Lithos 216–217 (2015) 73–80

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Helium isotopic evidence for modification of the cratonic lithosphere during the Permo-Triassic Siberian flood basalt event

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ARTICLE INFO

Article history:
Received 1 September 2014
Accepted 1 December 2014
Available online 6 December 2014

Keywords:
Helium
Helium isotopes
Noble gases
Peridotites
Siberia
SCLM
Udachnaya and Obnazhennaya

ABSTRACT

Major flood basalt emplacement events can dramatically alter the composition of the sub-continental lithospheric mantle (SCLM). The Siberian craton experienced one of the largest flood basalt events preserved in the geologic record — eruption of the Permo-Triassic Siberian flood basalts (SFB) at ~250 Myr in response to upwelling of a deep-rooted mantle plume beneath the Siberian SCLM. Here, we present helium isotope ($^3He/^4He$) and concentration data for petrologically-distinct suites of peridotitic xenoliths recovered from two temporally-separated kimberlites: the 360 Ma Udachnaya and 160 Ma Obnazhennaya pipes, which erupted through the Siberian SCLM and bracket the eruption of the SFB. Measured $^3He/^4He$ ratios span a range from 0.1 to 9.8 R_A (where R_A = air $^3He/^4He$) and fall into two distinct groups: 1) predominantly radiogenic pre-plume Udachnaya samples (mean clinopyroxene $^3He/^4He = 0.41 \pm 0.30$ R_A (1σ); $n = 7$ excluding 1 outlier), and 2) 'mantle-like' post plume Obnazhennaya samples (mean clinopyroxene $^3He/^4He = 4.20 \pm 0.90$ R_A (1σ); $n = 5$ excluding 1 outlier). Olivine separates from both kimberlite pipes tend to have higher $^3He/^4He$ than clinopyroxenes (or garnet). Helium contents in Udachnaya samples ([He] = 0.13–1.35 μcm^{3}STP/g; $n = 6$) overlap with those of Obnazhennaya ([He] = 0.05–1.58 μcm^{3}STP/g; $n = 10$), but extend to significantly higher values in some instances ([He] = 49–349 μcm^{3}STP/g; $n = 4$). Uranium and thorium contents are also reported for the crushed material from which He was extracted in order to evaluate the potential for He migration from the mineral matrix to fluid inclusions. The wide range in He content, together with consistently radiogenic He-isotope values in Udachnaya peridotites suggests that crustal-derived fluids have incongruently metasomatized segments of the Siberian SCLM, whereas high $^3He/^4He$ values in Obnazhennaya peridotites show that this section of the SCLM has been overprinted by Permo-Triassic (plume-derived) basaltic fluids. Indeed, the stark contrast between pre- and post-plume $^3He/^4He$ ratios in peridotite xenoliths highlights the potentially powerful utility of He-isotopes for differentiating between various types of metasomatism (i.e., crustal versus basaltic fluids).

1. Introduction

Helium isotopes ($^3He/^4He$) are powerful tracers for distinguishing between mantle-derived and crustal fluids. Radiogenic ^4He accumulates from the radioactive decay of U- and Th-series radionuclides and becomes strongly enriched in continental crust, whereas ^3He is overwhelmingly primordial, stored in Earth's mantle since accretion (e.g., Clarke et al., 1969). As a result, different tectonic domains exhibit markedly different $^3He/^4He$ ratios (typically reported relative to air; $R_A = {}^3He/^4He$ of air $= 1.4 \times 10^{-6}$), which can be used to distinguish between various terrestrial reservoirs and characterize the chemical structure of the mantle (see review by Hilton and Porcelli, 2014). Disparate ratios in mantle-derived samples illustrate the long-term isolation and preservation of high-$^3He/^4He$ (≥50 R_A; Stuart et al., 2003) plume-derived materials from the well mixed and more extensively degassed depleted MORB mantle (DMM) (8 ± 1 R_A; Graham, 2002). However, the He-isotope signature of the sub-continental lithospheric mantle (SCLM) remains relatively poorly characterized.

The SCLM represents a minor (~2.5%), but potentially important portion of the total terrestrial mantle. Due to isolation from the convecting mantle, the SCLM can potentially generate and preserve significant chemical heterogeneity over Gyr time scales (McDonough, 1990; Walker et al., 1989). Previous studies have demonstrated that

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http://dx.doi.org/10.1016/j.lithos.2014.12.001

the SCLM has slightly lower (i.e., more radiogenic) $^3He/^4He$ values than the DMM (Ackert et al., 1999; Barfod et al., 1999; Dunai and Baur, 1995; Dunai and Porcelli, 2002; Gautheron et al., 2005; Matsumoto et al., 1998, 2000; Porcelli et al., 1986; Reid and Graham, 1996), with an estimated $^3He/^4He$ ratio of 6.1 ± 0.9 R_A (Gautheron and Moreira, 2002). However, radiogenic ingrowth models predict significantly lower $^3He/^4He$ values, based on the relatively high U/He ratios measured in SCLM peridotites (e.g., Craig and Lupton, 1976). To sustain such high $^3He/^4He$ values in the SCLM, therefore, Ballentine (1997) and Gautheron and Moreira (2002) have proposed open-system, steady-state flux models, whereby He from the asthenosphere is fluxed into the SCLM over ~100 Myr timescales. Significantly, these studies have mostly focused on peridotites and largely ignored the petrological context and metasomatic history of samples, which can potentially complicate the helium budget in the SCLM via the addition of extraneous metasomatic helium fluxes.

