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Layered mafic-ultramafic intrusions of Fennoscandia: Europe's treasure chest for magmatic metal deposits

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Keywords: Layered intrusions, Fennoscandia, magmatic ore deposits, platinum, chromium, nickel, vanadium, copper

Abstract

Northeastern Fennoscandia hosts a rich diversity of mafic-ultramafic intrusions of variable shape and size, emplaced in different tectonic regimes over a period spanning ca. 600 million years (from 1.88 – 2.5 Ga). Several of the bodies contain world-class ore deposits, notably the Kemi Cr deposit and the Pechenga Ni deposits. Other deposits include Ni and Cu at Kevitsa, Kotalahti and Sakatti, V at Koillismaa, and platinum-group elements at Portimo and Penikat. These deposits constitute important resources to shield Europe from potential future supply shortages of key industrial metals.

Introduction

The world faces heightened competition for mineral resources in a global environment of increasing metal demand, but decreasing access to explorable and mineable terrains. The capacity or willingness of certain countries to provide metals to international industries throughout the coming decades are uncertain, as illustrated by recent (2014) supply restrictions for rare earth elements (REE) from China, the implementation of a law that bans the export of unprocessed Ni from Indonesia, or the repeated temporary suspension of Pd sales by Russia in 2000. These potential short-term supply problems that are caused by political decisions are superimposed onto long-term trends of resource depletion that threaten the availability of certain "critical" metals (i.e., those that are essential for modern high technology but whose supply is not assured).

Whether a metal is considered to be critical is dependent on a complex range of factors, as highlighted by the platinum-group elements (PGE: Os, Ir, Ru, Rh, Pt, Pd). Some authors argue that global PGE production has

already peaked (Sverdrup and Ragnarsdottir, 2014), which would threaten long term security of supply. On the other hand, legislation is currently being implemented by several European governments to phase out internal combustion car engines that use PGE as catalysts, with the aim to accelerate the transition to battery-electric vehicles. This could potentially reduce PGE demand over the long term. As an additional factor of uncertainty, it remains unclear to what extent hydrogen fuel cell vehicles (that also use platinum as a catalyst) can compete with battery-electric cars.

Uniquely amongst metals, the supply of PGE is largely controlled by 2 countries, South Africa and Russia, both of which face significant socioeconomic and political challenges. Mining of PGE reefs (relatively narrow, but laterally extensive layers of ore) in many of South Africa's underground mines is currently uneconomic. If it ceases, and PGE prices increase as a result, PGE deposits elsewhere may become economic, particularly if they are amenable to low-cost surface mining and located proximal to mature infrastructure (roads, railways, power grids) and a well-trained workforce.

The ambitious energy and climate targets of the European Union will have a major impact on metal supplies. The photovoltaic cells and wind turbines required for the transition to a low-carbon society will trigger a >100% increase in the demand for many key metals over the next decades (Vidal et al. 2013), including platinum-group elements (PGE), Cr, V, Cu, and Ni. To meet this potentially dramatic future supply shortage, society needs to make better use of their internal resources, not only through enhanced recycling and substitution, but also through improved efficiency in mineral exploration, mining and beneficiation.

The Fennoscandian Shield contains one of the largest concentrations of mafic-ultramafic intrusions on Earth, with more than 50

mineralised bodies identified so far in an area of approximately 1M km² (**Fig. 1**). The main deposits in the intrusions (**Table 1**) are of magmatic nature and include oxide ores of chromite, magnetite and ilmenite, as well as sulphide ores of pyrrhotite, chalcopyrite and pentlandite. The sulfides may contain significant Ni, Cu and Co as well as minor and trace metals such as As, Bi, Te, Se and PGE.

The intrusions were emplaced in diverse tectonic settings, resulting in variable sizes and shapes, degree of deformation and mineral endowment. The most important deposits are Kemi (Cr), Pechenga (Ni-Cu), Kevitsa and Sakatti (both Ni-Cu-PGE), and Koillismaa (V). The region is an example of the rich mineral endowment of Archean and Proterozoic cratons and their margins, while also illustrating that mineral potential is controlled by both the geometry and the tectonic setting of intrusions.

