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Paleoproterozoic rejuvenation and replacement of Archaean lithosphere: Evidence from zircon U–Pb dating and Hf isotopes in crustal xenoliths at Udachnaya, Siberian craton

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ABSTRACT

Cratons represent the oldest preserved lithospheric domains. Their lithosphere (lithospheric mantle welded to overlying Precambrian crystalline basement) is considered to be particularly robust and long-lived due to the protecting presence of buoyant and rigid "keels" made up of residual harzburgites. Although the cratons are mostly assumed to form in the Archaean, the timing of their formation remains poorly constrained. In particular, there are very few datasets describing concurrently the age of both the crustal and mantle portions of the lithosphere. In this study, we report new U–Pb ages and Hf isotope compositions for zircons in crustal xenoliths from the Udachnaya kimberlite in the central Siberian craton; this dataset includes samples from both the upper and lower portions of the crust. The zircon ages agree well with model melt-extraction Re–Os ages on refractory peridotite xenoliths from the same pipe; taken together they allow an integrated view of lithosphere formation. Our data reveal that the present day upper crust is Archaean, whereas both the lower crust and the lithospheric mantle yield Paleoproterozoic ages. We infer that the deep lithosphere beneath the Siberian craton was not formed in a single Archaean event, but grew in at least two distinct events, one in the late Archaean and the other in the Paleoproterozoic. Importantly, a complete or large-scale delamination and rejuvenation of the Archaean lower lithosphere (lower crust and lithospheric mantle) took place in the Paleoproterozoic. This further demonstrates that craton formation can be a protracted, multi-stage process, and that the present day crust and mantle may not represent complementary reservoirs formed through the same tectono-magmatic event. Further, deep cratonic lithosphere may be less robust and long living than often assumed, with rejuvenation and replacement events throughout its history.

1. Introduction

Cratons are the oldest continental domains on Earth; they formed early in its history, typically during the Archaean (>2.5 Ga), and remained stable for billions of years. Their longevity and stability are believed to be due to the presence of thick and cold lithospheric "keels" mainly composed of refractory harzburgites "welded" to roughly coeval crustal rocks (e.g. TTG, granulites, eclogites) (e.g. Lee et al., 2011). These rocks usually have specific modal and chemical compositions that distinguish them from younger off-craton crust and lithospheric mantle. It is generally assumed, implicitly or explicitly, that all or most of the lithosphere in a given craton formed concurrently in a large-scale tectono-magmatic event in the Archean that generated both the cratonic lithospheric mantle (CLM) and the crust (crust–mantle coupling) (e.g. Pearson and Wittig, 2014). Some support to this model comes from the broad similarity between the worldwide distribution of crust-forming ages (e.g. Condie and Aster, 2009) and CLM-forming ages (e.g. Carlson et al., 2005).

Conceptually, this supports a model of lithosphere formation over a protracted (50–200 Myr) event with partial melting of fertile convective mantle yielding a basaltic protocrust and a depleted

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residue (e.g. Herzberg and Rudnick, 2012). The residue ultimately accretes into the CLM (Lee et al., 2011; Pearson and Wittig, 2014), whereas the proto-crust is reworked, mainly by intracrustal processes with little or no further addition of matter, and is differentiated into a granite–gneissic upper to middle crust (e.g. Moyen and Martin, 2012) and a granulitic, restitic lower crust (e.g. Rudnick and Gao, 2014). Thus, the crust is assumed to have model ages (or crust extraction ages) similar to the age of the underlying CLM, and any subsequent evolution is regarded as due to reworking only. In this model, the Archaean crust could experience metamorphism, but not much rejuvenation (i.e. major additions of or replacement by younger components).

Although no specific geodynamic environment is deemed imperative in the craton formation, its primarily in-situ characteristics make it rather similar to intra-plate settings, with melting of asthenospheric mantle above something akin to a mantle plume head to form an oceanic plateau that then differentiates into a continental nucleus. Within the context of a lively debate on the styles of Precambrian global tectonics, these observations may favor tectonic models with no plates and no plate tectonics in the Archaean. This is somewhat at odds with preferred models for the genesis of crustal rocks, since many studies tend to favor a subduction (i.e. plate boundary) scenario for the genesis of the volumetrically dominant component of the Archaean crust, the TTG suite (e.g. review in Moyen and Martin, 2012).

However, this model largely relies on the global, worldwide correspondence between the main stages of crustal growth (Condie and Aster, 2009; Dhuime et al., 2011) and CLM formation (e.g., Carlson et al., 2005). On the other hand, only rare datasets combine, in a single locality or even province, geochronological information both on the CLM and the overlying crust. This is a result of sample availability because CLM samples are found as xenoliths in (mostly kimberlitic) volcanic rocks, that tend to be located in sag basins on top of cratons – such that the ancient crustal rocks are rarely, if ever, exposed in the vicinity of the kimberlite fields. Furthermore, the cratonic lower crust is seldom exposed, and of course not in the locations where the upper crust crops out. For instance, the relations between the age of the lower crust and the mantle in the Archean cratons in southern Africa are hard to constrain because the kimberlites hosting abundant peridotite xenoliths with prevalent Archean Re–Os ages contain few, if any, lower crustal xenoliths. Granulite xenoliths were only reported from those pipes in the central Kaapvaal craton (Schmitz and Bowring, 2003) that contain no peridotite xenoliths appropriate for Re–Os dating (e.g., Carlson et al., 2005). As a result, evidence for high-T crustal metamorphism and crust–mantle decoupling at 2.7 Ga (Schmitz and Bowring, 2003) cannot be linked to concurrent mantle events. On the Baltic Shield, lower crustal xenoliths (e.g. Kempton et al., 1995) do not occur in the same volcanic rocks as (much less common) mantle peridotites.

