Earth-Science Reviews 118 (2013) 45–68

Contents lists available at SciVerse ScienceDirect

Earth-Science Reviews

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

Widespread refertilization of cratonic and circum-cratonic lithospheric mantle

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ARTICLE INFO

Article history:
Received 21 August 2010
Accepted 24 January 2013
Available online 4 February 2013

Keywords:
Archean craton
Circum-craton
Subcontinental lithospheric mantle
Phanerozoic
Peridotite xenolith
Refertilization

ABSTRACT

Studies of mantle xenoliths have confirmed that Archean subcontinental lithospheric mantle (SCLM) is highly depleted in basaltic components (such as Al, Ca and Na) due to high-degree extraction of mafic and ultramafic melts and thus is refractory and buoyant, which made it chronically stable as tectonically independent units. However, increasing studies show that ancient SCLM can be refertilized by episodic rejuvenation events like infiltration of upwelling fertile material. The North China Craton is one of the most typical cases for relatively complete destruction of its Archean keel since the eruption of Paleozoic kimberlites, as is evidenced by a dramatic change in the compositions of mantle xenoliths sampled by Paleozoic to Cenozoic magmas, reflecting significant lithospheric thinning and the change in the character of the SCLM. The compositional change has been interpreted as the result of refertilization of Archean SCLM via multiple-stage peridotite-melt reactions, suggested by linear correlations between MgO and indices of fertility, covariations of Al_2O_3 with CaO, La/Yb, $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{187}Os/^{188}Os$ and Re-depletion ages (T_{RD}), high Re abundances, scatter in Re–Os isotopic plot, variable *in situ* T_{RD} ages of sulfides, and correlation between T_{RD} ages and olivine Fo of peridotite xenoliths in Paleozoic kimberlites and Cenozoic basalts on the craton.

By integrating major and trace element, Sr, Nd and Os isotopic compositions of peridotite xenoliths and orogenic massif peridotites from the continents of Europe, Asia, America, Africa and Australia, together with previous studies of petrology and geochemistry of global peridotites, we suggest that (1) refertilization of cratonic and circum-cratonic lithospheric mantle is widespread; (2) Archean SCLM worldwide has experienced a multi-stage history of melt depletion and refertilization since segregation from the convecting mantle; (3) cratonic SCLM may be more susceptible to compositional change caused by refertilization than is generally assumed; (4) the original character of much Archean cratonic mantle has been partly overprinted, or even erased by varying degrees of refertilization, which may play a key role in the rejuvenation and erosion of the SCLM beneath the Archean cratons.

Due to the refertilization of ancient SCLM, (1) many published whole-rock Re-depletion ages cannot represent the formation ages of peridotites, but the mixtures of different generations of sulfides. Thus, the chronological significance of the Re–Os isotopic composition in individual peridotite should be cautiously interpreted; (2) many kimberlite- and intraplate basalt-borne lherzolite xenoliths, with major element compositions close to primitive mantle, may be the fragments of the ancient SCLM, strongly refertilized by infiltration of asthenosphere-derived melts, rather than newly-accreted SCLM. Consequently, new accretion of SCLM beneath ancient cratons such as the North China Craton may be less than was previously assumed.

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http://dx.doi.org/10.1016/j.earscirev.2013.01.004

1. Introduction

The formation and evolution of subcontinental lithospheric mantle (SCLM) is critical to understanding the processes responsible for the development of Earth's continents. The SCLM is depleted in basaltic components owing to high degrees of partial melting (extraction of basaltic melt) of mantle peridotites (Frey and Green, 1974; Jordan, 1975, 1988; Boyd et al., 1985; Frey et al., 1985; Pollack, 1986; King, 2005; Griffin et al., 2009; Aulbach, 2012; Herzberg and Rudnick, 2012). Cratonic mantle most likely formed as residues after about 30% melting of ambient mantle at potential temperatures of 1500–1600 °C in the Archean. These conditions compare with about 7% melting to produce modern mid-ocean ridge basalt (MORB) at a potential temperature of 1350 °C. When melting is hot and extensive, the primary magmas are FeO-rich and these leave behind residues that are FeO-poor. Extensive melting also depletes the residues in CaO and Al_2O_3, and the combined effects of low FeO, CaO and Al_2O_3 makes them buoyant (Herzberg, 2004; Herzberg et al., 2010).

There is a secular evolution from depleted Archean mantle (Mg-rich), represented by the peridotite xenoliths in the African and Siberian kimberlites, to more fertile Phanerozoic mantle. Thus, newly formed SCLM, as represented by the peridotite xenoliths in some intraplate basalts, has become progressively less depleted from Archean, through Proterozoic to Phanerozoic time, in terms of Al, Ca and other basaltic components (Boyd, 1989; Boyd et al., 1997; Griffin et al., 1998a, 1999a, 2003a, 2009; O'Reilly et al., 2001). This is displayed by a large database of xenoliths and xenocrysts showing that the SCLM stabilizing during different geologic eons has distinctly different mean compositions that are broadly correlated with the tectonothermal ages of the crust (Griffin et al., 1998a, 1999a).

