Chemical Geology 391 (2015) 42–55

Contents lists available at ScienceDirect

Chemical Geology

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

Paleoproterozoic formation age for the Siberian cratonic mantle: Hf and Nd isotope data on refractory peridotite xenoliths from the Udachnaya kimberlite

Luc S. Doucet [a,b,f,*], Dmitri A. Ionov [c,g], Alexander V. Golovin [d,e]

[a] Université J. Monnet (PRES-Lyon), 42023 Saint Etienne, France
[b] Laboratoire G-Time, Université Libre de Bruxelles, 1000 Brussels, Belgium
[c] Géosciences Montpellier, UM2, 34095 Montpellier, France
[d] V.S. Sobolev Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences, Novosibirsk 630090, Russia
[e] Novosibirsk State University, Novosibirsk 630090, Russia
[f] UMR-CNRS 6524, 42023 Saint Etienne, France
[g] UMR-CNRS 5243, 34095 Montpellier, France

ARTICLE INFO

Article history:
Received 2 July 2014
Received in revised form 10 October 2014
Accepted 21 October 2014
Available online 29 October 2014

Editor: K. Mezger

Keywords:
Lithospheric mantle
Siberian craton
Peridotite xenolith
Hf–Nd isotopes
Melt-extraction age
Crust–mantle coupling

ABSTRACT

The formation age of the Siberian cratonic mantle is not well established as yet. Re–Os data on various mantle-derived materials have shown that it contains Archaean components, but the reported Re-depletion ages show a broad variation range (3.4 to 1 Ga) and are commonly ≤2 Ga for peridotite xenoliths. We report Hf and Nd isotope data for cpx and garnet separated from nine refractory spinel and garnet peridotite xenoliths from the Udachnaya kimberlite. The cpx from low-opx spinel harzburgites show extremely high εHf values, from +607 to +2084, which testify to long-term evolution of these rocks with high Lu/Hf ratios, consistent with their residual origin and near absence of post-melting enrichments in the Lu–Hf system. Such high εHf values are unusual for cpx from other cratonic peridotites and are higher than those reported for depleted cpx in off-cratonic peridotites. The clinopyroxenes from low-opx spinel harzburgites yield Hf model ages from 1.9 to 1.7 Ga while the cpx from high-opx spinel harzburgites yield Hf model ages from 3.0 to 1.9 Ga. When plotted together, they define a Lu/Hf isochron with an age of 1.80 Ga, which we consider as a robust estimate of the formation age (melt extraction event) because it is obtained on residual rocks that show no evidence for HREE and Hf enrichments and because the model ages for three out of four individual samples are similar to each other. The cpx have high εNd of +94 to +123, which are inconsistent with their low Sm/Nd_{PM} of <1 and yield no meaningful age estimates. The consistently high, positive εNd in these cpxs can be interpreted in terms of long-term evolution of refractory peridotites with high Sm/Nd, followed by relatively recent LREE enrichments.

We infer that a significant part of the lithospheric mantle in the central Siberian craton may have been formed during a major event (or a series of events) at around 1.8 Ga. Older ages reported for the central Siberian craton may refer to less common materials from cratonic or other domains formed in the Archaean that were later incorporated into the cratonic roots. The transition from the "Archaean" to "modern" tectonic regimes in Siberia and possibly elsewhere may have taken place at 1.8–1.9 Ga rather than at ~2.5 Ga, i.e. in the second half of the Paleoproterozoic rather than at the Archaean–Proterozoic boundary, at which time the asthenospheric mantle became generally too cold to experience high-degree melting on a large scale. The ~1.8 Ga formation age of the Siberian cratonic mantle is coeval with that for a major part of the ancient continental crust in the central Siberian craton. The temporal crust–mantle links may be explained either by the generation of the initial source materials for continental crust in the same melting event that formed the residual peridotites or, alternatively, by subduction and melting of pre-existing proto-lithosphere destabilized by a major mantle upwelling that formed the residual mantle.