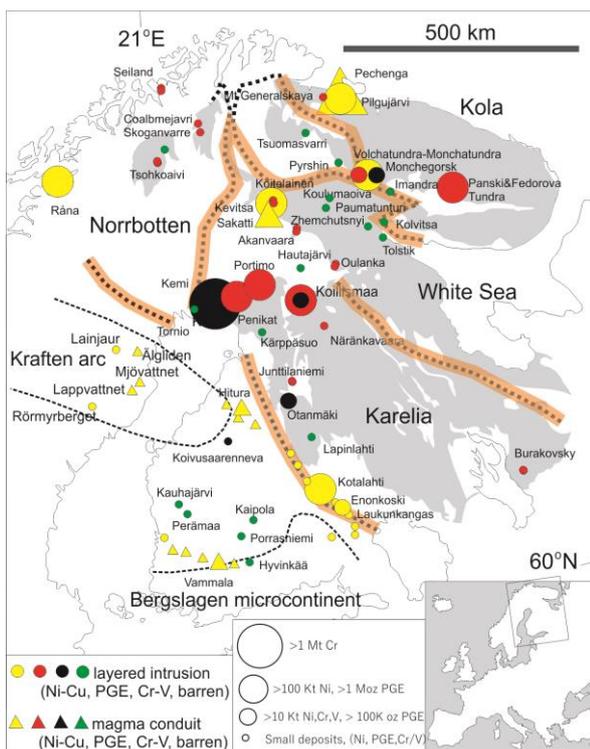


Fig. 1: Precambrian mafic-ultramafic layered intrusions and magmatic feeder conduits of Fennoscandia. Highlighted dashed lines represent craton margins and suture zones (modified after Maier and Groves, 2011).

2.44-2.50 Ga intracratonic intrusions emplaced into rifted Archean basement

This Paleoproterozoic magmatic event comprises more than 20 layered intrusions identified so far in Finland and NW Russia (**Fig. 1**). They define 2

age populations (~2.44 Ga and ~2.50 Ga), which correlate with those of the Matachewan and Mistassini dyke swarms and the sulfide-mineralised River Valley, East Bull Lake and Agnew intrusions in Canada. Bleeker et al. (2016) have suggested that the Fennoscandian and Superior continents were part of a common Paleoproterozoic supercontinent and were affected by the same mantle plume melting events.

The Fennoscandian layered intrusions can be up to ~500 km² in surface area (Burakovsky, Koitelainen), and >3 km in stratigraphic thickness (Penikat, Koitelainen). Several of the intrusions have been interpreted as tectonised members of an originally larger body (Karinen et al. 2015). It is thus possible that even larger intrusions existed originally. The intrusions are believed to have crystallised from Mg-basaltic parent magmas, exposed in a suite of coeval dykes (Vuollo and Huhma 2005). They show all the features of classic open-system layered intrusions, with laterally extensive cyclic units of ultramafic-mafic rocks, local transgressive features referred to as potholes or depression structures, and economically important reefs of chromite, PGE-Ni-Cu-rich sulfide, and V-bearing magnetite.

The economically most important member of the suite is the Kemi intrusion in Finland (Huhtelin 2015), which hosts one of the largest Cr deposits on Earth. The Cr layer measures just a few centimetres at the margins of the body, but reaches a thickness of > 100m near the base of the central trough-like portion of the intrusion (**Fig. 3**). The ores have been explained by chromite supersaturation in response to magma mixing, followed by gravitational settling of chromite, preferentially near a putative feeder vent situated below the central trough (Alapieti et al. 1989). However, based on the texture of the chromitite ore (**Fig. 3**), the authors of this article argue that slumping of chromite slurries during chamber formation played a role in ore formation.