Archean SCLM is distinctive in containing significant proportions of refractory harzburgites with minor lherzolites (Herzberg, 2004) and highly refractory dunites (Bernstein et al., 2006, 2007), marking the most significant difference between Archean SCLM and that beneath younger terranes (Griffin et al., 1999a). The compositional variations significantly contribute to the difference in the density of SCLM of different ages. Mean density increases significantly from Archean through Proterozoic to Phanerozoic SCLM (Griffin et al., 1998a, 1999a, 2003a, 2009; O'Reilly et al., 2001). Thus, Archean lithosphere is highly buoyant and cannot be delaminated through gravitational forces alone. The buoyancy, as well as the refractory nature of Archean SCLM, offers a simple explanation for the thickness and longevity of Archean lithospheric keels (Jordan, 1988).

Archean and Proterozoic SCLM is forever unless it is physically disrupted (e.g. rifting, thinning and displacement) with associated thermal and chemical erosion (metasomatism) (O'Reilly et al., 2001). Changes tracked in the SCLM in several regions, such as the Wyoming craton (Eggler and Furlong, 1991) and the North China Craton (Fan and Menzies, 1992), show that Archean mantle can be transformed by mechanical destruction (lithospheric thinning and rifting) and refertilized (chemical re-enrichment) by episodic infiltration of upwelling fertile material (O'Reilly et al., 2001; Foley, 2008; Griffin et al., 2009; Zhang et al., 2009a). The term "refertilization" is commonly used to describe a phenomenon occurring within the lithospheric mantle as metasomatic fluids/melts continually percolate through this layer and modify its composition (Griffin et al., 2009). Thus, refertilization means the chemical re-enrichment of originally depleted protoliths by introduction of fluids/melts via metasomatism or peridotite-melt/fluid reactions. The percolating fluids/melts were rich in Fe, Ca, Al, Na and incompatible trace elements and derived from the asthenosphere or recycled crust. Refertilization of a depleted peridotite could be linked to heating, partial melting and melt migration on a scale of kilometers, related to asthenospheric upwelling (Griffin et al., 2009 and references therein).

Although cratons, the ancient continental nuclei characterized by tectonic inactivity, thick SCLM and low heat flow, are stable as tectonically independent units for at least the past 2 billion years, they have experienced episodic rejuvenation events throughout their history (Foley, 2008 and references therein). Is the process of refertilization of depleted Archean mantle identified in previous studies a common phenomenon? In other words, did most Archean SCLM around the world undergo the process of refertilization?

In order to answer these questions, we will summarize and analyze critical evidence for refertilization of cratonic and circum-cratonic lithospheric mantle worldwide by integrating the existing data, including major and trace element, Sr, Nd and Os isotopic compositions of mantle peridotite xenoliths and orogenic massif peridotites. Firstly, the North China Craton will be selected to represent the typical region for the destruction of its Archean keel and the critical evidence for refertilization of the SCLM beneath the craton will be analyzed in detail. Then, advances in petrology and geochemistry of mantle peridotites from other cratonic and circum-cratonic regions worldwide (Africa, America, Siberia, Australia and Europe; Fig. 1) will be reviewed and comprehensively compared with those of the North China Craton. The integrated results suggest that refertilization of ancient SCLM is widespread and that the original character of Archean cratonic mantle has been transformed by varying degrees of refertilization, leading to the rejuvenation and erosion of ancient mantle.

2. Refertilization of Archean mantle beneath the North China Craton

The North China Craton is one of the major continental blocks in eastern Eurasia (Fig. 1), preserving Archean crustal remnants as old as 3.8 Ga (Liu et al., 1992). The lithosphere of the craton was cold, thick (>200 km), refractory and typically Archean craton in chemical composition during the early Paleozoic, as is proved by extensive studies of peridotite xenoliths, mineral xenocrysts and diamond inclusions in the Mid-Ordovician diamondiferous kimberlites (Chi et al., 1992; Dobbs et al., 1994; Meyer et al., 1994; Chi and Lu, 1996; Wang et al., 1998; Wang and Gasparik, 2001; Zheng et al., 2001; Gao et al., 2002; Wu et al., 2006; Zhang et al., 2008a; Chu et al., 2009). In contrast, the Tertiary basalts on the craton sampled a hot, thin (<120 km), fertile and relatively young lithosphere, showing characteristics similar to "oceanic" mantle (Song and Frey, 1989; Fan and Menzies, 1992; Griffin et al., 1992, 1998b; Tatsumoto et al., 1992; Menzies et al., 1993; Menzies and Xu, 1998; Xu et al., 1998; Zheng et al., 1998, 2005, 2006a; Fan et al., 2000; Xu, 2001; Rudnick et al., 2004; Chu et al., 2009; Zhang et al., 2009a, 2010; Tang et al., 2012). These observations reflect a dramatic change in physical property and chemical composition of the SCLM beneath the North China Craton during the intervening time interval. Briefly, the Archean SCLM has been considerably destroyed and a relatively young SCLM has formed beneath the North China Craton since the Paleozoic (Griffin et al., 1992, 1998b; Menzies et al., 1993;