1. Introduction

Important insights into the history of the cratonic lithospheric mantle have so far been obtained on peridotite xenoliths from South Africa and North America (Aulbach et al., 2004; Carlson and Moore, 2004; Carlson et al., 1999; Hanghoj et al., 2010; Irvine et al., 2001, 2003;

---

* Corresponding author at: Laboratoire G-Time, Université Libre de Bruxelles, 1000 Brussels, Belgium. Tel.: +32 2 650 22 52.
E-mail address: ldoucet@ulb.ac.be (L.S. Doucet).

http://dx.doi.org/10.1016/j.chemgeo.2014.10.018
0009-2541/

Menzies et al., 1999; Pearson et al., 1995a; Simon et al., 2007; Westerlund et al., 2006; Wittig et al., 2008, 2010) while the age and evolution of the Siberian cratonic mantle remain poorly constrained.

Nearly all available isotope data on the Siberian cratonic lithosphere are from two studies on mantle xenoliths from the Udachnaya kimberlite (central Siberia) (Pearson et al., 1995a, 1995b) and from a study on mantle xenoliths from the Tokinsky Stanovik Range (Tok) near the southern rim of the Aldan shield (Ionov et al., 2006b). The Udachnaya kimberlite is the only one on the Siberian craton that has provided large numbers of mantle xenoliths adequate for chemical and isotopic studies (Boyd et al., 1997; Ionov et al., 2010; Sobolev, 1977). The Udachnaya xenoliths represent, on the one hand, a complete P–T range of the lithospheric mantle in the central Siberain craton and, on the other hand, a comprehensive range of textures and modal and chemical compositions (Boyd et al., 1997; Ionov et al., 2010). The Tok xenoliths are garnet-free peridotites, which commonly show petrographic and chemical evidence for pervasive metasomatism (Ionov et al., 2005b). They represent only the uppermost, largely reworked mantle while the lithospheric roots at the SW margin of the craton may have been largely removed (Ionov et al., 2006a).

Re–Os data on mantle xenoliths (including "megacrystalline dunites" and eclogites) from Udachnaya have shown that the Siberian cratonic mantle contains very ancient, Archaean components. The reported Re-depletion ages (T_{RD}) show a broad variation range (3.4 to 1 Ga) and are commonly under 2 Ga for peridotite xenoliths. Archaean ages have been obtained almost exclusively on megacrystalline dunites and eclogites (Pearson et al., 1995a, 1995b). This may reflect long-term craton creation or metasomatic overprinting. No Hf isotope data have been published as yet for Udachnaya xenoliths. Isotope data on Tok xenoliths (Re–Os, Lu–Hf and Sm–Nd) may only be relevant for the SW rim of the craton and appear to mainly reflect its reworking in the Phanerozoic.

Petrologic and chemical data have been recently provided for an important new collection of large and fresh peridotite xenoliths from the Udachnaya-East kimberlite. These data enable to constrain in detail the depth, degrees and tectonic settings of the formation of the cratonic mantle in the central Siberian craton by melt extraction as well as post-melting processes (Doucet et al., 2012, 2013). Radiogenic isotope data on these xenoliths can provide further insights into the formation age and major evolution stages of the Siberian cratonic mantle.

We report here Hf and Nd isotope data for cpx and garnet separated from 4 spinel harzburgite and 5 garnet peridotite xenoliths from the Udachnaya kimberlite. Detailed petrologic and chemical data for these samples have been reported by Doucet et al. (2012, 2013).

The major objective of this paper is to outline the Hf and Nd isotope composition of the most refractory components of the lithospheric mantle in the central Siberian craton, in particular to better constrain its formation (melt extraction) age. We choose samples (mainly spinel peridotites) with little evidence for metasomatism, which have low concentrations of moderately incompatible elements similar to those in pristine melting residues produced during craton formation (Doucet et al., 2012). Another major objective is to explore craton evolution (mainly from garnet peridotites) and outline the links between the cratonic mantle and the continental crust during the assembly of the craton.

2. Materials and analytical methods

2.1. Geologic setting

Xenoliths in this study were sampled in 2003 to 2009 in remarkably well-preserved type-I kimberlites from the Udachnaya-East pipe (66°26′ N, 112°19′ E) in central Siberia (KML file). The pipe erupted at 360 Ma (Kinny et al., 1997) through the Daldyn block of the Siberian craton (Rosen et al., 1994). This block is exposed on the Anabar shield north of Udachnaya, with U–Pb zircon and model Sm–Nd crustal ages from 1.8 to 3.6 Ga (mainly 1.8–2.6 Ga) (Koreshkova et al., 2009; Zonenshain et al., 1990). Several publications provide detailed information about the Udachnaya kimberlite (Chakhmouradian et al., 2013; Kamenetsky et al., 2009a, 2009b, 2012, 2014; Zinchuk et al., 1993) as well as comprehensive petrologic and geochemical data on fresh Udachnaya peridotite xenoliths, including all samples from this study (Agashev et al., 2013; Bascou et al., 2011; Doucet et al., 2012, 2013, 2014; Goncharov et al., 2012; Ionov et al., 2010; Yaxley et al., 2012).

