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# Plume impingement on the Siberian SCLM: Evidence from Re–Os isotope systematics

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We report Re–Os and platinum group element (PGE) systematics for a suite of 16 mantle peridotites from the Udachnaya (360 Ma) and Obnazhennaya (160 Ma) kimberlite pipes, Siberia. Xenoliths from these pipes bracket the thermal climax of the Siberian plume, which is represented by the emplacement of the ~250 Ma Siberian Flood Basalts (SFBs). Thus, these xenoliths represent snapshots of the sub-continental lithospheric mantle (SCLM) before and after plume modification. Pre-plume Udachnaya peridotite xenoliths generally display unradiogenic Os-isotopes with respect to CI-chondrite (expressed by γOs, the percentage difference between the Os-isotope composition of a sample and the average chondrite composition; $^{187}Os/^{188}Os - 0.127$), coupled with low $[Pd/Ir]_N$, for both whole-rock and olivine mineral-fraction analyses. Such signatures are typical of an ancient depleted cratonic mantle that underwent melt extraction. The preservation of unradiogenic Os-isotope compositions (γOs −5 to −14), coupled with low (<0.4) $^{187}Re/^{188}Os$ ratios, provides robust melt extraction age estimates, ranging from ~3 Ga to ~1.2 Ga. This indicates that craton stabilization/growth events not only occurred during the Archean, but also extended into the Proterozoic. A number (4) of post-plume Obnazhennaya peridotites display $^{187}Os/^{188}Os$ ratios (>0.1292), which overlap the convecting mantle range. At first glance, these observations are in agreement with garnet chemistry data, which indicate that high-degrees of silicate-melt percolated through the lithosphere during the emplacement of the SFB. However, Obnazhennaya olivine mineral-separates display 'depleted' systematics (>Fo 92 and low $[Pd/Ir]_N$), consistent with 'pristine' melt residues. We suggest that these Obnazhennaya xenoliths represent 'newly formed' residues associated with partial melts extracted from the impinging Siberian plume on the SCLM. During plume impingement, thermo-chemical erosion of the lithosphere is thought to be an important process, acting to remove the original depleted material. In the space created, new refractory residues may be able to infill this void; i.e., plume-subcretion. Importantly, two Obnazhennaya peridotites display very unradiogenic Os-isotope compositions (γOs −9 and −10) indicating that ancient depleted lithosphere is preserved after the emplacement of the SFB. Overall, we suggest that plume impingement may not be ubiquitous within the SCLM, leaving a lithosphere that is characterized by both its original depleted residues and newly formed, plume related residues.

In addition, two samples from Obnazhennaya and one from Udachnaya, contain highly radiogenic $^{187}Os/^{188}Os$ ratios (γOs > +85). Such radiogenic values cannot be accounted for by kimberlitic or plume-related metasomatism. Instead, these samples reflect metasomatism from fluids that derived from a source characterized by long-term high $^{187}Re/^{188}Os$, such as recycled subducted material (i.e., oceanic crust and sediments). These lithologies were introduced into the SCLM during craton growth events from ~1.8 to 3.0 Ga. The identification of such samples reflects an important metasomatic source within the SCLM. Overall, these two suites of mantle peridotites reveal the complex evolution of the Siberian cratonic lithosphere, from birth in the Archean, followed by major depletion events during the Proterozoic, and ending with major tectonothermal perturbation during the impingement of the Siberian plume.



## 1. Introduction

Cratons are commonly underlain by thick lithospheric roots, which vary in composition and thermal state, reflecting the tectonothermal history of the overlying crust (e.g., Boyd et al., 1985; Pearson, 1999;