The PGE reefs in the Fennoscandian intrusions (Portimo, Penikat, Koillismaa, Monchepluton) are currently sub-economic. An unusual deposit comprising PGE-rich sulfide veins occurs below the Portimo intrusion (at Kilvenjärvi, Andersen et al. 2006). These are somewhat

reminiscent of the Sudbury offset deposits, and cross-cutting dm- to m-wide Ni-rich sulfide veins in the Monchepluton (Sharkov and Chistyakov 2014). They constitute types of targets that, due to their apparent rarity, are seldom considered in PGE-Ni-Cu exploration.

Table 1: Mineralised Fennoscandian mafic-ultramafic intrusions

Name	Age (Ga)	Commodity	Grade	Reserves ¹ /Resources ² /Mined tonnage ³	Tect. Setting	Deposit Style	Ref
Kemi	2.44	Cr	26 % Cr ₂ O ₃ , Cr/Fe 1.6-1.7	50.1 Mt ¹	rift - CLI	contact massive	1
Portimo	2.44	PGE (Ni-Cu)	1ppm Pt+Pd	265 Mt ²	rift - CLI	contact diss. + reef	2
Koillismaa	2.44	V, PGE (Ni-Cu)	1ppm Pt+Pd 0.91% V	23.6 Mt ² 99 Mt ¹	rift - CLI	contact diss. + reef reef	2
Penikat	2.44	PGE (Ni-Cu)	4.6 ppm Pd, 3.2 ppm Pt	~15 Mt ²	rift - CLI	reef	2
Monchepluto	2.5	Ni-Cu-PGE	na	na	rift - CLI	contact diss.+reef+veins	3
Kevitsa	2.058	Ni-Cu (PGE)	0.3%Ni, 0.41%Cu, 0.47ppm PGE	240 Mt ²	rift-conduit	conduit dissem	5
Sakatti	~2.05	Ni-Cu (PGE)	na	na	rift-conduit	conduit mass+diss.	6
Pechenga	1.98	Ni-Cu (PGE)	1.18%Ni, 0.63%Cu, 0.3ppm PGE	339 Mt ²	rift-conduit	conduit massive	4
Kotalahti	1.85	Ni-Cu	0.66%Ni, 0.25%Cu	13.3 Mt	arc-LI	contact massive	7
Hitura	1.85	Ni-Cu	0.61% Ni, 0.21% Cu	19.3 Mt	arc-conduit	conduit massive	7

Notes: (C)LI=(continental) layered intrusion. References: 1 Huhtelin (2015), 2 Iljina et al. (2015), 3 Sharkov and Chistyakov (2014), 4 Naldrett 2004, 5 Santaguida et al. (2015), 6 Brownscombe et al. (2015), 7 Makkonen (2015)

