

# Rifting-related mafic-ultramafic magmatism and ore potential in NE Fennoscandia

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Multiple stages of Paleoproterozoic rifting have been recorded in several cratons, which resulted in the break-up of the Kenorland supercontinent and later disruption of individual cratons. These extensional tectonic events were associated with widespread mafic-ultramafic magmatism producing important ore deposits of Cr, Ti, V, Ni, Cu and PGE. We studied the geochemistry of Paleoproterozoic mafic-ultramafic volcanic rocks from different belts in NE Fennoscandia (Fig. 1) to constrain the fertility and sulfide saturation history of the magmas and their potential to form magmatic sulfide deposits.

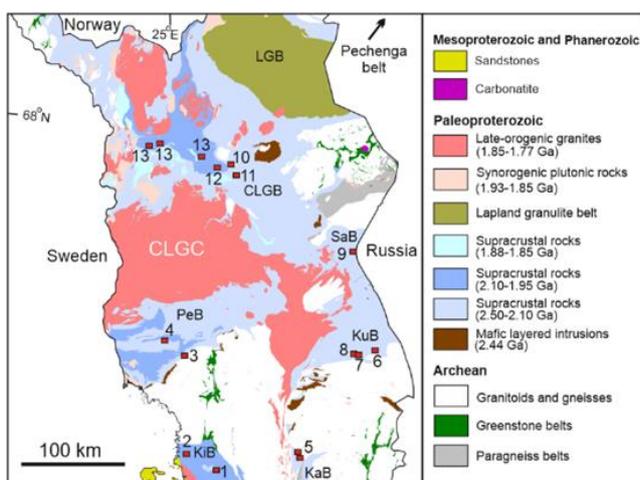


Fig. 1. Sampled volcanic formations shown by red squares on a simplified geological map of northern Finland (based on DigikP, the digital map database of the Geological Survey of Finland, Version 1.0; available at: [www.geo.fi/en/bedrock.html](http://www.geo.fi/en/bedrock.html)). 1 = Kiiminki Fm, 2 = Haukipudas Fm, 3 = Runkaus Fm, 4 = Jouttiaapa Fm, 5 = Vintaselkä and Matinvaara Fms, 6 = Kuntijärvi Fm, 7 = Petäjävaara Fm, 8 = Ruukinvaara Fm, 9 = Mäntyvaara Fm, 10 = Möykkelmä Fm, 11 = Sattasvaara Fm, 12 = Kautoselkä Fm, 13 = Vesmäjärvi Fm. Abbreviations for geological units: CLGB = Central Lapland greenstone belt, CLGC = Central Lapland Granitoid Complex, KaB = Kainuu belt, KiB = Kiiminki belt, KuB = Kuusamo belt, LGB = Lapland granulite belt, PeB = Peräpohja belt, SaB = Salla belt. The Pechenga belt is located outside the map in the Kola Peninsula, NW Russia.

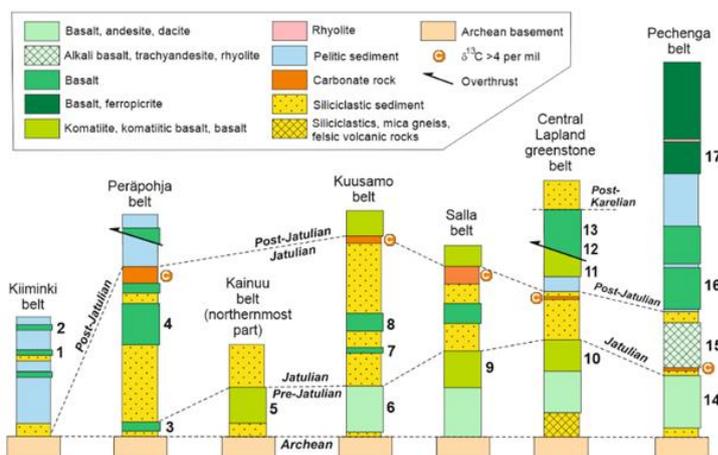


Fig. 2. Simplified stratigraphic columns of the study areas and their correlation [7,8,9,11,13]. Numbers referring to the studied volcanic formations are the same as in Fig 1.