2.2. Lu, Hf, Sm and Nd abundances in peridotites and sample selection

Bulk-rocks of Udachnaya peridotites are inadequate to constrain the isotopic composition of Hf and Nd in the mantle. The patterns of highly incompatible elements (Th to Ho) in the Udachnaya bulk-rocks are similar to those of host kimberlites (Agashev et al., 2013; Kamenetsky et al., 2012) and appear to be mainly controlled by contamination with host magmas (Ionov et al., 2010). This is consistent with evidence for kimberlite-related interstitial material found in thin sections in some samples from our collection (see ESM 3 in Doucet et al. (2013) and (Sharygin et al., 2012)). The best way to estimate the Hf and Nd isotope compositions of the xenoliths is to analyse pure mineral separates. LA–ICPMS analyses of Udachnaya peridotites show that Lu, Hf, Sm and Nd are mainly hosted by cpx and garnet (Ionov et al., 2010). In spite of very low abundances (close to ICPMS detection limits), the opx may host a significant proportion of the whole-rock budget of Lu and Hf in particular in spinel harzburgites (up to 50%) as well as some Sm and Nd (Ionov et al., 2005a; Stracke et al., 2011). Because it is challenging to separate and process sufficient quantities of opx for isotope analysis, only cpx and garnet were analysed in this study.

This study is based on peridotite xenoliths, which are as close as possible, in terms of modal and chemical compositions, to pristine melting residues and contain some cpxs (± garnet). Because enough material must be available for precise Hf–Nd isotope analyses, only four spinel and five garnet peridotites among Udachnaya xenoliths reported by Ionov et al. (2010) and Doucet et al. (2012, 2013) were selected, mainly based on the amount and Hf and Nd concentrations of the cpxs. The xenoliths are listed in Table 1, which provides a summary of petrologic information. Major and trace element compositions of their minerals and bulk-rocks are listed in Tables 1 to 4 of Supplementary data (ES).

2.3. Petrography and chemical composition of xenoliths in this study

2.3.1. Spinel peridotites

The spinel peridotites are "low-T" (818–851 °C) cpx-bearing harzburgites with protogranular to mosaic-equigranular microstructures and cpx as small grains in the vicinity of opx (Table 1, Fig. 1a–b). Two xenoliths, Uv-101/03 and Uv-454/09, have <30% opx and low modal cpx (~2%), and they are referred to below as low-opx harzburgites. The other two, Uv-90/03 and Uv-585/09, have higher modal opx (>30%) as well as cpx (3–5%) and are referred to as high-opx harzburgites below.

The two low-opx samples plot on the trends defined by other Udachnaya spinel harzburgites on major oxide co-variation plots, e.g. Al_2O_3 vs. FeO and SiO_2 (Fig. 2), and were interpreted as pristine residues of partial melting that initially formed the Siberian cratonic roots (Doucet et al., 2012). In particular, their Al_2O_3 and FeO contents plot close to lines of equal degrees of anhydrous melt extraction at either ~45% batch melting or ~38% fractional melting starting at 7–4 GPa and ending at ≤1–3 GPa (Supplementary Fig. 2a–b). Rare earth element (REE) patterns of the cpxs from the low-opx spinel harzburgites (Fig. 3a) show a continuous decrease from Lu to Ho (Uv-101/03) or Tb (Uv-454/09), i.e. follow heavy REE (HREE) trends typical of melt extraction residues. Hf concentrations in the cpxs normalized to the primitive-mantle (Hf_{PM}) are an order of magnitude lower than for HREE ($Lu/Hf_{PM} \gg 1$) and plot on the extensions of the HREE depletion trends (Fig. 3a). The HREE and Hf in these cpxs appear to be of