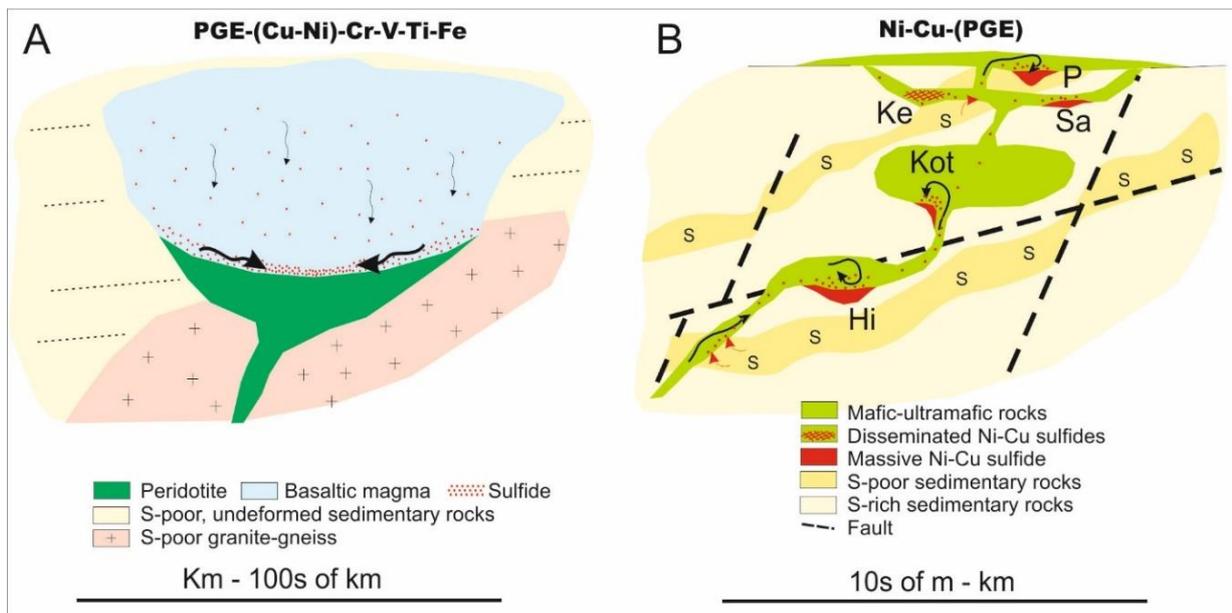


Fig. 2: Schematic model for sulfide ore location in (A) large layered intrusions, and (B) dynamic magma conduit systems including lava channels. Hi=Hitura, Kot=Kotalahti, Sa=Sakatti, Ke=Kevitsa, P=Pechenga. Modified after Maier and Groves (2011).

1.98-2.06 Ga intracratonic intrusions emplaced into rifted sedimentary basins

The 1.98 Ga Pechenga Ni-Cu sulfide deposits collectively form one of the 5 largest magmatic Ni provinces globally (Naldrett 2004). They were discovered in 1921 and have been exploited since 1940. The deposits occur in the upper part of the Pechenga greenstone belt, within the Kola craton of NW Russia. They are

hosted by concordant or sub-concordant, differentiated mafic-ultramafic bodies, from a few tens of meters to ~500 m in vertical thickness, that were intruded into a sedimentary unit (referred to as the “Productive Formation” by Russian geologists) composed of greywackes and shales rich in sulfides and carbonaceous matter (Fig. 4). The largest intrusion is Pilgijärvi, which, in addition to basal Ni-Cu sulfide ores, also

contains a V-bearing magnetite horizon. Mineralised feeder dykes are found in the underlying pillow lava sequence (Hanski et al. 2011). The parental magma to the ore-bearing

intrusions was a hydrous, Fe-rich primitive ferropicrite, with relatively high incompatible trace element contents and enriched Os and Nd isotopic signatures that resemble ocean island

