The birth, growth and ageing of the Kaapvaal subcratonic mantle

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Introduction

There is general consensus that the subcratonic lithospheric mantle originated in the Archean by high degrees of partial melting and subsequently suffered metasomatic overprint (e.g. Pearson and Wittig 2008). It consists of two major compoments, volumetrically dominating ultramafic rocks (peridotites) and a subordinate mafic portion (eclogites and garnet pyroxenites) which are the metamorphic equivalents of seafloor altered basaltic magmas and their low pressure cumulates. Less consensus exists about the melting regime and the geodynamic setting in the Archean. Due to the metasomatized nature of cratonic peridotite, only compatable and moderately incompatible elements like the HREE, V, Sc and Cr are suitable to deduce the melting regime. A strong case can be made that partial melting occurred mainly at low pressures based on abundances of these elements and their ratios. Much fewer samples indicate the presence of residua from higher pressure melting in the garnet stability field. The Archean age of the cratonic mantle has been clearly established with the Re-Os isotope system. However, the concept of Rhenium depletion age (T_{RD}) yields a continuum of mainly Archean ages with broad, prominent modes at 2.7-3.0 Ga for Kaapvaal peridotites in an age density distribution curve (see e.g. summary by Pearson and Wittig 2008). A continuum for mantle melting contrasts with the episodic events recorded in the overlying crust. The discrepancy may be blamed to the disguising effects of ubiquitous metasomatism in cratonic mantle samples. The dilemma for obtaining accurate ages of mantle processes is furthered by the facts that xenoliths are generally contaminated along grain boundaries and reaction rims by the host kimberlite magma and that, consequently, the lithophile element systematics like the Rb-Sr, Sm-Nd and Lu-Hf isotope systems of the bulk rocks are disturbed.

Our approach

We use garnet xenocrysts with low calcium contents (subcalcic garnets) from the older Group II generation of kimberlites from the Kaapvaal craton to evaluate old, Archean processes. This is because samples from the younger Group I kimberlites are likely to be metasomatized by the preceding kimberlite magmatism in addition to previous events. Subcalcic garnets are mostly derived from clinopyroxene-free garnet harzburgites. They are rare as xenoliths but their debris is common in heavy mineral concentrates from diamond mining and best preserved as subcalcic garnet grains. They are the major host for most trace elements of their host rocks including those of the Sm-Nd and Lu-Hf isotope systems (Lazarov et al. 2009; Shu and Brey 2015). Results on these isotope systems from such xenocrysts can be treated as bulk rock compositions. Characterization of source materials may be tested in isochron diagrams, by model age calculations and intial isotope values. We further used clean garnet and clinopyroxene separates from Finsch peridotite xenoliths to reconstruct bulk rock compositions and test for agreement with subcalcic garnets. The Re-Os isotope and PGE data were also determined in the same Finsch peridotite xenoliths from which Lu-Hf and Sm-Nd isotope data were obtained. We also examined the mafic counterparts, eclogite and garnet pyroxenite xenoliths, to obtain further constraints on the formation and developement of the Kaapvaal mantle via the Lu-Hf and Sm-Nd isotope systems.

Results and Discussion

Our results on major and trace elements fortify the arguments for a predominance of residua from low pressure melting in the Kaapvaal mantle, evidenced e.g. by high and variable Cr/Al ratios and extremely low HREE abundances. Model calculations indicate that most of the peridotite xenoliths are residues of 25-40% partial melting mainly in the spinel stability field (e.g. Lazarov et al. 2012 a,b). The Lu-Hf isotope system in subcalcic garnets records a series of ancient metasomatic events in the

Kaapvaal craton by a) a 2.64 Ga Lu-Hf isochron for subcalcic garnet xenocryst from the Finsch mine with εHf(t) = +26 and a further at 1.9 Ga [εHf(t) = 0], b) a 2.95 Ga isochron from the Roberts Victor mine [εHf(t) = +2.4] and c) a 3.2 ± 0.5 Ga errorchron from Lace mine (Lazarov et al. 2009 and 2012; Shu et al. 2013). Quantitative model calculations on metasomatic processes demonstrate that the subcalcic garnets were affected by 0.3 to 3% carbonatitic to kimberlitic melts (Shu and Brey 2015). Some garnet xenocrysts yield extraordinary negative εHf(0) and εNd(0) values, one extreme case with εHf(0) at -65 and εNd(0) at -41. The negative εHf and εNd values correspond to the initial ratios of the metasomatizing agent that most likely was derived from an ancient (early Archean or even Hadean) crustal component. Extremely negative εNd values are also characteristic for garnet inclusions in diamonds and are also an argument for an early Archean growth of diamonds (Richardson et al., 1984).

