of pyrite and pyrrhotite in drill core KV-297 (outside the ore domain, see figure 4 for location). The observed range in Sr isotope compositions is depicted by the gray shaded column. PX - pyroxenite, OLPX - olivine pyroxenite, Basal PX-GAB - basal pyroxenite-gabbro. Po - pyrrhotite, Py - pyrite. Figure is from Luolavirta et al. (2018b) .

Tepley & Davidson (2003) describe an up-sequence increase in the $^{87}Sr/^{86}Sr$ ratio of plagioclase towards a unit contact in the Rum layered intrusion, which is interpreted to reflect the interplay of crystal fractionation and contamination taking place near the wall rocks of the intrusion. This is analogous to what is observed in the zones of pOLWB in the Kevitsa intrusion (Fig. 9, Luolavirta et al., 2018b). Although the origin of pOLWB zones remains ambiguous, these rocks likely crystallized in a close proximity to the margins of the intrusion, representing either roof sequence(s) of individual magma pulses or separate sills, which were formed at the time when the geometry of the Kevitsa intrusion was largely different from what is currently observed, or disconnected blocks of some former marginal phase rock of the Kevitsa intrusion (autoliths).

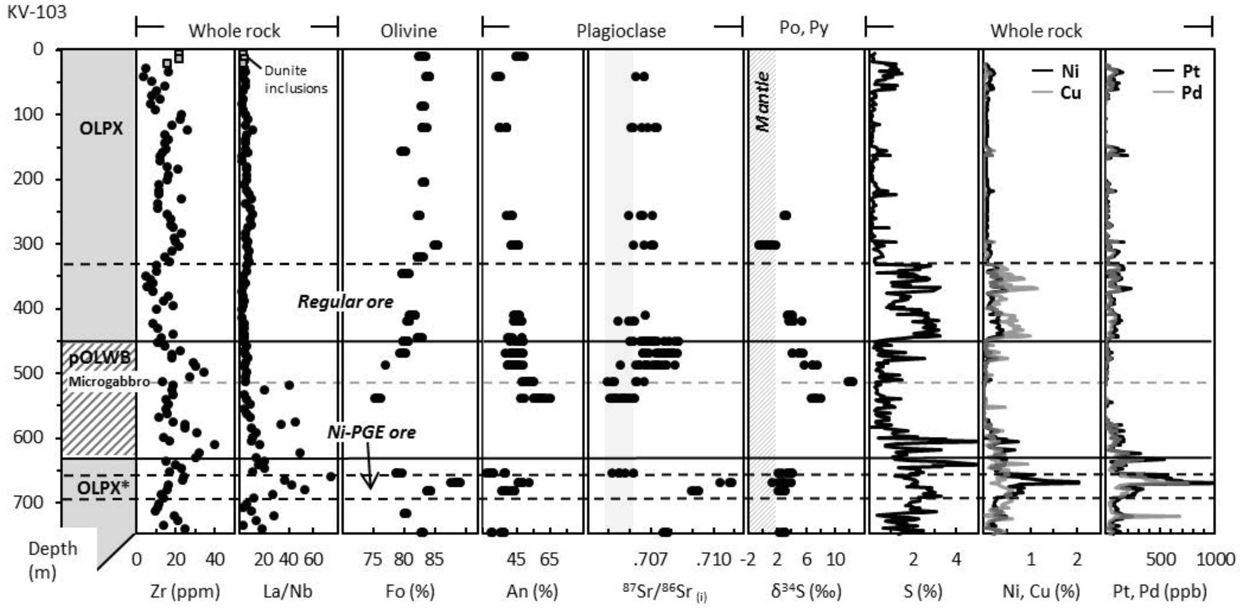


Fig. 9 Stratigraphic variations of whole-rock Zr, S, Ni, Cu, Pt and Pd contents and La/Nb ratio, Fo content of olivine, Sr isotope composition and An content of plagioclase, and S isotope compositions of pyrite and pyrrhotite in drill core KV-103 (ore domain, see figure 4 for location). Gray shaded column represents the range in Sr isotope compositions observed in drill core KV-297 (see Fig. 8). PX - pyroxenite, OLPX - olivine pyroxenite, Basal PX-GAB - basal pyroxenite-gabbro. Po - pyrrhotite, Py - pyrite. Figure is from Luolavirta et al. (2018b).

