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Timing of final depletion of the lithospheric mantle beneath the Kaapvaal craton: Constraints from Lu-Hf dating of garnet peridotites from the Finsch mine (South Africa)

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Introduction

Processes connected with the formation and modification of the sub-continental lithospheric mantle (SCLM) are mainly recorded in the trace element and isotope signatures of the constituent peridotites. Several years of intensive studies of different isotope systems revealed that the Lu-Hf (Schmidberger et al., 2002; Pearson and Nowell, 2004; Wittig et al., 2007), together with the Re-Os system (Pearson et al., 1995; Menzies et al., 1999; Carlson et al., 1999; Irvine et al., 2001; Pearson and Nowell, 2004; Simon et al., 2007) appear to be most reliable for dating of old Archaean depletion. Both the Re-Os and the Lu-Hf system are relatively robust to mantle metasomatism. The Sm-Nd system, although insensitive to surface processes, may be fully reset by mantle metasomatism. It may provide a tool to date these processes. Metasomatic enrichment may lead to a decoupling of the Hf and Nd isotopes depending on the nature of the metasomatic agent. While Lu-Hf may have preserved information about the timing, preconditions and degrees of depletion, Sm-Nd may provide information about the timing and character of enrichment event(s).

Mineral separates from fifteen coarse grained, high temperature garnet (grt) peridotites from the Finsch mine were analysed for their Sm, Nd, Lu and Hf isotopes. The intention was to obtain depletion ages (using the Lu-Hf isotopic system), as well as to determine the timing of the enrichment processes (Sm-Nd) from recalculated bulk rock compositions.

Samples studied

The sample suite includes 2 lherzolites (lhz), 9 harzburgites (hzb), one cpx-free hzb, one dunite and 2 cpx-free dunites i.e. twelve samples have Ca-saturated garnets coexisting with clinopyroxene (cpx) and three have Ca-undersaturated garnets and are cpx-free. High Mg-numbers in olivine and low incompatible element concentrations in grt, opx and cpx including low HREE suggest strong depletion of the harzburgites and dunites. Complex trace element patterns with light REE and LILE elevated in various degrees testify that all peridotites were affected by variable metasomatic processes. One sample is even modally metasomatised and contains rutile and pentlandite in addition to grt, cpx, opx and olivine.

Nevertheless, all samples have well equilibrated major and trace elements, as evident from internally consistent P-T estimates with independent geothermobarometers and from consistent trace element partitioning between garnet and cpx. This suggests also isotopic equilibrium between the coexisting minerals.

We were able to obtain 15 garnet, 7 clinopyroxene and 7 orthopyroxene separates from 15 mantle xenoliths in amounts sufficient for isotope analysis. Their Sm-Nd and Lu-Hf isotope compositions were determined by MC-ICP-MS. Garnet-orthopyroxene pairs were measured from four cpx-bearing harzburgites and one cpx-free harzburgite, and cpx-bearing dunites, and garnet-clinopyroxene pairs were measured from 2 lherzolites, 4 harzburgites and one dunite. From three clinopyroxene bearing peridotites all three coexisting minerals were measured.

Mineral isotope compositions

Garnets dominate the Lu and Hf budgets in four phase peridotites and therefore are governing the Hf isotopic system in such rocks. Concentrations of Lu and Hf in the Finsch garnets vary by more than one order of magnitude (0.014-0.397 ppm for Lu and 0.086-1.88 ppm for Hf) with correspondingly high variations in $^{176}Lu/^{177}Hf$ (0.00820-0.27986). The large range in Lu/Hf resulted in εHf ranging from -42 up to +263. All clinopyroxenes, except that from the rutile-pentlandite bearing harzburgite, have positive εHf. Like for garnet, clinopyroxene also displays a strong correlation of $^{176}Lu/^{177}Hf$ and $^{176}Hf/^{177}Hf$ with no correlation between $^{176}Hf/^{177}Hf$ and 1/Hf. The latter excludes a mixing

relation and the correlation between Lu/Hf and the Hf isotope ratios must have age significance. All orthopyroxene separates are corrupted by kimberlite contamination and their isotopic composition (including the Sm-Nd system) is not considered any further.

The $^{147}Sm/^{144}Nd$ ratios in garnets vary widely from sub-chondritic to slightly higher than the depleted mantle (0.1795-0.4629). They also have the largest spread of εNd from all measured mineral phases, ranging from very unradiogenic (-15.5) to radiogenic (+6.8). Clinopyroxenes have higher concentrations of both Sm and Nd than opx and garnet. However, the range in $^{147}Sm/^{144}Nd$ is small (0.0725-0.1117) as is $^{143}Nd/^{144}Nd$ (0.51219-0.51273). In contrast to the Hf isotope compositions, with mostly superchondritic values, all cpx have subchondritic εNd isotopic signatures. Garnet and cpx display a crude correlation of $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$, but not of $^{143}Nd/^{144}Nd$ and 1/Nd, indicting that variable $^{147}Sm/^{144}Nd$ ratios and Nd isotope compositions are not produced by mixing.

A decisive possibility to check mineral separates for contamination by the kimberlitic melt is to compare the isotope dilution (ID) concentrations of mineral separates with concentrations obtained by LA-ICP-MS on carefully selected, clean spots on the same minerals. For the majority of the garnets and cpx both analytical procedures yield identical results for Nd and Hf within analytical uncertainties. However, the LA-ICP-MS results for opx are significantly lower than the ID values (although uncertainties for the LA-ICP-MS measurements, especially for Hf, are relatively high). The most likely explanation is that all opx have suffered from kimberlite contamination, which persisted strong acid leaching (even with concentrated HF acid) and went undiscovered during mineral separation. Kimberlite contamination is most effective in opx due to its very low trace element concentrations relative to kimberlite. Therefore, only grt and cpx were used to estimate whole rock compositions, e.g. for Hf and Nd age constraints.