On a regional scale, possible mismatch between crust and CLM formation ages has been raised for a long time (see Foley, 2008 and Lee et al., 2011 for reviews). Yet, crust–mantle relations in such processes often remain unresolved or are inferred from indirect or incomplete evidence, like modern heat flow or seismic data, tectonic setting, xenolith geotherms and compositions (e.g. Carlson et al., 2014). A relatively small North China craton with exposed Meso- and Neoarchean crustal rocks is a unique case of hugely discordant mantle and crustal ages. Geophysical data and xenolith studies show that its ancient roots were removed and replaced with younger mantle in the Mesozoic (e.g. Liu et al., 2011; Menzies et al., 1993; Rudnick and Gao, 2014; Zheng et al., 2012), but the relations between the fate of its mantle and crustal sections remain to be fully elucidated, partly because no single locality yields sufficient numbers of xenoliths representing the evolution of its mantle, lower and middle crustal components.

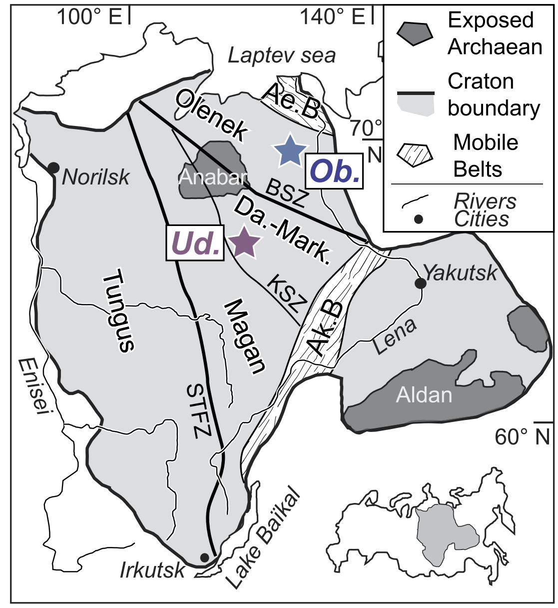

Fig. 1. A simplified geological map of the Siberian craton, showing the extent of the Siberian craton, the exposed crustal basement on the Anabar and Aldan shields, and reworked mobile belts (AeB: Aekit orogenic belt; AkB: Akitkan fold belt). The craton consists of several crustal domains (Da.-Markh.: Daldyn-Markha), two of which (Anabar and Aldan) share their name with the respective exposed shields, separated by tectonic zones (BSZ: Billyakh Shear Zone; KSZ: Kotuykan Shear Zone; STFZ: Sayan–Taimyr Shear Zone). Black stars indicate the position of the Udachnaya (Ud.; 66°26′N, 112°19′E) and Obnazhennaya (Ob.: 70°15′N, 121°35′E) kimberlite pipes. Inset shows the outline of the Siberian craton within the Russian Federation. Geographic names (rivers and cities) are in italics.

The Siberian craton offers a rare opportunity to access all lithospheric levels in one place and thus to compare the age of formation of the CLM, the lower crust and the Precambrian upper crust in the same locality. The Udachnaya kimberlite pipe in the center of the craton is located in a sedimentary basin covering the Precambrian basement (Fig. 1) and contains a wealth of xenoliths ranging from spectacularly well preserved peridotites (Ionov et al., 2010) to lower crustal granulites (Koreshkova et al., 2011) to upper crustal rocks including amphibolites, tonalites and granites.

In this study, we report U–Pb ages and Hf isotope data for zircons in various crustal xenoliths from Udachnaya, with particular emphasis on middle to upper crustal samples that have not as yet been reported in the international literature. We show that: (1) most of the lower crust and the CLM formed concurrently, at ca. 1.8 Ga, whereas (2) the upper crust is much older (ca. 2.7 Ga). The Hf compositions of the zircons indicate that large portions of this lower crust do not correspond to reworked neo-Archaean crust, but to addition of totally different material. These results, consistent with recent data on CLM ages, challenges the model of single-stage development of cratonic lithosphere by melting of fertile mantle and differentiation of the basaltic protocrust. Here, we argue instead for a two-stage scenario involving delamination and rejuvenation of the lower lithosphere (lower crust and lithospheric mantle) in the Paleoproterozoic.

2. Geological setting and samples

Much of the ca. 4×10^6 km^2 surface area of the Siberian craton (Fig. 1) is covered by Phanerozoic sediments and flood basalts. Archaean to Paleoproterozoic rocks crop out in two regions, the Anabar and Aldan shields in the northern and southeastern (SE) craton, with ages ranging from 1.7 to 3.7 Ga, but largely grouped into intervals of ca. 1.8–2.0 Ga and 2.8–3.4 Ga (Rosen, 2002; Rosen et al., 2005). The craton is divided in four “provinces” or

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