The evidence of crustal contamination is reasonably definite in the Kevitsa intrusion, as deduced from the bulk-rock chemistry (Mutanen, 1997), and the radiogenic Sr and non-radiogenic Nd isotope compositions (Luolavirta et al., 2018b; Huhma et al., 2018). Furthermore, the $\delta^{34}S$ values of the Kevitsa ore samples as well as "barren" rocks generally exceed +2‰ (Grinenko et al., 2003; Luolavirta et al., 2018b), being heavier than the sulfur isotope composition of the mantle (-2 to +2‰; Ripley & Li, 2003). Non-mantle-like S isotope compositions are a common feature of Ni-Cu deposits (see Fig. 5) and hence the role of externally derived sulfur in triggering S-saturation is considered important in the generation of large sulfide ore deposits (e.g., Keyes & Lightfoot, 2010; Ripley & Li, 2013). In this respect, the Kevitsa sulfide ores are not an exception.

While S isotopes can be utilized to assess the source of sulfur and to evaluate the cause of sulfide liquid segregation in sulfide ore deposits, further information on the sulfide saturation history of magmas can be obtained by investigating the chalcophile element abundances, such as Cu and PGEs (Li et al., 2001; Maier et al., 1998; Song et al., 2009: Yang et al., 2012), and olivine $Ni_{(OL)}$-Fo relationships (Li & Naldrett, 1999; Li et al., 2002; Li et al., 2007; Thakurta et al., 2008; Li et al., 2013). Olivine $Ni_{(OL)}$-Fo relationships in Kevitsa rocks reveals a marked Ni depletion in olivine in the false ore type mineralization (Fig. 6). This is likely a result of a previous S-saturation event leading to a Ni-depleted magma, from which olivine later crystallized.

Recently, Le Vaillant et al. (2017) argued that the false ores found around the ore domain (see Fig. 7a) formed within xenolith-laden early-stage sill-like intrusions and the restricted mixing efficiency of the sulfides and silicate melts resulted in low metal tenors of the ores. Although the heavy S isotope compositions of the false ores is in line with significant crustal assimilation of the country rocks, xenoliths around the ore-bearing domain of the intrusion are small-numbered and the observed compositional and Sr isotopic homogeneity of a rock succession reaching several hundred meters in thickness (see Fig. 8) and depletion of Ni in olivine is hard to reconcile with this model.