Discussion

The calculated whole rocks (WR) for seven garnet-cpx pairs show a good correlation between $^{176}Hf/^{177}Hf$ and $^{176}Lu/^{177}Hf$ (Fig. 1) and plot around a 2.5 Ga isochron. Two samples with low $^{176}Hf/^{177}Hf$ and $^{176}Lu/^{177}Hf$ plot below this isochron. They (one of them is rutile bearing sample) also show strong metasomatic enrichment by the Hf-rich melt. The five remaining samples provide an isochron age of 2.55±60 Ga (Fig. 1).

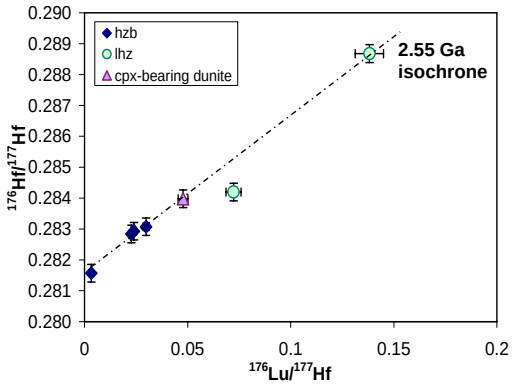

Fig. 1 $^{176}Hf/^{177}Hf$ versus $^{176}Lu/^{177}Hf$ for the Finsch peridotite whole rocks calculated by grt-cpx isotopic compositions. Hf isotopic data plot along the 2.5 Ga reference "isochron". Pure analytical errors are with in the size of the symbols, and error bars consider the possible effect of opx on whole rock calculations.

The calculated whole rock age is in good agreement with a Lu-Hf age of 2.52 Ga obtained for Finsch single grain subcalcic garnets (Lazarov et al., 2008) and with Re-Os ages obtained on sulphides from other Finsch peridotites (T_{RD}= 2.4 Ga, Irvine et al., 2001) and other Kaapvaal craton localities (2.4-2.8 Ga - Walker et al., 1989; Carlson et al., 1999; Menzies et al., 1999). This age is considered as the final depletion event of the SCLM connected with the cratonisation and stabilisation of the Kaapvaal craton.

The initial of the calculated WR isochron is 16 epsilon units above $CHUR_{2.5Ga}$ ($^{176}Hf/^{177}Hf$ = 0.28118), which cannot be explained by the non-consideration of opx. It rather shows that, by 2.5 Ga, the Finsch peridotites were already the residues of a previous depletion event i.e. the present day Finsch peridotites are the products of at least two depletion events. This is identical to the findings obtained from the subcalcic garnets (Lazarov et al. 2008). It is also in agreement with the major and trace element data of these samples, which suggest polybaric depletion for the majority of the peridotites.

In contrast to Lu-Hf, the calculated whole rock Sm-Nd isotope ratios do not form an isochron (Fig. 2). They plot around a 400 Ma isochron with a very large scatter. This suggests that the Sm-Nd isotope system experienced metasomatic overprint after the depletion at around 2.5 Ga. Investigations on the Finsch subcalcic garnets (Lazarov et al., 2008) implied two such metasomatic events that affected the subcontinental lithospheric mantle underneath Finsch - the first one at around 1.3 Ga and the second one at around 400 Ma. The first event was not observed from the peridotite whole rock Sm-Nd data. However, we can assume a parallel history of the various lithologies from Finsch from a similar depth range. Possibly, the Sm-Nd signature of the first enrichment was overwhelmed by the second metasomatic event.

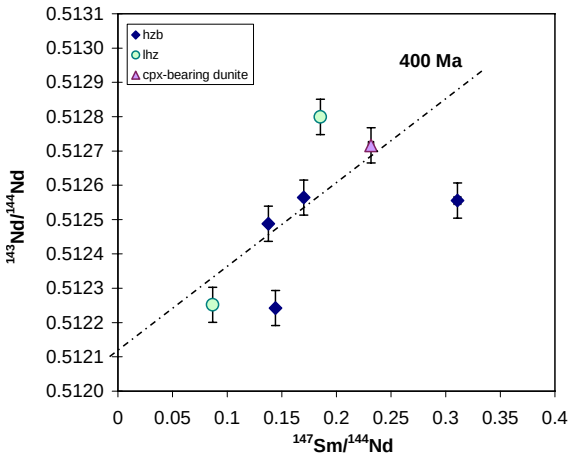

Fig. 2 $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ for the Finsch peridotite whole rocks calculated from the isotope compositions of respective garnets and cpx. Data plot around a 400 Ma isochron with an initial that agrees with $^{143}Nd/^{144}Nd$ of the Finsch kimberlite (0.51212 - Nowell et al., 2004).

In conclusion, the Lu-Hf system indicates a final depletion event for the Finsch peridotites at 2.5 Ga, in agreement with final cratonisation in the late Archean. Depletion is followed by Proterozoic and Phanerozoic re-enrichment, as exhibited by Sm-Nd isotope systematics. Although this latter metasomatism overwhelmed the Nd isotope signature of all samples, it apparently did not much affect the more robust Hf isotope system.

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