



Chrome spinel-hosted melt inclusions in Paleoproterozoic primitive volcanic rocks, northern Finland: Evidence for coexistence and mixing of komatiitic and picritic magmas

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ABSTRACT

The Paleoproterozoic ca. 2.05 Ga ultramafic volcanic rocks occurring in the Central Lapland Greenstone Belt are classified as Ti-enriched komatiites and picrites. Some of the rocks are high in Cr (ca. 4000 ppm) and contain fresh chrome spinel grains hosting melt inclusions up to 50 μm in size. These inclusions enabled us to study the compositional features of the magmas at the time of melt entrapment. Chrome spinels are divided into the low-Ti and high-Ti types reflecting crystallization from komatiitic and picritic parental magmas, respectively. There is a good correlation between the major element compositions of the melt inclusions and their host spinels, with picritic melts being found in high-Ti spinels and komatiitic melts in low-Ti spinels. MgO contents measured in the inclusions range between 10 and 22 wt.%. Trace element analyses performed by LA-ICP-MS and SIMS revealed two contrasting magma compositions, which are either depleted or highly enriched in incompatible elements and produce convex-upwards or LREE-enriched chondrite-normalized REE patterns, respectively. Due to the shielding effect of the host spinel, melt inclusions provide information on the original mobile trace element contents (Li, K, Ba, Sr, Be) and LILE/HFSE ratios of the magmas.

Interestingly, spinel grains carrying both depleted and enriched melt inclusions were discovered in a single komatiitic sample, demonstrating the coexistence and mixing of two different primitive magma types. The whole-rock and melt-inclusion geochemical data together with previous Nd and Os isotopic results indicate an asthenospheric origin of the magmas with insignificant crustal contamination or interaction with the sub-continental lithospheric mantle. We suggest that adiabatic upwelling of a Paleoproterozoic mantle plume was able to simultaneously produce komatiitic and picritic magmas from an originally depleted source via dynamic melting involving re-fertilization and re-melting processes and re-melting processes, though the details of these processes are difficult to constrain in a quantitative manner. These processes should be taken into account when using the geochemistry of Precambrian primitive magmas for assessing the temporal evolution of mantle plume reservoirs.

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1. Introduction

Melt inclusions (MI) or their devitrified counterparts trapped in magmatic minerals provide a tool for studying the compositional features of magmas at the time of melt entrapment (e.g., Kamenetsky, 1996; Danyushevsky et al., 2002a). They can reveal information on magmatic processes, such as magma mixing, that may be unavailable from whole-rock chemical data, and if trapped in early-crystallizing phases such as Mg-rich olivine and chrome spinel, they can retain chemical information on the most primitive magma composition before it was modified by crystal fractionation, crustal contamination or magma mixing. In addition, due to the shielding effect of the enclosing mineral phase, melt inclusions have a potential to record the original

mobile and volatile element characteristics (Li, K, Ba, Sr, Be, CO₂, H₂O) and LILE/HFSE ratios of the magmas, even for metamorphosed early Precambrian rocks. McDonough and Ireland (1993) were the first to characterize komatiitic magmas by *in-situ* analysis of melt inclusions hosted by olivine phenocrysts. Since then, several studies have been carried out using olivine- or spinel-hosted melt inclusions in komatiites, particularly in attempts to unravel the original volatile element concentration of komatiitic melts and obtain constraints on the temperature of the erupted melts and their mantle sources (Shimizu et al., 2001, 2009; Danyushevsky et al., 2002b; Kent et al., 2005; Kallio et al., 2007; Berry et al., 2008; Kamenetsky et al., 2010; Gurenko and Kamenetsky, 2011).

In this paper, we present new chemical data on crystallized melt inclusions and their host chrome spinels discovered in Palaeoproterozoic primitive volcanic rocks from the Central Lapland Greenstone Belt in northern Finland. These volcanic rocks are characterized by a large variation in the parental magma compositions (Hanski et al., 2001),

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and preserved melt inclusions in early formed spinels provide a good tool to unravel the relationship between these magmas.

