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

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

1. Introduction

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

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

2. Preliminary studies and results

2.1. Penikat intrusion

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

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

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

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

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

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

2.2 Sr isotope stratigraphy of the Penikat intrusion

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

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

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

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

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

The results indicate that there are different types of magmas involved in the genesis of the Penikat intrusion; the MCU I-III, and particularly MCU IV and MCU V all record different Sr

isotopic signatures. Hence, the parental magmas for the Penikat intrusion, is likely more diverse than previously thought. The Sr-isotope data, accompanied with lithological and chemical data from previous studies, indicate recharge of new magma at the sites of the SJ and PV reefs, and mixing of magmas with different isotopic composition, especially between MCU V and MCU V.

3. Future prospects

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

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References:

- Alapieti TT, Filen BA, Lahtinen JJ, Lavrov MM, Smolkin VF, Voitsekhovskiy SN (1990) Early Proterozoic layered intrusions in the northeastern part of the Fennoscandian Shield. *Mineral Petrol* 42:1-22.
- Alapieti T, Halkoaho T (1995) Cryptic variation of augite in the Penikat Layered Intrusion, Northern Finland, with reference to megacyclic units and PGE-enriched zones. *Mineral Petrol* 54:11-24.
- Alapieti T, Lahtinen J (1986) Stratigraphy, petrography and platinum-group element mineralization of the early Proterozoic Penikat layered intrusion, Northern Finland. *Econ Geol* 81:1126-1136.
- Halkoaho TAA, Alapieti TT, Lahtinen JJ (1990a). The Sompujärvi PGE reef in the Penikat layered intrusion, northern Finland. *Mineral Petrol* 42:39-55.
- Halkoaho TAA, Alapieti TT, Lahtinen JJ (1990b) The Ala-Penikka PGE reefs in the Penikat layered intrusion, Northern Finland. *Mineral Petrol* 42:23-38.
- Halkoaho TAA, Alapieti T, Huhtelin T (2005). The Sompujärvi, Ala-Penikka and Pasivaara PGE reefs in the Penikat layered intrusion, northern Finland. In: Alapieti, TT, Kärki AJ (eds) *Field Trip Guidebook*. Geological Survey of Finland, pp 110.
- Huhtelin T, Alapieti T, Lahtinen J (1990) The Paasivaara PGE Reef in the Penikat layered intrusion, Northern Finland. *Mineral Petrol* 42:57-70.
- Iljina M, Hanski E (2005) Layered mafic intrusions of the Tornio-Näränkävaara belt. In: M. Lehtinen, P. Nurmi, T. Rämö (eds.) *Precambrian Bedrock of Finland – Key to the Evolution of the Fennoscandian Shield*. Elsevier, Amsterdam, pp 103-138.
- Maier WD, Halkoaho T, Huhma H, Hanski E, Barnes SJ (2018) The Penikat intrusion, Finland: geochemistry, geochronology, and origin of platinum-palladium reefs. *J Petrol* 59:967-1006.