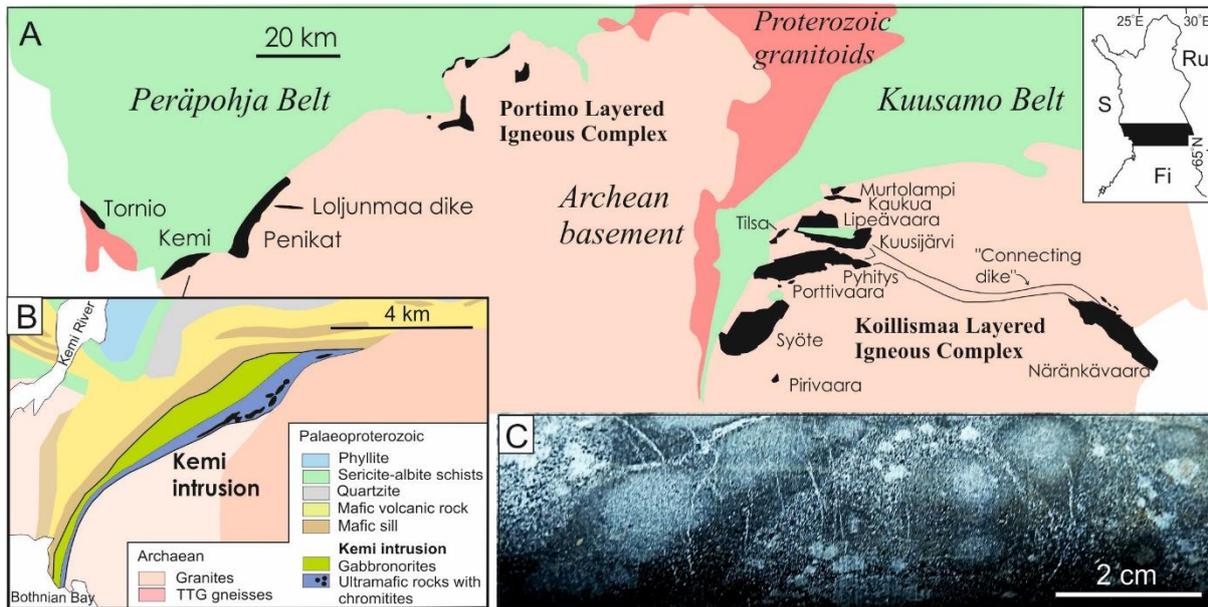


Fig. 3: (A) Layered intrusions of the Tornio-Näränkäväära belt. Inserts show details of Kemi intrusion (B) and sample of Kemi Cr ore (C). Note rounded fragments of dense chromite in matrix of disseminated chromite and plagioclase, interpreted to result from slumping of chromite slurries during ore formation.

basalts (Walker et al. 1997) and suggest a similar enriched mantle source. The thick accumulations of tholeiitic pillow lavas that preceded and followed the ferropicritic magmatism attest to an advanced stage of continental rifting, possibly related to plume impingement near a continental margin.

Mafic-ultramafic Ni-Cu mineralised intrusions emplaced into rifted sedimentary basins of the Karelian craton include the 2.058 Ga Kevitsa intrusion (Mutanen 1997; Santaguida et al. 2015) and the recently discovered Sakatti intrusive cluster (Brownscombe et al. 2015). The intrusions form relatively small bodies (Kevitsa: 16 km² surface area and at least 1.5 km thick; Sakatti: 0.25 km² surface area for the main intrusion and at least 0.8 km thick) that are difficult to detect using regional geochemical and geophysical exploration programs, suggesting that further deposits remain to be discovered. Both Kevitsa and Sakatti are interpreted as magma conduits and genetically related to broadly coeval or slightly younger komatiitic and Mg-basaltic volcanics of the Karasjok-type

that are locally PGE-Ni-Cu mineralised (at Lomalampi, Törmänen et al. 2016). Both intrusions have been emplaced into black shales which, together with the presence of abundant shale xenoliths and elevated γ O_s and low ϵ Nd isotopic ratios (Hanski et al. 1997), suggest that assimilation of crustal sulfide was an important trigger in ore formation. Kevitsa and Sakatti are of similar age and are located within 15 km of each other in the Central Lapland greenstone belt, highlighting that such deposits tend to occur in clusters. The relative enrichment of Pt over Pd in the sulfide ores of the 2 intrusions is unusual amongst global magmatic sulfide deposits, but it is also seen in the associated komatiitic lavas (Fiorentini et al. 2012) and the coeval Bushveld Complex. Maier et al. (2016) have proposed that this may reflect melting of asthenospheric mantle containing chemical anomalies stemming from late meteorite bombardment. This model could potentially also explain the highly anomalous Ni contents of some of the sulfides in the Kevitsa deposit.

