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Volatile concentrations in olivine-hosted melt inclusions from meimechite and melanephelinite lavas of the Siberian Traps Large Igneous Province: Evidence for flux-related high-Ti, high-Mg magmatism

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ABSTRACT

The origin of high-Mg melts remains one of the most highly debated questions in igneous petrology. There are two contrasting points of view, namely, (1) melt initiation in a rising high-temperature plume, and (2) mantle melting due to fluxing by water. To address this question we determined H_2O, CO_2, F, Cl and S concentrations in olivine-hosted melt inclusions of high-Mg volcanic rocks of the Siberian Traps Large Igneous Province that bracket the main pulse of volcanism at about 252–250 Ma, and can be classified as melanephelinites and meimechites. Both rock types belong to the high-Ti rock series. Correcting measured H_2O, CO_2, F, Cl and S concentrations in homogenized primary meimechite melt inclusions to primary meimechite melt composition using experimental melt compositions resulted in corrected melt-inclusion, volatile compositions of ~3.88 wt% H_2O, ~1477 ppm CO_2, ~4214 ppm F, ~2.08 wt% Cl and ~2490 ppm S. These values are viewed as minimum estimates for the original volatile concentrations in the melt because of the high probability for degassing during melt crystallization and/or during experiment homogenization. Olivine-hosted homogenized melt inclusions from melanephelinites yielded lower corrected concentrations of ~1.06 wt% H_2O, ~998 ppm CO_2, ~3242 ppm F, ~607 ppm Cl and ~2131 ppm S. We also measured water concentrations in clinopyroxenes of melanephelinites by FTIR, obtaining values as high as 133 ppm H_2O, which corresponds to 0.91 wt% in the melt, in general agreement with data obtained by SIMS on the olivine-hosted melt inclusions. Olivine grains from melanephelinites are characterized by evolved compositions (Fo 0.80–0.86). Extrapolation to a primitive melanephelinite melt by simple fractional crystallization suggests that it could also contain high H_2O concentrations (up to ~ 3 wt%). Analyzed meimechite and melanephelinite whole-rock samples are characterized by trace-element patterns that are typical of mantle-derived melts and by Sr-Nd isotope ratios that exclude crustal contamination or derivation from ancient lithospheric mantle. Thus, high volatile concentrations can be attributed to sub-lithospheric mantle source regions. This supports the notion that high-Mg melts form by volatile fluxing of the asthenospheric mantle rather than by decompression melting under relatively dry conditions of a rising abnormally high-temperature mantle plume.

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1. Introduction

The origin of high-Mg melts such as picrites, boninites, komatiites and meimechites remains a hot topic in igneous petrology, with both a decompressing high-temperature plume (e.g., Arndt et al., 1998a,b; Sobolev et al., 1991, 2009b), and water-fluxed melting (e.g., Fiorentini et al., 2008; Gurenko and Kamenetsky, 2011) serving as the contending models. Sometimes, the same rock types are attributed to one or another model (e.g., Arndt, 2003; Parman and Grove, 2005; Sobolev et al., 2016). Some high-Mg melts (boninite lavas are an obvious example) exhibit both high-temperature and water fluxing characteristics (e.g., Danyushevsky et al., 1995). Meimechites are of particular interest because of their abundance in the Siberian Traps, one of the largest igneous provinces in the world. Elkins-Tanton et al. (2007) assumed there was 1 wt% H_2O in candidate primary meimechite melts and estimated their temperature as 1700 °C at 5.5 GPa, based on a phase equilibrium experiment. Sobolev et al. (2009b) assumed that primary meimechite melt contained 6 wt% CO_2 and they measured for such melt 2 wt% H_2O by using secondary ion mass spectrometry (SIMS), from which calculated that their temperature was 1600–1800 °C at 6–8 GPa. Such temperature estimations are among the highest for Earth magmas. However, real concentrations of H_2O and other volatiles in meimechites may be higher than reported previously. In this paper we address this question by analyzing H_2O, CO_2, F, Cl and S concentrations in olivine-hosted melt inclusions from high-Mg melts of the Siberian Traps Large Igneous Province. We also discuss applicability of Cr-spinel-hosted melt inclusions for estimation of the primitive meimechite melt. We obtain lower MgO concentrations for the primitive meimechite melt in comparison to previous estimations, which were based on experiments with olivine-hosted melt inclusions. The measured concentrations for H_2O, CO_2, F, Cl and S are higher than reported in previous studies, suggesting that mantle melting temperatures to produce meimechite magmas are not as high as previously reported.

2. Outline of geology

The Siberian Traps Large Igneous Province is an enormous magmatic region which was active from the late Permian to the Late Triassic (Ivanov et al., 2013), with the peak of volcanic activity occurring at the Permian-Triassic boundary (Renne and Basu, 1991; Reichow et al., 2002, 2009; Burgess and Bowring, 2015). Volcanic and intrusive rocks with these ages spread from the Uralian mobile belt in the west to the central part of the Siberian Craton in the east, and from the Altay mobile belt in the south to the Taimyr mobile belt in the north (Fig. 1). The lavas covered ~7×10^6 km^2 (Masaitis, 1983) of northern Pangea, which at the time was bounded by long-established Paleozoic and Mesozoic subduction systems (Nikishin et al., 2002; Ivanov, 2007, 2015) (Fig. 2).