The 2.5-2.45 Ga magmatism formed large layered intrusions in the Kola and Karelian cratons, which are thought to be products of a large mantle plume event. The lowermost volcanic rocks in the Kainuu, Central Lapland, and Salla and Kuusamo belts belong to this event. Guo et al. [4] studied the 2.45 Ga mafic dyke swarms in the Karelian craton and subdivided these dykes into two major groups, siliceous high-magnesium basalt (SHMB) and tholeiite groups. The SHMB group was favoured to have formed via crustal contamination of a komatiitic magma, whereas the tholeiitic group experienced less crustal contamination. The co-eval volcanic rocks in different supracrustal belts show that the majority of the volcanic rocks show relatively primitive magma compositions with high MgO contents, being similar in composition to the SHMB mafic dyke swarms, in terms of both major elements and trace elements. Only two samples from the Salla belt resemble chemically the tholeiitic dykes. The new results indicate that the SHMB magma occurs more widely than the tholeiite group, consistent with the observation that parental magmas of most of the 2.45 Ga layered intrusions have a SHMB affinity. This group of volcanic rocks displays moderate PGE content values, with Pt ranging from 5 to 10 ppb. Primitive rocks show mantle-like Ni/Pt ratios, whereas more evolved rocks show clearly elevated Ni/Pt ratios indicative of sulfide saturation. Volcanic rocks in different belts show rather similar geochemical signatures, suggesting similar histories of magmatic evolution.

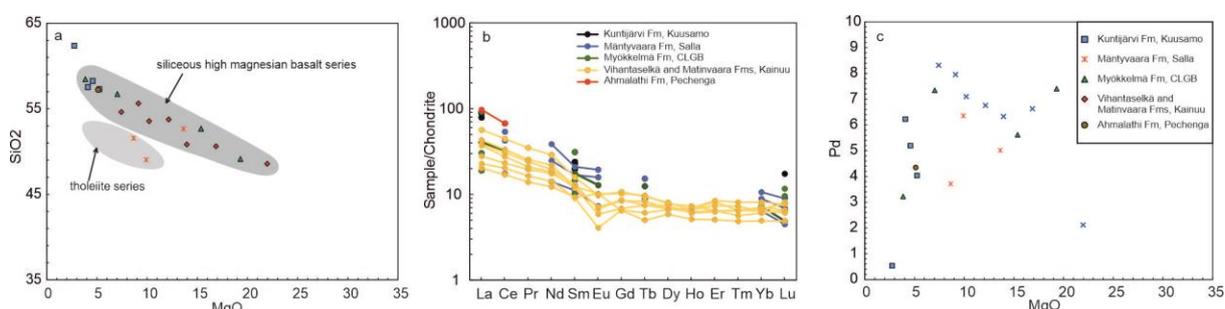


Fig. 3 a. Plot of MgO (wt.%) vs. SiO<sub>2</sub> (wt.%). b. Chondrite-normalised rare earth element (REE) patterns of the 2.45 Ga volcanic rocks. Normalisation values from Sun and McDonough (1989). c. Plot of MgO (wt.%) vs. Pd (ppb) of the 2.45 Ga volcanic rocks.

The Runkaus basalt formation was probably derived from a similar magma that produced the 2.31 Ga mafic dykes in Russian Karelia [14]. This group of basalts has relatively low MgO contents and low PGE contents, indicating that the magma has equilibrated with sulfide, probably in the source mantle due to a low degree of partial melting in the upwelling asthenosphere, though the available data are limited. Hence, this pulse of magma may have less potential to form economic PGE deposits.

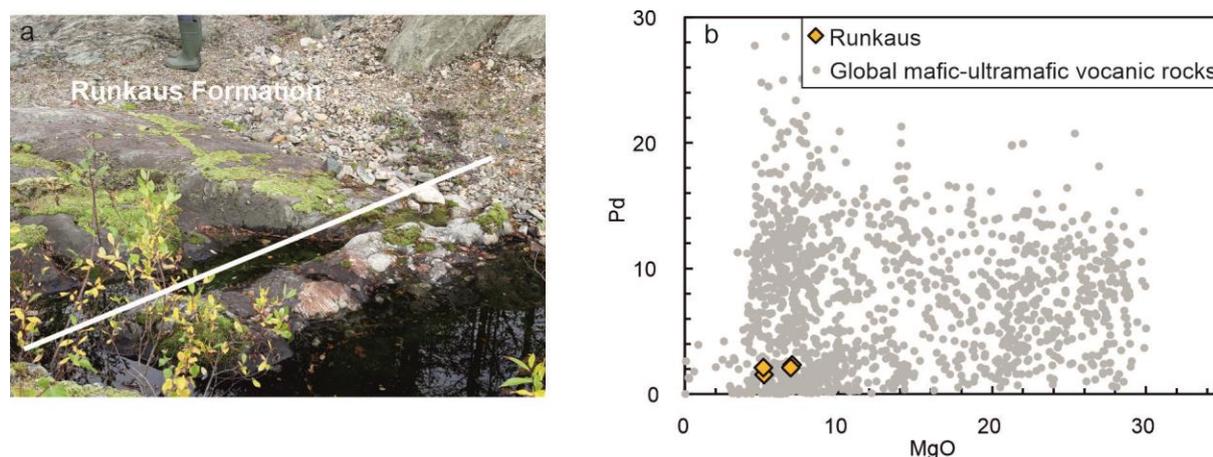


Fig. 4 a. Field photo of the Runkaus Formation lying a basal conglomerate. b. Plot of MgO (wt.%) vs. Pd (ppb) for the Runkaus Formation. Global mafic-ultramafic volcanic rocks data are from Barnes and Fiorentini [2].