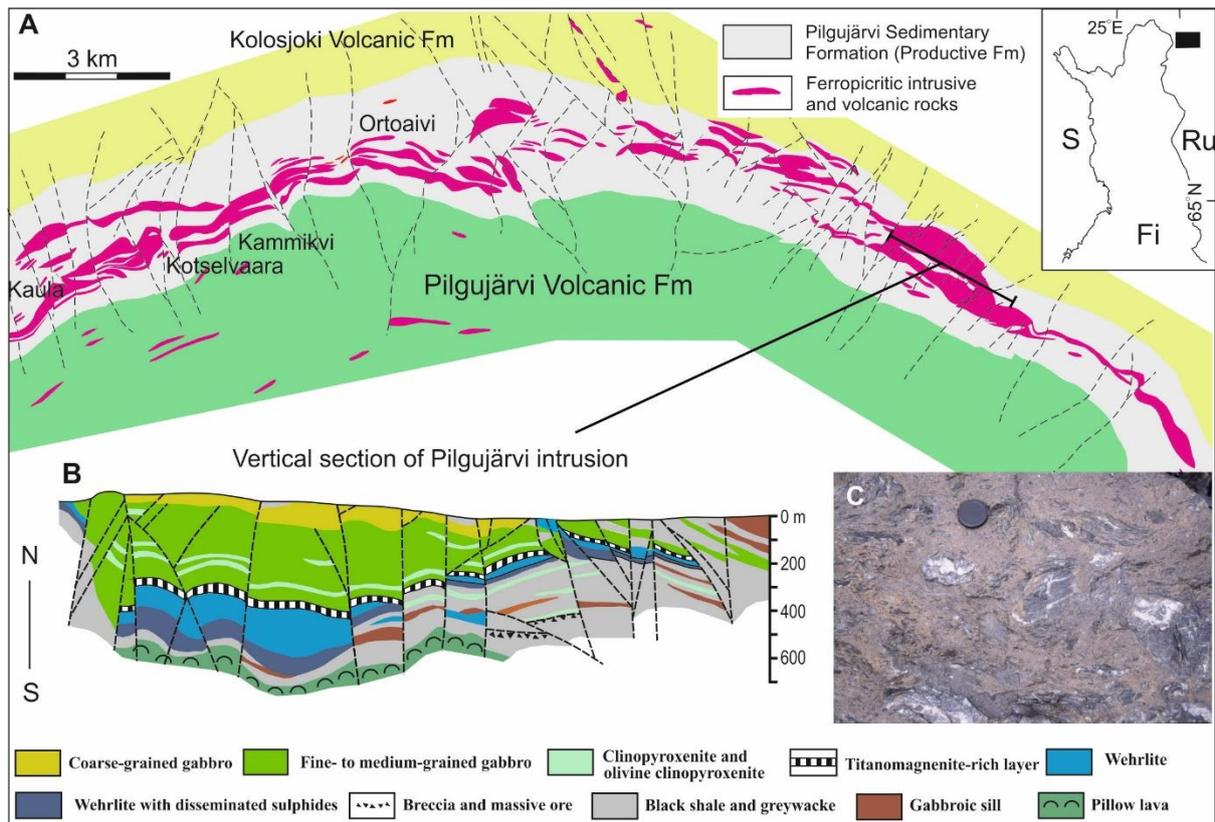


Fig. 4: A) Geological map of the Pechenga belt with ferropicritic intrusive and volcanic rocks. B) Details of Pilgijärvi layered intrusion (Modified from Hanski et al. 2011, and Smolkin, 2013). C) Massive ore breccia in the floor of intrusion.

1.88 Ga intrusions along the SW margin of the Karelian craton

Geographically, these intrusions are grouped into the Kotalahti and Vammala belts (Papunen et al. 1979; Makkonen 2015) and were mined from 1941 to 2013, with the largest deposits being Kotalahti and Hitura. The intrusions are coeval with synorogenic granitoids and were emplaced during the collision of arcs and microcontinents with the Karelian craton, marking the beginning of the amalgamation of Fennoscandia and Laurentia. The Kotalahti and Vammala belts have analogies in the Halls Creek mountain building event (Australia), the Appalachians of northeastern USA and eastern Canada, and the Tianshan and Altay mountain belts of China (Makkonen 2015, and references therein). The ores are hosted in deformed layered intrusions or magma conduits (Papunen et al., 1979) that crystallised from Mg-basalt. The contrasting architecture of the individual intrusions is interpreted to reflect

variation in crustal thickness; Intrusions emplaced through thick crust along the craton margin could fractionate during magma ascent, whereas in the thinner crust of SW Finland, the magmas ascended without significant intermittent ponding (Papunen et al. 1979). Crustal contamination (up to 40% by mass with sulfidic sediments) is deemed to have been important in the formation of the sulfide ores, based on trace element signatures as well as Os, Nd and S isotopes (Makkonen 2015). Because the intrusions were emplaced at variable depths (shallow to 20 km) during the Svecofennian orogeny, they were intensely deformed and dismembered resulting in a multitude of intrusive fragments of variable size (dms to >10 km in length and diameter) and grade of mineralisation (Fig. 5). This makes exploration challenging, but it also opens the possibility of future discoveries. Thus, undiscovered resources are estimated to equal those mined already (Makkonen 2015).