The thickest lava units are located in the northern strip of the exposed part of the province in the Noril'sk-Kharaelakh – Maimecha-Kotuy area (Fig. 1). There is a continuous ~3.5 km thick lava pile at the Noril'sk-Kharaelakh area (Fedorenko et al., 1996), which is famous for the cross-cutting intrusions that host the largest Cu-Ni-PGE deposit in the world (Naldrett et al., 1992; Ryabov et al., 2013; Krivolutskaya, 2016). The great majority of this lava pile is composed of compositionally uniform low-Ti basalts (Figs. 3, 4C). However, the oldest formation in this lava pile is composed of high-Ti basalts. Atop that lava flow are the Gudchikhinsky and Tuklonsky Formations, both containing several picrite units. Variable picrite, lamproite and felsic dykes cut the Noril'sk-Kharaelakh section (Ivanov et al., 2013; Ryabov et al., 2013). Geologic, paleomagnetic and geochronologic data show that the lava pile was formed rapidly at the Permian – Triassic boundary at about ~252 Ma over a duration of less than one million years (Kamo et al., 1996; Reichow et al., 2009; Pavlov et al., 2011, 2015; Burgess and Bowring, 2015) (Fig. 3).

The Maimecha-Kotuy area is the toponym for meimechite — a high-Mg, high-Ti volcanic rock (Le Bas and Streckeisen, 1991; Le Bas, 2000) (Fig. 4). Meimechites have also been discovered in the Paleoproterozoic Cape Smith Belt (Baragar et al., 2001), the Permian Tarim Large Igneous Province in China (Jiang et al., 2004), and the Jurassic Karoo Large Igneous Province in South Africa (Heinonen and Luttinen, 2008). Meimechite in the Maimecha-Kotuy area occurs as flows and dykes in the upper part of a ~4-km thick lava pile (Fedorenko et al., 1996) (Fig. 3). The meimechite lava unit is underlaid by high-Mg alkaline lavas of the Delkansky Formation. The lower half of the Maimecha-Kotuy lava section is composed of low-Ti basalts, and the Arydzhansky Formation of high-Ti alkaline lavas (Figs. 3, 4C). According to regional stratigraphic schemes the Arydzhansky Formation is coeval to the lowermost tuffaceous unit (Fedorenko et al., 1996). Paleomagnetic data suggests that the Arydzhansky Formation corresponds to the Noril'sk-Kharaelakh lava section (Fetisova et al., 2014).

The Maimecha-Kotuy area is also known for the Guli massif of ultrabasic alkaline rocks and carbonatites (Fedorenko et al., 1996). Geologic relations suggest that meimechites cap the Guli massif and finalize the voluminous volcanic episode, whose total duration is estimated by U-Pb geochronology to be about 2 million years, starting within the latest Permian and continuing mainly during the Early Triassic (Kamo et al., 2003; Burgess and Bowring, 2015).

The Late Permian - Early Triassic volcanism was the most volumetrically intensive and widespread within the Siberian Traps Large Igneous Province (Reichow et al., 2009; Burgess and Bowring, 2015). Noteworthy is the fact that the dominant magma type during that episode was low-Ti basalt (Figs. 3, 4C). The volume of meimechite and high-Mg alkaline lavas and intrusions is also significant and has been estimated as ~5×10^4 km^3 (Ivanov et al., 2013). However, it is two orders of magnitude smaller than the total volume of ~4×10^6 km^3 of the Siberian Traps Large Igneous Province (Masaitis, 1983; Ivanov, 2007).

Following the cataclismic Late Permian - Early Triassic volcanic outpourings, a new eruptive episode – also dominated by low-Ti basalt – occurred during the Middle to Late Triassic, producing an estimated volume ~1.8–3.75 $\times 10^5$ km^3 (Ivanov et al., 2013).

3. Samples and methods

3.1. Samples

For this work we collected high-Mg rock samples with large olivine crystals, which are most abundant in the high-Ti rock series. The studied samples include two melanephelinite lavas (samples 1700 and 1787) and three meimechite lavas (samples 1656, 1792 and M9a). According to the International Union of Geological Sciences (IUGS) classification scheme, meimechite is high-Mg and high-Ti rock with MgO > 18 wt% and TiO_2 > 2 wt%, when calculated on volatile-free basis (Le Bas and Streckeisen, 1991; Le Bas, 2000). One of the meimechite samples (sample 1656) is characterized by MgO > 35 wt%, and is enriched in cumulative olivine. Here, we characterize this rock as a high-Mg meimechite. Olivine-grain separates from another meimechite sample (1658), for which rock chips and powders are no longer available, have also been used in this study.

Meimechite samples 1658, 1792 and M9a belong to the Maimecha Formation and high-Mg meimechite (sample 1656) is from a dyke that cross cuts the lava layers (Fig. 3). Melanephelinites are silica undersaturated alkaline rocks with SiO_2 in the range of 41–45 wt%, picritic MgO (12–18 wt%), and normative olivine and nepheline. Studied samples 1700 and 1787 have 3 wt% TiO_2 (Table 1). They were collected from the Delkansky and Arydzhansky Formations, respectively (Fig. 3). Although the number of samples in this study is relatively modest, our sample suite contains all major high-Ti melts erupted in the Maimecha-Kotuy area (Fig. 1), and they temporally bracket the most voluminous Late Permian - Early Triassic volcanic episode of the Siberian Traps Large Igneous Province (Fig. 3).