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Rudnick and Nyblade, 1999; Griffin et al., 2002). Thus, constraining the age and evolution of the sub-continental lithospheric mantle (SCLM) has important implications for our understanding of continent evolution over geological time. In particular, the Siberian craton contains some of the oldest continental crustal rocks on Earth (e.g., ~3.5 Ga TTG complexes; Turkina et al., 2007). It is generally considered that craton stabilization occurred at this time, whereby large degree partial melts (>30%) were extracted from the mantle (e.g., Rosen et al., 1994; Walter, 1998; Griffin et al., 2002). Consequently, this resulted in the formation of a thick refractory harzburgitic keel, isolated from the convecting asthenosphere (Boyd et al., 1985; Pearson et al., 1995a; Pearson, 1999; Herzberg, 2004; Aulbach, 2012). Fragments of the lithosphere under Siberia have been sampled as xenoliths, brought up by kimberlitic magmas. Numerous kimberlite pipes of various ages have been described within the Siberian craton, providing invaluable 'snapshots' of the evolution of the Siberian SCLM over time. In particular, geochemical studies of xenoliths obtained from Paleozoic kimberlites (e.g., Udachnaya) suggest that a thick (~200 km), old (~3–1.8 Ga), diamondiferous lithosphere was present at this time (e.g., Pearson et al., 1995a; Boyd et al., 1997; Griffin et al., 2002; Ionov et al., 2011). In contrast, xenoliths brought up by younger Mesozoic kimberlite pipes (e.g., Obnazhennaya) appear to sample a significantly thinner (~150 km), diamond-barren lithosphere (Griffin et al., 1999b; Pokhilenko et al., 1999; Ashchepkov et al., 2014; Howarth et al., 2014).

The age and evolution of such lithospheric regions can be effectively constrained by investigating the Re–Os isotopic systematics of well characterized mantle xenoliths. The Re–Os isotopic system is particularly effective in seeing past local metasomatic disturbances, tracking major tectonothermal episodes, such as melt extraction events (i.e., craton stabilization). This is largely due to the behavior of Re–Os during melting. The P-PGEs (Pt and Pd) and Re are more incompatible than the I-PGEs (Os, Ir, and Ru) during melting (e.g., Walker et al., 1989; Carlson and Irving, 1994; Pearson et al., 1995a, 2002, 2004; Shirey and Walker, 1998; Griffin et al., 2002). During melting, Re is preferentially partitioned into the melt; however, Os is retained in the Re-poor residue. This results in low, time-integrated $^{187}Os/^{188}Os$ ratios. Over geological time, this has led to large differences in Os-isotopic ratios between the SCLM, which is typically characterized by unradiogenic values, i.e., $\gamma Os < 0$ (average cratonic $^{187}Os/^{188}Os$ — 0.113; Shirey and Walker, 1998 and references therein), and the convecting mantle (i.e., DMM $^{187}Os/^{188}Os$: 0.1230–0.1290; Snow and Reisberg, 1995). Thus, large deviations from typical unradiogenic Os-isotope ratios in samples from lithospheric regions are thought to reflect major tectonothermal disturbances, such as the destruction of old depleted lithosphere (e.g., North China craton, Gao et al., 2002; Zhang et al., 2009; Tang et al., 2012). The eruption of the Siberian traps at 250 Ma (Reichow et al., 2002; Carlson et al., 2006) represents such a large tectonothermal event at this time, such an event is likely to have resulted in lithospheric perturbations (e.g., Griffin et al., 1999b; Pokhilenko et al., 1999; Ashchepkov et al., 2014; Howarth et al., 2014). Therefore, the Siberian craton provides an appropriate case-study to investigate the potential modifying geochemical effects that plume impingement has on the SCLM; particularly by sampling mantle xenoliths from Udachnaya and Obnazhennaya that pre- and post-date the Siberian plume tectonothermal event.

The petrography and chemical compositions for this suite of xenoliths have recently been reported by Howarth et al. (2014). In this contribution, we present Re–Os isotope systematics and extended-PGE profiles (PGE + Re) on the same suite of well characterized garnet lherzolite xenoliths of the Paleozoic Udachnaya and Mesozoic Obnazhennaya kimberlite pipes. Both whole-rock fractions and olivine mineral separates were targeted for analysis. The PGE and Re budget of the lithosphere is largely controlled by trace amounts of sulfides, both as interstitial phases, and housed as inclusions within silicates (e.g., Peach et al., 1990; Hart and Ravizza, 1996; Fleet et al., 1999; Brenan, 2002; Day, 2013). Burton et al. (1999, 2000) demonstrated that inclusion-bearing silicates can often yield older melt extraction ages than whole-rock fractions. This was accounted for by the presence of older sulfides enclosed within the silicates. This has particularly been shown to be the case for olivines, which are generally more robust against metasomatism compared to other peridotite minerals such as clinopyroxene (e.g., Boyd et al., 1997; Stachel and Harris, 1997; Doucet et al., 2013). Thus, by targeting inclusion-rich olivines (which have been shielded from the modifying effects of kimberlite metasomatism), coupled with whole-rock Re–Os analyses, we are able to provide insight into the evolution of the Siberian SCLM during the impingement of the Siberian plume. In particular, we aim to investigate whether the ancient depleted lithosphere under the Siberian craton was destroyed by plume impingement (i.e., plume erosion), or whether the existing depleted material has been overprinted by extensive percolation of basaltic melts.