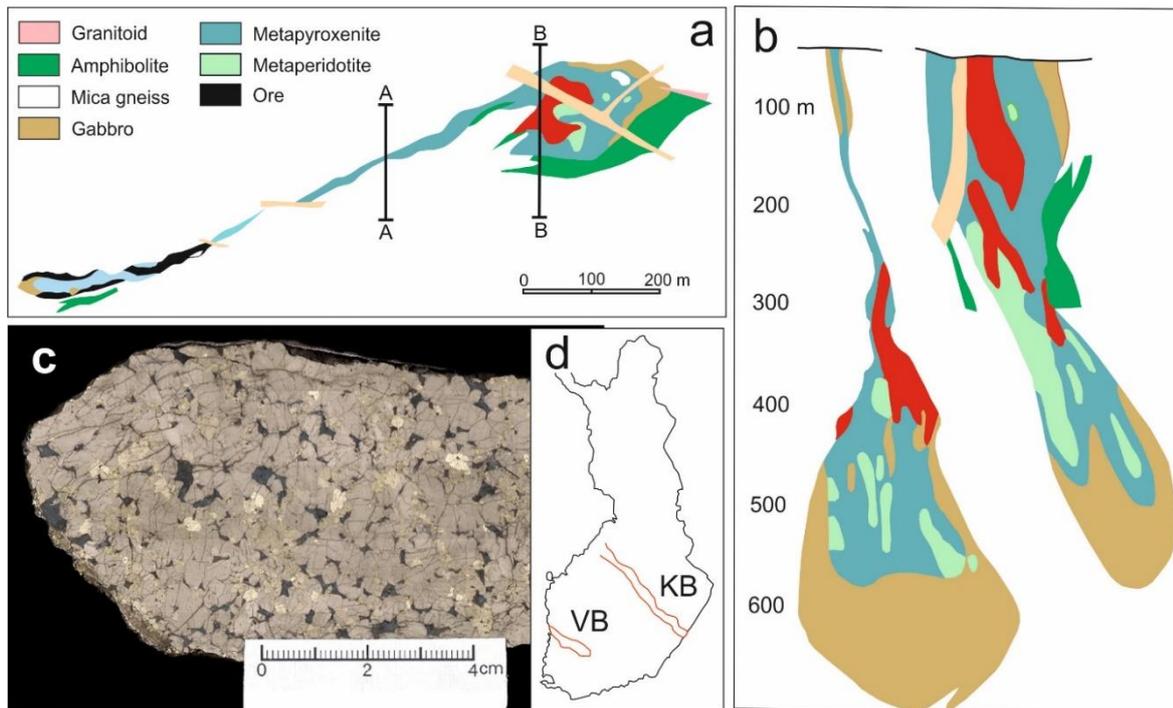


Fig. 5: (a) Map view of Kotalahti intrusion (modified after Papunen et al., 1979). (b) Cross-sections of the Kotalahti intrusion, shown in (a). (c) Massive pyrrhotite-pentlandite ore at Laukunkangas. Gangue is magnetite and amphibole (http://tupa.gtk.fi/karttasovellus/mdae/raportti/37_Enonkoski.pdf). (d) Regional setting of Kotalahti (KB) and Vammala belts (VB).