The Siberian craton was assembled by the amalgamation of several island-arc terrains during the Archean and Proterozoic (Pearson et al., 1995a,b; Rosen et al., 1994). It has subsequently experienced a complex history of Phanerozoic metasomatism, including emplacement of >1000 kimberlite intrusions between Silurian and Jurassic times (Howarth et al., 2014; Fig. 1). Here we focus on petrologically well-characterized peridotite xenoliths, which were transported to the surface by two Siberian kimberlites: the Late-Devonian Udachnaya (360 Ma) and Jurassic Obnazhennaya (160 Ma) pipes (Bristow et al., 1991; Smelov and Zaitsev, 2013). As these eruptions bracket the ~250 Ma Siberian flood basalts (SFB) (Ivanov et al., 2013; Reichow et al., 2002), they provide insight into the Phanerozoic metasomatic history of the Siberian SCLM. Pre-SFB Siberian kimberlitic material displays SCLM-like He-isotopes (i.e., ~5.7 R_A; Sumino et al., 2006), which are interpreted to represent radiogenic addition to a high (~15 R_A) He-isotope plume source. Notably, the highest measured He-isotope values associated with the SFB are ~12.7 ± 0.2 R_A (Basu et al., 1995), suggesting a discernible plume contribution, clearly distinct from low-degree partial melts derived from the continental lithosphere–asthenosphere boundary ($^3He/^4He < 7\ R_A$; Day et al., 2005).

In this contribution, we report the He isotopic and abundance characteristics in minerals from Siberian mantle peridotite xenoliths that erupted both prior to and following the SFB to assess the effects of metasomatism and plume impingement on volatiles of the Siberian SCLM. In addition, we report U, Th, and Li results for a subset of the xenolith mineral separates, and combine these results with previously published major- and trace-element data to investigate responses in the Siberian SCLM to pervasive flood basalt melt modification at the Permo-Triassic boundary. We have selected various mineral phases from peridotite xenoliths, equilibrated at different temperatures and depths in the mantle, to provide a comprehensive overview of changes occurring throughout the lithosphere. By considering petrological constraints, together with He-isotope variations, we are able to assess the potential effects of plume–lithosphere interaction and the role of metasomatic fluids in modifying the SCLM.

2. Materials and methods

2.1. Sample petrology and petrogenesis

All xenolith samples ($n = 10$ for Obnazhennaya; $n = 10$ for Udachnaya) are granular to sheared spinel and garnet lherzolites (Lz) and have been characterized for their petrography and mineral chemistry by Howarth et al. (2014). These authors found that melts calculated

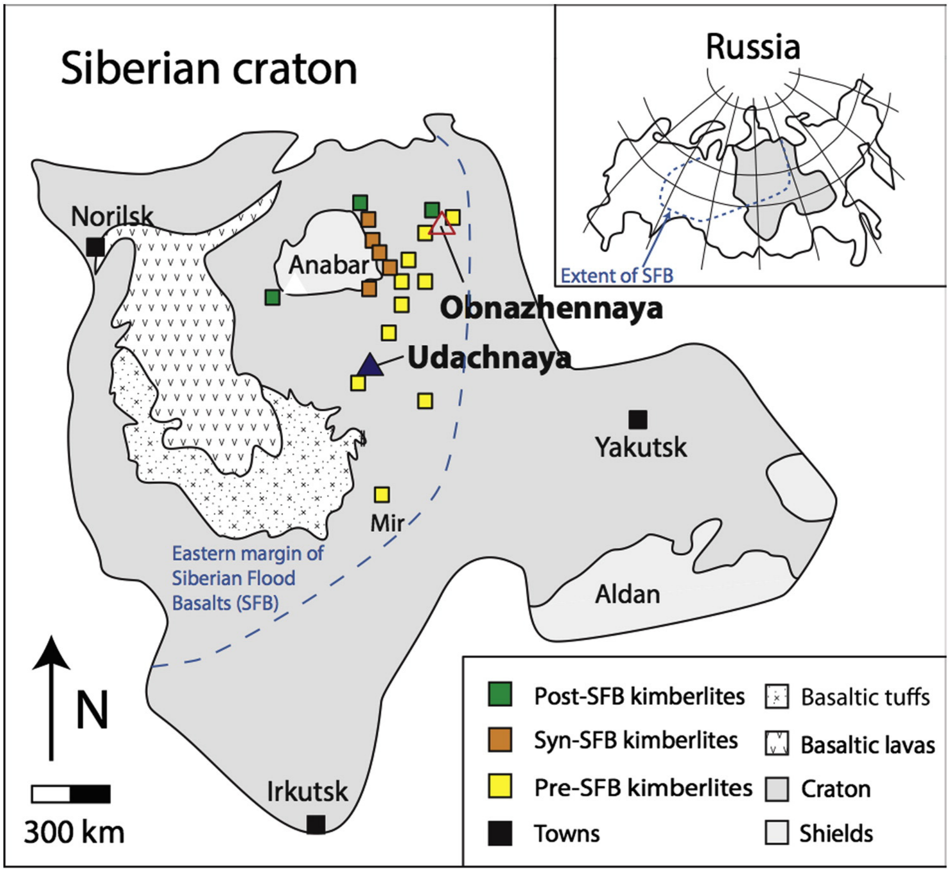

Fig. 1. Geological map of the Siberian craton with dashed lines showing the extent of the Siberian Large Igneous Province (LIP) associated with the Siberian Flood Basalts (SFB). Kimberlite pipes marked are divided by magmatic episode: Pre-SFB kimberlite: Silurian–Carboniferous (420–345 Ma). Syn-SFB kimberlite: Triassic (245–215 Ma). Post-SFB kimberlite: Jurassic (160–149 Ma). Map modified from Howarth et al. (2014).