## 2. Geological setting and sample descriptions

The Siberian craton, situated in north-central Asia (Fig. 1), contains >1000 known kimberlite pipes that are divided into three Phanerozoic magmatic events: 1) Silurian to Lower-Carboniferous (420–345 Ma); 2) Triassic (245–215 Ma); and 3) Upper-Jurassic (160–148 Ma) (Davis et al., 1980; Kinny et al., 1997). The Udachnaya pipe erupted during the earliest magmatic phase at ~360 Ma (Griffin et al., 1999b), it has been suggested that the kimberlite activity at this time relates to the formation of an aulacogen that resulted in the emplacement of the near-by Viluy Traps between 367–338 Ma (Courtillot et al., 2010; Blanco et al., 2013). By contrast the Obnazhennaya pipe erupted during the most recent kimberlite magmatic phase at ~160 Ma. This phase has been linked to subduction processes that took place along the present day north–east margin of the Siberian craton (Blanco et al., 2013). The Siberian plume (represented at the surface by the Siberian Flood Basalts; SFBs), is thought to have reached its thermal climax at 250 ± 2 Ma (Reichow et al., 2002; Carlson et al., 2006). Thus, the Udachnaya and Obnazhennaya kimberlites bracket the eruption of the SFBs, providing mantle xenoliths that sample the mantle before and after the thermal climax of the Siberian plume.

The petrology and geochemistry of Udachnaya peridotite xenoliths have been extensively studied over the past several decades (e.g., Boyd et al. 1984; Boyd et al., 1997; Pearson et al., 1995a; Griffin et al., 1999b; Ionov et al., 2010; Agashev et al, 2013; Howarth et al., 2014). Typically, garnet- and spinel-bearing lherzolite and harzburgite xenoliths are recovered. Two textural 'end-members' have been described within the literature: coarse-granular and deformed-sheared peridotites (e.g., Ionov et al., 2010). These peridotites are typically depleted in magmaphile elements and display whole-rock co-variations of CaO, $TiO_2$, and $Al_2O_3$ vs. MgO, indicating their residual nature (Ionov et al., 2010; Agashev et al., 2013). Based on such whole-rock systematics, both granular and deformed peridotites indicate that melt-extraction took place between 2 and 7 GPa (Ionov et al, 2010; Doucet et al., 2012; Doucet et al., 2013). The refractory nature of Udachnaya peridotites has been further illustrated by the relationship of modal olivine versus olivine Fo continent. Ionov et al. (2010) and Doucet et al. (2013) reported that both deformed and granular peridotites fall generally along the 'oceanic trend' of Boyd (1989). Bulk peridotites typically display whole-rock trace-element enrichments, with the deformed peridotites typically displaying greater enrichments in incompatible elements. This has been suggested to be the result of metasomatism. In particular, trace-element compositions of garnets and clinopyroxenes have commonly been reported to be in equilibrium with kimberlitic melts, suggesting late-stage modal metasomatic addition (Boyd et al., 1997; Simon et al., 2003; Kopylova and Caro, 2004). In general, mineral modes reported by Ionov et al. (2010) and Doucet et al. (2013) indicate that the granular and deformed peridotites have similar modal proportions of garnet (up to ~8%), however, Doucet et al. (2013) noted that clinopyroxene abundance were lower than granular peridotites (2.4 vs. 4%). Only a few xenoliths (3 samples; Ionov et al., 2010) were found to be 'enriched' in clinopyroxene and garnet (9–17%). In contrast to Udachnaya, Obnazhennaya peridotites have received little