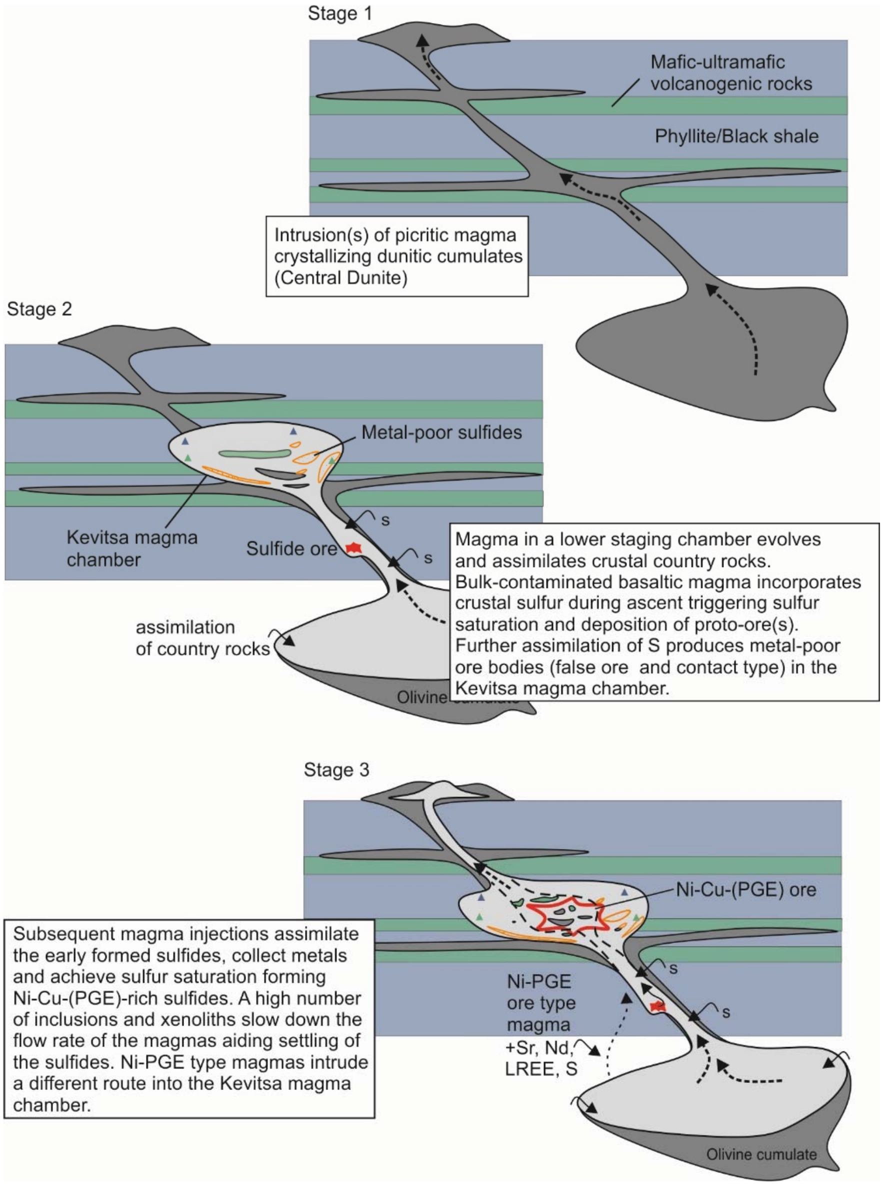
According to the model by Le Vaillant et al. (2017), the Kevitsa Ni-Cu ores (regular ore) formed under conditions of efficient sulfide melt–silicate melt mixing (high R-factor) as the intrusion expanded into a freely convecting magma chamber. The compositional stratigraphic variations observed within the Kevitsa ore domain (see Fig. 9) are interpreted to reflect dynamic (open system) magma emplacement providing circumstances under which the sulfide liquid may interact with a large volume of magma, resulting in high metal tenors (e.g., Barnes & Lightfoot 2005; Naldrett et al. 2011). In addition, the Ni-depleted nature of olivine in the false ores indicates that at the initial stage of filling of the Kevitsa magma chamber, some sulfides precipitated and accumulated at some depth within the magma conduit. These early-formed sulfides may have interacted with later invading magma patches, resulting in upgrading of their metal contents and formation of Ni-Cu ore bodies. Such "cannibalization" of proto-ores is proposed to have been operating, e.g., at Voisey´s Bay (Li & Naldrett, 1999), Noril´sk (Naldrett, 2004) and Kabanga (Mayer & Barnes, 2001) deposits, and also at Kevitsa (Yang et al., 2013a).

The origin of the Kevitsa Ni-PGE ore type is enigmatic. Yang et al. (2013a) explained the Ni-enriched nature of olivine and high Ni tenors of the Kevitsa Ni-PGE ores by assimilation of Ni-rich sulfides from dunitic xenoliths. The authors related these olivine-dominated inclusions to an early-stage komatiitic magmatism. This model is reasonable in terms of relating the coeval komatiitic magmatism (~2.06 Ga, Hanski et al. 2001) in the area and the Kevitsa intrusion with its abundant ultramafic inclusions. Yet, for instance, the crustal-like isotopic signatures (high $Sr_{(i)}$ 0.709-0.711, Luolavirta et al., 2018b), and low ε_{Nd} -6.4, (Huhma et al., 2018) and enrichment in LREE (Luolavirta et al., 2018a; Hanski et al., 1997) are hard to explain by this model. Also, the elevated Pd/Ir and Pt/Ir ratios of this ore type are not consistent with a komatiitic magma (Le Vaillant et al., 2016). The origin of the Kevitsa Ni-PGE ore type remains debatable but it is proposed that the magma producing Ni-PGE ore intruded a different route into the Kevitsa magma chamber, assimilating different, yet unidentified, country rock material (Luolavirta et al., 2018a,b).

