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Superplume metasomatism: Evidence from Siberian mantle xenoliths

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ABSTRACT

The Siberian craton contains >1000 kimberlite intrusions of various ages (Silurian to Jurassic), making it an ideal locality for a craton-wide study on the evolution of the sub-continental lithospheric mantle (SCLM). The primary objective of this study is to characterize the temporal and spatial metasomatic effects on the Siberian SCLM, focusing on the metasomatic imprint rendered by the Siberian superplume. We report new major- and trace-element mineral data for mantle peridotite xenoliths, obtained from the Late Devonian Udachnaya and the Late Jurassic Obnazhennaya kimberlites, which bracket the thermal climax of the Siberian superplume.

Garnet compositions have two distinct trends in CaO–Cr_2O_3 space: 1) increasing CaO at constant Cr_2O_3 within the harzburgite field, and 2) decreasing CaO and Cr_2O_3 within the lherzolite field, moving from ultramafic compositions of Udachanaya toward more mafic compositions of Obnazhennaya. Zoned garnet grains have sinusoidal-REE patterns within their cores and display a gradational change to flat MREE–HREE profiles at the rims. Clinopyroxenes typically are LREE-enriched and have high Ti/Eu, indicating kimberlite rather than carbonatite metasomatism. Re-constructed melts in equilibrium with garnet REE chemistry indicate that Obnazhennaya garnets were overprinted by plume-derived basaltic fluids, whereas Udachnaya garnets were overprinted by kimberlite fluids. The ubiquitous plume signatures from the younger Obnazhennaya garnets is clear evidence for extensive metasomatism by mafic fluids within the SCLM during Siberian flood basalt (SFB) emplacement.

We present a four-stage model for the temporal evolution of the SCLM over the life cycle of the Siberian superplume: 1) Early-stage metasomatism from fluids circulating within the SCLM, resulting in refertilization from harzburgite to lherzolite in the SCLM; 2) kimberlitic metasomatism, caused by small-degree partial melting of SCLM, induced by superplume upwelling; 3) Syn-SFB basaltic metasomatism, as the result of extensive percolation of basaltic fluids derived from the main stages of superplume activity; and 4) Post-SFB local kimberlitic metasomatism, resulting in LREE enrichment of Obnazhennaya clinopyroxenes related to the eruption of the host kimberlite.

1. Introduction

Kimberlites provide rare windows into the sub-continental lithospheric mantle (SCLM), bringing mantle xenoliths to the Earth's surface from a region of depleted, less-dense material that is isolated from asthenospheric convection, and generally situated under ancient stable cratons. The majority of early studies of cratons were based on xenoliths derived from kimberlites of the Kaapvaal (South Africa) and Siberian cratons (Russia), which documented ubiquitous metasomatism of the SCLM (e.g., Boyd et al., 1997; Griffin et al., 1999a; Harte, 1987; Menzies et al., 1987; Pearson et al., 1995a). In particular, the SCLM beneath the Udachnaya kimberlite, Siberia, is one of the most geochemically well-characterized mantle sections, consisting of thousands of geochemical analyses of peridotite and eclogite xenoliths (e.g., Pokhilenko et al., 1999; Snyder et al., 1997; Sobolev et al., 1973). Metasomatism is a pervasive process in the mantle, as exhibited by mantle xenoliths worldwide (e.g., Menzies et al., 1987; Pokhilenko et al., 1993). Furthermore, metasomatic fluids are important agents for chemical exchange in the mantle; e.g., metasomatism is responsible for refertilization of previously depleted mantle sources (e.g., Doucet et al., 2013) and triggering diamond growth (Liu et al., 2009). However, to date, relatively few studies have considered the temporal evolution of the metasomatic processes responsible for the compositional variations reported in peridotites (e.g., Pokhilenko et al., 1999). Therefore, understanding the metasomatic effects of superplume-related fluids over the life cycle of the Siberian superplume has important implications for the evolution of the Siberian SCLM, which has previously not been discussed in detail.

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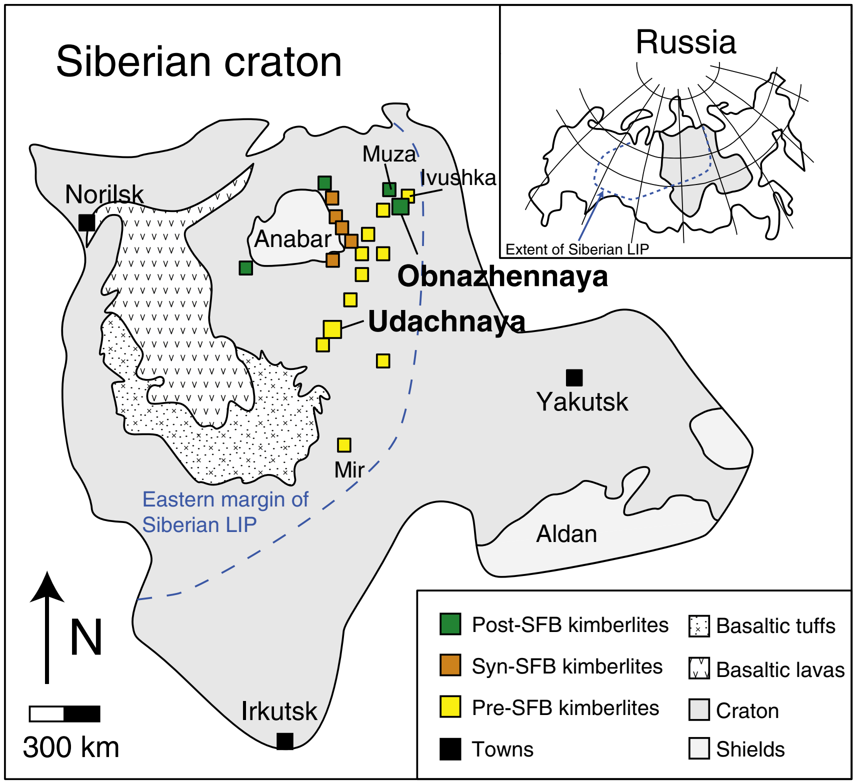