The Jatulian stage (2.2-2.06 Ga) volcanic rocks can be related to mafic dyke swarms across the Karelian craton. Volcanic rocks from different belts show variable geochemical features with either depletion or enrichment in LREE and were probably derived from diverse mantle sources. The Jouttiaapa Fm basalts from the Peräpohja belt have been dated at 2.13 Ga based on cross-cutting

mafic dykes and sills [8]. Based on their major element composition, the Jouttiaapa basalts can be divided into 'high Ti' (TiO<sub>2</sub> 1-1.5%) and 'low Ti' series (TiO<sub>2</sub> 0.5-1%), and both groups are comparable to the low Ti series of other large igneous provinces. Trace and minor elements compositions indicate that they were evidently derived from a depleted mantle source, and the 'low Ti series' may have experienced higher degrees of previous melt extraction than the 'high Ti series'. New PGE data show that both magma series have similar PGE contents and are rich in Pt and Pd, broadly similar to fertile basaltic rocks globally. This indicates that the previous melting may have not depleted the PGE in the mantle source. These rocks show mantle-like Ni/Pt ratios without signs of PGE depletion, indicating no sulfide saturation prior to final eruption.

There is debate on the mantle source of magma for PGE-rich deposits. One group of investigators suggests that the sub-continental lithospheric mantle has a great contribution of PGE to magma [3,17], and the other group suggests that SCLM may not have a significant contribution [1,10,16] (Barnes et al., 2016 and references therein; Yang et al., 2016; Maier et al., 2017). The Peräpohja basalts also provide an excellent case that a magma derived from an asthenospheric mantle or a plume mantle, without much contribution of a subcontinental lithospheric mantle, could have high PGE contents.

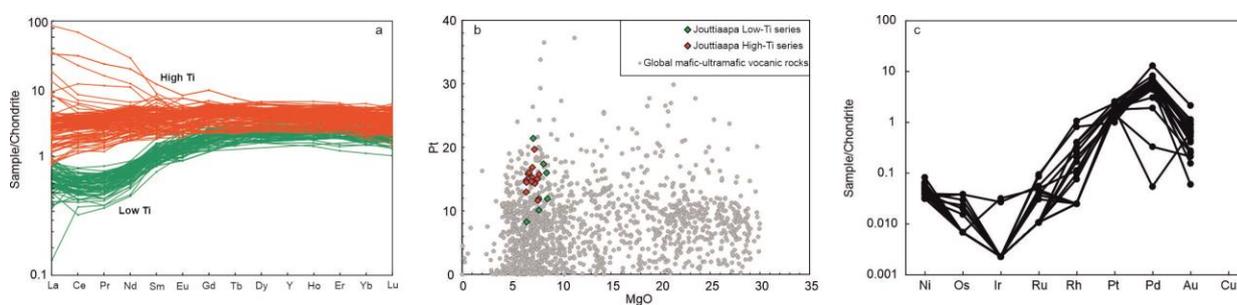


Fig. 5 a. Chondrite-normalised rare earth element (REE) patterns of the Jouttiaapa basalts. Normalisation values from Sun and McDonough (1989). b. Global mafic-ultramafic volcanic rocks data are from Barnes and Fiorentini [2] (2012). c. Primitive mantle normalized chalcophile element diagram for the Jouttiaapa Formation. Normalization values taken from McDonough and Sun [12] (1995).

In the late-stage rifting, there were two plume events at 2.06 Ga and 1.98 Ga that formed significant Ni-Cu-dominated sulfide deposits (e.g., Kevitsa, Sakatti, and Pechenga). Komatiitic or picritic rocks were formed in these events due to a high degree of partial melting [5,6]. Komatiitic rocks from the Sattasvaara Formation (corresponding to 2.06 Ga magmatism) and Kolosjoki Formation (corresponding to 1.98 Ga magmatism) show moderate to high Pt and Pd contents, indicating a fertile magma rich in chalcophile metals. These rocks also show relatively high Ir and Ru contents (up to about 4 ppb), indicating a high mantle melting degree. The Kiiminki Formation is estimated to be co-eval with the 1.98 Ga magmatism. A limited amount of samples show relatively low MgO contents and variable PGE contents, indicating that sulfide saturation may have occurred. In general, these two pulses of magmatism have great potential for Ni-Cu sulfide deposits due to the fertility of magma and the availability of sulfur-rich sedimentary rocks during that time.

In the long rifting stage, different stages of magmatism across different belts generally show similar features. With the exception of the Runkaus Formation, most magma pulses show broadly fertile PGE contents. The key factors controlling ore formation may include the capability to form large magma chambers to form PGE deposits or dynamic feeder conduits and the access of external sulfur to form Ni-Cu sulfide deposits.

#### Acknowledgements

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