As mentioned, ultramafic inclusions and xenoliths and discrete zones of pOLWB are particularly common within the ore-bearing domain of the Kevitsa intrusion. The presence of chaotic assemblages of rocks, minerals or inclusions is a rather common feature for many Ni-Cu ores (Lightfoot, 2007). Voisey´s Bay is one notable example where the sulfide ores are spatially associated with gneissic country rock xenoliths (Lightfoot & Naldrett, 1999) and the interaction between the xenoliths and magma is well demonstrated by chemical and mineral compositions as well as by visual evidence for partial melting of the rock fragments (Li et al., 2000; Li & Naldrett, 2000; Lambert et al., 2000; Ripley et al., 2002). Detailed petrological studies and characterization of the inclusions within the Kevitsa deposit suggest that they were derived from the large dunite body (Central Dunite) that is closely associated with the Kevitsa intrusion and from komatiitic country rocks (Luolavirta et al., *in press*). Re-evaluation of the preliminary xenolith-interpretation for the Central Dunite (Mutanen 1997) suggests it to represent a separate intrusion and conduit of picrite-basalt volcanic rocks of the Savukoski Group with a temporal and genetic link to the Kevitsa olivine-pyroxene cumulates (Luolavirta et al., *in press*).

The role of the inclusions in the genesis of the Kevitsa deposit is enigmatic. Pelitic xenoliths appear to occur near the margins of the intrusions while ultramafic inclusions dominate within the ore domain. Except for local attainment of equilibrium between the ultramafic inclusions and their immediate host rocks and possible remobilization of low-temperature phases (plagioclase, hydrous minerals) by the Kevitsa magma, any significant contribution of the dunitic inclusions or komatiitic xenoliths to the overall composition of the host rocks to the Kevitsa sulfide ores or sulfide phases themselves remains debatable (Mutanen, 1997; Luolavirta et al., *in press*; Yang et al., 2013a). Gregory et al. (2011) proposed that the sulfides in the Kevitsa ores accumulated at the basal parts of individual magma pulses. Luolavirta et al. (*in press*) proposed that the entrapment of a vast number of inclusions decreased the flow rate of Kevitsa magmas, aiding the settling of suspended sulfide droplets.

One of the outcomes of this PhD study is the construction of a geologic model for the origin of Kevitsa intrusive suite rocks, which is summarized in Fig. 10. The model proposes a complex multi-stage magmatic evolution for the intrusion. At stage 1, olivine-chromite cumulates (Central Dunite) accumulated in a picritic magma conduit and were followed by intrusions of more evolved basaltic magma crystallizing olivine-pyroxene cumulates and enclosing drafts of stage 1 dunitic cumulates and country rocks xenoliths (stages 2 and 3). The contrasting intrusive stratigraphy obtained from the Kevitsa ore domain and the surrounding part of the intrusion is interpreted to reflect different emplacement histories. It is proposed that the Kevitsa magma chamber was initially filled by stable continuous flow ("single" input) of compositionally homogeneous basaltic magma followed by crystal fractionation in an at least nearly closed system (stage 2). At this stage, some sulfides precipitated at depth in the magmatic system, resulting in metal-poor magma precipitating false ore bodies in the Kevitsa magma chamber. At the following stage (stage 3), magmas were repeatedly emplaced into the hot interior of the intrusion in a dynamic (open) system, forming the sulfide ore bodies. The formation of the Ni-Cu ore bodies may involve assimilation of proto-ores formed at stage 2.



Intrusion(s) of picritic magma crystallizing dunitic cumulates (Central Dunite)

Magma in a lower staging chamber evolves and assimilates crustal country rocks. Bulk-contaminated basaltic magma incorporates crustal sulfur during ascent triggering sulfur saturation and deposition of proto-ore(s). Further assimilation of S produces metal-poor ore bodies (false ore and contact type) in the Kevitsa magma chamber.