Fig. 1. Simplified geological map of the Siberian craton. Dashed line indicates the extent of the Siberian Large Igneous Province (LIP). Kimberlite pipes marked are divided by magmatic episode: Pre-SFB kimberlite: Silurian–Carboniferous (420–345 Ma). Syn-SFB kimberlite: Triassic (245–215 Ma). Post-SFB kimberlite: Jurassic (160–149 Ma).

The Siberian craton, which contains numerous (>1000) kimberlite pipes of various ages (Fig. 1), represents an ideal location for such a study. Here, we present major- and trace-element mineral data for xenoliths of Late Devonian Udachnaya and the Late Jurassic Obnazhennaya kimberlites. These xenoliths were selected in order to better characterize the temporal evolution of metasomatic processes affecting the SCLM over the life cycle of the Siberian superplume, as they represent sections of SCLM that pre- and post-date the Siberian flood basalts (SFB), respectively.

2. Geological setting

The Siberian craton (Fig. 1) encompasses ~4.4 × 10^6 km^2 of north-central Asia, extending from Lake Baikal in the south, towards the Arctic Ocean in the north, and bounded by the Yenisei River in the west and the Sea of Okhotsk to the east. The craton is comprised of several amalgamated Archean terranes ranging in age from 3.6 to 3.0 Ga (Rosen et al., 2005; Zonenshain et al., 1990), overlain by the SFB and Phanerozoic sediments. Of the Archean terranes, only three (Olenek, Anabar, and Magan) contain kimberlite pipes, which are divided into three Phanerozoic magmatic events: 1) Silurian to Early-Carboniferous (420–345 Ma); 2) Triassic (245–215 Ma); and 3) Late-Jurassic (160–149 Ma) (Davis et al., 1980; Griffin et al., 1999a; Kinny et al., 1997; Kostrovitsky et al., 2007; Pokhilenko et al., 1999). The Udachnaya pipe is one of the oldest within the craton, (~360 Ma, Griffin et al., 1999b); in contrast, the Obnazhennaya pipe was erupted during the youngest phase of kimberlite magmatism, at ~160 Ma (Blanco et al., 2013; Kinny et al., 1997). All Mesozoic kimberlites, including the Obnazhennaya pipe, are non-diamondiferous. Geographically, these kimberlites broadly trend N–NE across the craton, which has been suggested to reflect the migration of the craton over the Siberian superplume (Griffin et al., 2005; Pokhilenko et al., 2002).

The SFB represents the main stage of Siberian superplume activity, during which, large volumes of magma were generated and extruded over a relatively short time-interval (1–2 Ma; Kamo et al., 2003) at ~250 Ma (Carlson et al., 2006; Ivanov et al., 2013; Reichow et al., 2002). The arguments for and against the involvement of a mantle plume are finely balanced (c.f., Elkins-Tanton and Hager, 2000; Saunders et al., 2005). However, several lines of evidence, including uplift in the West Siberian Basin (Saunders et al., 2005), the requirement of a thermal anomaly in order to account for the formation of the basalts (Sharapov et al., 2008), and high ^{3}He/^{4}He ratios (Basu et al, 1995) all favor the involvement of a deep-rooted mantle plume. The SFB represents one of the largest igneous provinces in the world, having erupted an estimated 2 × 10^6 km^3 of basaltic magma (Zhuravlev, 1986), and consequently has often been referred to as a 'superplume' (e.g., Dobretsov, 2003; Pokhilenko et al., 1999).

3. Samples and petrography

The suites of samples analyzed in this study were obtained from the extensive peridotite xenolith collection at the V.S. Sobolev Institute of Geology and Mineralogy in the Siberian Branch of the Russian Academy of Sciences, Novosibirsk. Representative suites of peridotite samples from the Udachnaya and Obnazhennaya kimberlite pipes were acquired for detailed mineralogical analyses (Table 1). The Udachnaya pipe was selected due to the extremely fresh nature of the xenoliths and the well-defined mantle profile in this region (Boyd, 1984; Griffin et al., 1999b; Pokhilenko et al., 1999). The Obnazhennaya suite was selected as it is a significantly younger kimberlite post-dating the eruption of the SFB, thus representing a mantle section that has been affected by the main stage of superplume activity.

The majority of Udachnaya peridotite xenoliths are garnet lherzolites, however, less-common garnet harzburgites were also included in this