2. Primitive volcanic rocks in northern Finland

Paleoproterozoic ultramafic volcanic rocks are widely distributed in the Central Lapland Greenstone Belt in northern Finland and its extensions in northern Norway (e.g., Barnes and Often, 1990; Hanski et al., 2001), being found in a zone several hundred kilometers in length. In northern Finland, they are assigned to the Savukoski Group together with associated pelitic metasediments and mafic metavolcanics (Hanski and Huhma, 2005). They occur as massive or pillowed lavas and various volcanoclastic deposits (Saverikko, 1985; Hanski et al., 2001).

Hanski et al. (2001) classified the primitive volcanic rocks of the Central Lapland Greenstone Belt into two main types, Ti-enriched komatiites and picrites, with both varieties occurring along the whole length of the greenstone belt. For the discussion of the adopted nomenclature, the reader is referred to Hanski et al. (2001). In the field or under the microscope, the two rocks types do not differ from each other. In terms of the MgO content, the komatiites and picrites are also comparable with their MgO often exceeding 20 wt.%, but they differ drastically with respect to their incompatible element characteristics (Hanski et al., 2001). As the name implies, Ti-enriched komatiites are higher in titanium than the typical Archean Munro Township-type komatiites. In spite of this moderate enrichment in TiO₂, the rocks have low contents of LREE and low (LREE/MREE)_{CN} ratios (<1; CN indicates chondrite-normalized). This is coupled with high (MREE/HREE)_{CN} (>1) resulting in hump-shaped chondrite-normalized REE patterns. The picrites are still higher in TiO₂ and, in contrast to the komatiites, display high (LREE/HREE)_{CN} ratios. Due to a variable enrichment in TiO₂, Al₂O₃/TiO₂ ratios are subchondritic in both magma types, ranging between 5 and 14. Intermediate types between the mentioned end-members have also been found. In addition, the primitive volcanic rocks are often accompanied by basaltic rocks that were evolved from komatiitic or picritic parental magmas.

Using the Sm–Nd method, Hanski et al. (2001) determined an age of ca. 2.05 Ga for the komatiites of the Savukoski Group. Minor variation in initial ε_{Nd} (from +2 to +4) was concluded by Hanski et al. (2001) to be a result of a small degree of assimilation of country rock sediments. The obtained Nd isotopic data indicate that, despite their compositional differences, both the LREE-depleted komatiites and LREE-enriched picrites were generated from a similar mantle source with a long-term LREE depletion (initial ε_{Nd} +4) similar to that of the contemporaneous model depleted mantle (cf. DePaolo, 1981). Before this study, chromites separated from Lapland komatiites were utilized for obtaining a precise initial Os isotopic composition (γ_{Os} = 0.1 ± 0.5) of komatiitic melts, implying a nearly chondritic isotopic evolution of the mantle source (Gangopadhyay et al., 2006). In this respect, the Lapland komatiites share the source characteristics of typical Archean Munro Township-type komatiites (cf. Gangopadhyay and Walker, 2003; Puchtel et al., 2004a). The trace element and isotopic data are consistent with an asthenospheric origin of the magmas and preclude significant contamination during the passage of the magmas through the subcontinental lithospheric mantle (SCLM) and continental crust. Hanski et al. (2001) concluded that the large differences in incompatible trace element concentrations between komatiitic and picritic lavas are unlikely to be the result of variations in the conditions of partial melting of a single homogenous mantle source.