Ore forming models and the search for critical metals

Past studies of the tectonic setting and the emplacement history of the Fennoscandian intrusions have resulted in a much improved understanding of how the mineral deposits formed, which is essential in order to devise efficient exploration guidelines for critical metals. The main model applied to the formation of magmatic ore deposits is one of gravitational concentration of relatively dense sulfide liquid and oxide crystals that collected metals during equilibration with large volumes of silicate magma (see Mungall and Naldrett, 2008, and references therein). Amongst the petrogenetic aspects that remain intensely debated, two may be highlighted:

(i) What was the trigger for saturation of the magma in oxide crystals and sulfide liquid? The debate has centred on the question of whether crustal contamination is required in the process. Many intrusions that contain sulfides along their basal contacts have been emplaced into sulfidic country rocks. This observation suggests that addition of external, sedimentary-derived sulfur to the magmas

triggered early saturation of sulfide melt in the magma. The model is consistent with isotopic and trace element data for several of the Fennoscandian intrusions (Hanski et al. 1997; Andersen et al. 2006; Makkonen and Huhma 2007; Brownscombe et al. 2015).

(ii) How did the oxides and the Ni-Cu-Co-PGE-rich sulfide liquid concentrate to form economically viable mineral accumulations? Sulfide ores in magma conduit systems are often explained by hydrodynamic concentration of dense sulfide liquid in widened portions of the conduits or at the base of larger staging chambers (Fig. 2b; Naldrett 2004). In addition, ores may form via downward percolation of sulfide melt in the conduits (Barnes et al. 2016). Regarding the formation of sulfide and oxide reefs in layered intrusions, the classical model has been one of mixing of compositionally different magmas. According to this model, saturation of the hybrid magma in oxide minerals or sulfide liquid is followed by phase settling (Campbell et al. 1983). Other models are summarised in Mungall and Naldrett (2008). One problem not adequately explained by this model is that the

ore layers often have sharp lower and upper contacts, implying highly efficient phase separation. As an alternative, Maier et al. (2013) explained reef-type deposits by hydrodynamic processes. These mechanisms include kinetic sieving of oxides and sulfides in crystal slurries that slump to the centres of subsiding intrusions, somewhat analogous to density currents cascading down continental slopes to form turbidites (**Fig. 2a**).

Conclusions

Fennoscandia contains more than 50 mafic-ultramafic layered intrusions and magma feeder conduits, many of them hosting important deposits of Cr, Ni-Cu, PGE, V and Ti. Including the world-class Kemi, Pechenga, and Kevitsa deposits. The morphology of the intrusions and style of emplacement varies from large, mostly relatively undeformed intrusions to small, highly-deformed and fragmented feeder conduits within intracratonic sedimentary basins and arcs along the craton margins. The intrusions of the Pechenga belt are of an intermediate type, comprising both large sill-like intrusions, as well as thin sills and feeder conduits.

From an exploration perspective, it is important to note that the type of mineralisation is controlled by intrusion size and tectonic setting. The large intracontinental intrusions are sulfide-poor, but host reefs of PGE-Cu-Ni, chromite and V-Ti-bearing magnetite. The reefs are interpreted to have formed via hydrodynamic sorting of crystal mushes during crustal subsidence. Whereas most Fennoscandian PGE reefs are currently sub-economic, the relatively recent discovery of high-grade PGE reefs in the Flatreef (Ivanhoemines.com) and Waterberg projects of the Bushveld Complex (platinumgroupmetals.net) serves to highlight that reef grade can be far more variable along strike and dip of layered intrusions than generally perceived and that even in well-explored intrusions and terranes, high-grade deposits remain to be discovered.

In contrast to the large intrusions, the smaller layered intrusions and feeder conduits at the craton margin and within rifted intracontinental sedimentary basins

assimilated significant external sulfide, triggering the formation of economically important massive and semi-massive Cu-Ni sulphides.

On a global scale, Fennoscandia appears to show one of the highest densities of mafic-ultramafic intrusions. This could be due to its remarkable ~600 Ma history of episodic mafic/ultramafic magmatism associated within multiple rift basins. In addition, the region has a long history of mining and exploration spanning several 100 years. It is all the more remarkable that significant new discoveries keep on being made, as recently demonstrated most notably by the large Sakatti deposit.

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