Subsequent magma injections assimilate the early formed sulfides, collect metals and achieve sulfur saturation forming Ni-Cu-(PGE)-rich sulfides. A high number of inclusions and xenoliths slow down the flow rate of the magmas aiding settling of the sulfides. Ni-PGE type magmas intrude a different route into the Kevitsa magma chamber.

Fig. 10 Schematic illustration of the emplacement of the Kevitsa intrusive suite rocks and formation of the Ni-Cu-(PGE) ore.

Practical implications and recommendations for further research

This study demonstrates that even in the case of relatively small magmatic bodies, different evolutionary histories can be deduced from different locations of the intrusion and hence caution should be obeyed when interpreting magmatic histories of intrusive rock suites based on limited number of data. This study provides an example of a sulfide deposit with a complex internal structure and establishes a link between dynamic magma emplacement and formation of an economic sulfide ore. Various evidence for open magma chamber processes can be deduced from the Kevitsa deposit; lithological complexity, stratigraphic fluctuations in whole rock and mineral chemistry and isotopic variations (Luolavirta et al., 2018a, b). Hence, these signals in mafic-ultramafic rocks series can be viewed as encouraging in exploration for viable sulfide ores. Furthermore, it provides additional S isotope evidence for the importance of external sulfur in ore genesis. In particular, the importance of dynamic magma emplacement in ore genesis is highlighted as it is reasonably well established that the economic ore resources at Kevitsa occur at the site of repeated magma pulses, whereas magma emplacement was likely far less vigorous within the ”unmineralized” part of the intrusion.

From the view of the Kevitsa mine, the aim of the PhD project focusing on the internal structure and on the broad concept of magmatic evolution of the Kevitsa intrusion was to improve the understanding of the emplacement of the intrusion, its stratigraphic sequences and its mineralization, which could potentially help the ongoing exploration to localize additional resources. Giving that around the Kevitsa ore domain there are no lithological, compositional or isotopic heterogeneities which could be correlated with the stratigaphy of the ore domain, vectoring towards the Ni-Cu-(PGE) ores outside the present ore resources is highly complicated. Nevertheless, rocks from the ”unmineralized” parts of the intrusion also record heavy S isotopic compositions indicating the magmas assimilated crustal sulfur. Also Ni-depleted olivines were found suggesting some sulfides precipitated from the magma prior its emplacement to its current position. These observations can be considered as indicators of potential existence of metal-rich sulfide ores elsewhere within the intrusive system.

It is well established that the MgO-rich intrusive and extrusive rocks of komatiitic, picritic and basaltic compositions are widespread within the Savukoski Group and prospective for Ni-Cu-PGE deposits. Consequently, numerous exploration campaigns have been conducted in the area, resulting in discoveries of the Sakatti and Lomalampi deposits, for example. The Geological Survey of Finland and the mining companies have produced a lot of geological and geochemical data along with their exploration operations, which could potentially be utilized in correlating these magmatic systems and their related deposits to be discussed in a more regional context. Mapping of similarities and differences between the intrusions and volcanics in the area and furthermore investigations on magmatic rocks with sulfide occurrences and bodies that are virtually barren could potentially improve understanding of the genesis of magmatic Ni-Cu-PGE deposits and improve exploration guidelines in the area but also on a global scale. For example, Mutanen (1997) interpreted the Kevitsa and the neighboring Satovaara mafic-ultramafic intrusion to represent an originally coherent intrusive body that was later separated by NE-trending faults. The intrusions are contemporaneous (Peltonen et al., 2014), yet the genetical relationship of the parental magmas is not established. So far no sulfide ores are found from the Satovaara intrusion and hence, interesting questions such as the key factors and processes governing the formation of notable Ni-Cu-PGE deposits could potentially be addressed by comparison of these magmatic bodies.

As said, this PhD study discusses the overall petrogenesis of the Kevitsa intrusion and its Ni-Cu-(PGE) sulfide ores. Still there are a number of research questions regarding the details of the ores and their formation (e.g., what were the conditions, such as redox state, during sulfide precipitation? Are there metals derived from contaminants? Was sulfide percolation a significant process?). Furthermore, the reasons to the peculiar REE and isotopic characteristics of the Ni-PGE ore type remain debatable.

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