Our new results on the Re-Os isotope system from Finsch together with data of Griffin et al. (2004) yield T_{RD} ages mostly around 2.6 Ga which is in good agreement with the Lu-Hf metasomatic age. The Re-Os iotope system in Finsch peridotites may also record the Archean metasomatic overprint and even the oldest may represent only minimum ages for partial melting. Such an interpretation is further supported by a decent positive correlation between the modal abundances of garnet (and subordinate with cpx and opx) and $^{187}Os/^{188}Os$. It indicates that the reintroduction of fertility-indicator mineral(s) and of Re-Os back to a depleted lithosphere result from the same metasomatic process.

Various ways for estimating the age of eclogite xenoliths from cratonic mantle gave mainly late Archean ages (summary by Aulbach and Jacob 2016). A direct measure of a minimum age are extremely low $^{87}Sr/^{86}Sr$ ratios (0.7008-0.7009) in clinopyroxenes from eclogite xenoliths in the Kaapvaal craton (Jacob et al. 2005 and Shu et al. 2016). Projection of such low values onto a mantle evolution line yields minimum ages for eclogites of close to 3.2 Ga. Attempts to obtain eclogite ages with reconstructed bulk rock compositions from two-point garnet-clinopyroxene tie-lines are not successful for the Sm-Nd and Lu-Hf isotope systems. The various types of eclogites and garnet pyroxenites generally yield a scatter of data points in isochron diagrams and protolith or metamorphic ages cannot be derived. Nevertheless, the usefulness of garnet-clinopyroxene tie-line ages lies in the possibility to derive cooling rates for the subcratonic mantle (Shu et al. 2014). Plotting the temperatures of last equilibration as derived from Fe–Mg exchange thermometry between garnet and clinopyroxene against the garnet-clinopyroxene two-point isochron ages yields a) a low temperature alignment for both the Sm-Nd and Lu-Hf isotope systems of increasing age with decreasing temperature, and b) an alignment around the kimberlite eruption ages at high temperatures. The intersect between the two temperature limbs gives about 920°C as closure temperature for the Lu–Hf system and about 850°C for the Sm–Nd system. These systematics allow to derive a cooling rate of around 0.1°C/Ma at least since the beginning of the Proterozoic (Shu et al. 2014).

A brief synthesis

Highly depleted peridotitic lithosphere was generated by partial melting at low pressures, possibly in settings analogues to modern mid ocean ridges at least in the mid-Archean as evidenced by: (i) oldest T_{RD} ages from the Kaapvaal craton around 3.3 Ga, (ii) the extremely positive initial εHf ratio of the 2.64 Ga metasomatic isochron from Finsch peridotites, (iii) extremely unradiogenic Nd isotope data (εNd=-41) in subcalcic garnet xenocrysts and garnet inclusions in diamonds and iv) the minimum age for eclogites of 3.2 Ga. The partial melts and their differentiates cooled in an ocean floor environment. The package of depleted residues (harzburgite), seafloor-altered basalts, picrites, komatiites and sediments was eventually subducted to greater depths from where the xenoliths are derived.

Subduction of this cooler material likely occurred under very low geothermal gradients by a compressional process (Sommer et al. 2017) into a hotter mantle. This created immediate massive thermal and chemical disequilibrium within an early lithospheric keel. Thermal adjustment to a stable geothermal gradient was induced by heat flow between a continental lid containing high abundances of radioactive elements and a deep convecting asthenosphere (Michaut and Jaupart 2007). The resulting gradient would have been significantly higher in the Archean than today. The subducted packages were heated possibly up to 1400 - 1500°C during such a process. Thermal equilibrium could be reached within less than 500 Ma according to the model of Michaut and Jaupart (2007).

Based on the information from radiometric systems, the main stage of metasomatism which is responsible for modifying the lithospheric keel of the Kaapvaal craton, occurred during the time leading up to thermal equilibrium. The cooler, subducted portions of lithosphere with low melting components such as seafloor altered basalts or carbonated and hydrous sediments (e.g. black shales) were heated, hybrid melts from reactions between them and peridotite percolated into surrounding and overlying peridotite to drive prevailing metasomatism in the cratonic mantle. The Lu-Hf isochrons and possibly the mode of the T_{RD} ages mostly record the main stage of this process. After reaching equlibration and except for local disturbances, the subcratonic mantle as a whole has cooled with a rate of about 0.1°C/Ma.

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