The metavolcanic rock samples that are the subject of this study were picked from two areas, Jeesiörova and Peuramaa, located ca. 30 km apart from each other (Fig. 1). Though having a limited exposure, the Jeesiörova area was chosen because of its mineralogical preservation, which is the best so far encountered in the komatiite belt in northern Finland, despite the closeness to a long fault zone, the “Sirkka line”, running on the southern edge of the Kittilä greenstone complex (Fig. 1). In this area, olivine has been ubiquitously replaced by secondary

minerals, but clinopyroxene occurs as a poikilitic intercumulus mineral in olivine cumulates, as prismatic grains in gabbroic differentiates and as needle-like crystals in pillowed and massive lavas (Fig. 2a). In addition, ultramafic lavas contain euhedral chromite grains, up to 0.3 mm in size, which were liquidus phases together with olivine during magma emplacement. These chromites are commonly translucent and dark brown in transmitted light (Fig. 2b) and, in reflected light, show no or only narrow magnetite rims, demonstrating that they are rather fresh. They often contain (recrystallized) rounded or ovoid melt inclusions up to 50 μm in size (Fig. 2c–d).

The lavas in the Peuramaa area are mostly basaltic and occur as massive and pillowed lavas, tuffs, and cogenetic mafic dikes. Picritic rocks are interbedded with the mafic lavas and occur either as massive, porphyritic lavas or lapilli tuffs. All the mentioned rock types form geochemically a coherent suite of rocks produced through fractional crystallization of a picritic parental magma (Hanski et al., 2001).

3. Samples and methods

The melt inclusion study was performed on chromites separated from three samples. These samples were collected from two areas, Jeesiörova and Peuramaa (Fig. 1), and belong to the sample set used in the earlier geochemical and isotopic studies by Hanski et al. (2001) and Gangopadhyay et al. (2006). Samples 17-EJH-97 and 12D-PPR-97 represent Jeesiörova komatiites and sample 800-LVP-46 is a picrite from Peuramaa. The bulk rock compositions of the samples were determined by Hanski et al. (2001) using the XRF and ICP-MS methods and are listed in Table 1. Analytical details are found in op. cit.

Employing standard separation methods (concentration table, heavy liquids, magnetic separation), chromite separates were produced from each sample. Chrome spinel compositions were determined at the Geological Survey of Finland, Espoo, using a CAMECA SX50 electron microprobe, operating at 25-kV accelerating voltage and 47-nA beam current with a beam diameter of 1 μm. After re-homogenization of the melt inclusions by heating the chromite grains for two minutes in a helium atmosphere at temperatures up to 1400 °C (see Sobolev et al., 1980), major and minor element abundances of the inclusions and their host minerals were obtained at the University of Tasmania (UT), Australia, with a CAMECA SX50 electron microprobe, using 15-kV accelerating voltage and 20-nA beam current.

Trace element concentrations of homogenized melt inclusions were determined *in situ* by two different methods, laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and secondary ion mass spectrometry (SIMS). Glasses were analyzed by LA-ICP-MS at the University of Tasmania. This instrumentation comprises a New Wave Research UP193SS Nd-YAG (193 nm) laser coupled to an Agilent 7500a quadrupole ICP-MS. Analyses were performed in a He atmosphere by ablating 20 to 40 μm-diameter spots at a rate of 10 shots/sec using a laser power of ~2 J/cm². The instrument was optimized for sensitivity on mid- to high-mass isotopes (in the range 80–240 a.m.u.) and for minimal molecular oxide species (i.e., ²³²Th¹⁶O/²³²Th < 0.3%) and doubly-charged ion species (i.e., ⁴⁴Ca⁺⁺/⁴⁴Ca⁺ < 0.3%) production. The analysis time for each sample was 60 seconds, comprising a 30 second measurement of background (laser off) and a 30 second analysis with laser on. Instrument calibration was performed by ablating the NIST612 glass standard. Data reduction was undertaken according to standard methods (Longerich et al., 1996) using the NIST612 glass as a primary reference material and SiO₂, analyzed by the electron microprobe (EMPA), as the internal standard. USGS BCR-2 g glass was repeatedly analyzed throughout analytical sessions and was used as a secondary reference material. The accepted values in BCR-2 g were reproduced within 5 relative % for most elements. The analytical quality was further tested by comparing CaO derived from EMPA and LA-ICPMS. The results from both methods deviate from each other by <2%.

Melt inclusion analyses by SIMS were performed at Institute of Microelectronics (Yaroslavl', Russia) using a CAMECA ims4f. Samples

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