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LU-HF AND SM-ND GEOCHRONOLOGY AND GEOTHERMOBAROMETRY OF THE LITHOSPHERIC MANTLE BENEATH THE GIBEON KIMBERLITE FIELD, NAMIBIA

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GEOLOGY, PREVIOUS WORK AND MOTIVATION

The Gibeon Kimberlite Province is located in Namibia between Keetmanshoop and Mariental on the border of the mid Proterozoic to Archean (?) Rehoboth Terrane to the 0.9 to 1.3 Ga old Namaqua-Natal belt. Both terranes are bordered to the east respectively north by the Kheis-Magondi belt and the Kaapvaal craton. The Rehoboth Terrane is a mixed age province with a possibly up to 2.9 Ga old Archean nucleus, products of major magmatic events from between 1.7 and 2.1 Ga and again from the time of the Namaquan orogeny between 0.9 and 1.3 Ga (according to summaries by Janney et al. (2010) and Cornell et al. (2011)).

Recent comparative work on mantle samples from on- and off-craton localities from Southern Africa (Bell et al., 2003; Janney et al., 2010; Mather et al., 2011) has shown that distinct differences but also strong similarities exist between mantle xenoliths from beneath the

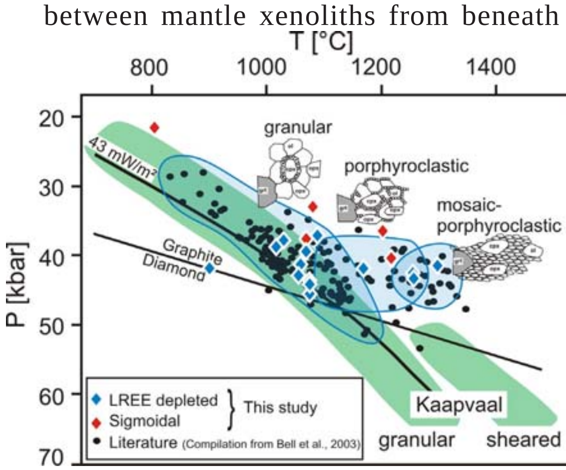

Fig.1. The thermal structure of the lithospheric mantle underneath Gibeon and the Kaapvaal Craton after a compilation of mantle xenoliths P/T conditions by Bell et al. (2003). Our new data for the Gibeon Townsland and Hanaus kimberlite pipes are shown as blue and red diamonds. Textural classification after Franz et al. (1996b).

...ies. ...age ...aO ...ntle ...in ...nic ...ion ...d to ...oic' ...s of ...om ...2.2 Ga (see also Pearson and Wittig (2008), and earlier work) and iii) in the lithosphere thickness which is thinner underneath the Proterozoic terranes by 30 – 40 km (see also Boyd et al. (2004) and Muller et al. (2009)). Similarities exist a) in the conductive limbs of the geothermal gradients indicating similar lithospheric thicknesses sometime in the past (see also Boyd et al. (2004), Franz et al. (1996a) and Mitchell (1984); Fig.1), b) with respect to the overabundance of orthopyroxene in the mantle samples [less pronounced in the residual peridotites from Gibeon

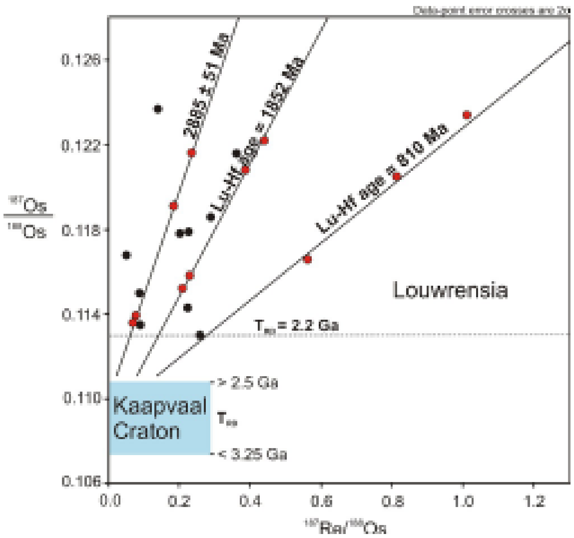

Fig.2. Reinterpretation of Re-Os data by Pearson et al. (2004) from Louwrensia in the light of our Lu-Hf results. The Lu-Hf age of 810 Ma closely correlates with three high 187Re/188Os samples which themselves would give 909 Ma. A further coincidence of 4 samples occurs with the 1852 Ma Lu-Hf age (the Re-Os age of these four samples is 1882 Ma). Four further data points give a Re-Os age of 2885 Ma which we take as the first partial melting event of parts (ó peridotites) of the Rehoboth mantle.

than from the Kaapvaal craton] -see also Boyd et al. (2004) and Franz et al. (1996b), and c) in the existence of garnets with sigmoidal REE patterns. These are common in Kaapvaal peridotites but subordinate in the Gibeon and Rietfontein area [see below and Hoal et al. (1994)].

Franz et al. (1996b) suggested that the orthopyroxene enriched peridotites represent samples of the Kaapvaal lithosphere rifted underneath the Rehoboth terrane in the wake of the Atlantic ocean opening or that the Kaapvaal lithosphere extended underneath the Rehoboth terrane. Both models were rendered unlikely because of the lack of TRD ages older than 2.2 Ga (Boyd et al., 2004; Pearson et al., 2004). The alternative is that Archean mantle forming processes continued into the Proterozoic in a waning thermal regime which enabled only lower degrees of partial melting. It is also unclear why such depleted and in a particular way reenriched mantle portions are juxtaposed to less depleted and differently reenriched mantle material. We have set out to clarify these questions by creating an extensive major and trace element mineral data set and by analyzing and evaluating the Sm-Nd and Lu-Hf isotope systems. These could give supplementary answers to the Re-Os system or enable a more comprehensive interpretation of these data. We assume in our approach that clinopyroxene and garnet carry almost the entire incompatible trace element inventory of the rock and that their analysis combined with the mineral proportions gives the bulk rock Sm-Nd and Lu-Hf isotope composition.

TRACE ELEMENTS AND ISOTOPES

Two peridotite types can be distinguished from the REE patterns: 13 samples with LREE depleted garnet REE patterns (Type 'Δ' – Fig. 3a) and 5 samples with sigmoidal garnet REE patterns (type 'σ' – Fig. 3b).

Most of our Ä samples stem from PT-conditions between 35 to 45 kbar and 1000 – 1100°C and half of the ó types from similar pressures, but temperatures between 1200 – 1250°C (Fig.1).

In order to determine the melting regimes, whole rock REE patterns were calculated based on the relative amounts of clinopyroxene and garnet and averaged amounts of olivine and orthopyroxene taken from Franz et al. (1996b) which were assumed to contain no trace elements and were compared to non modal fractional melting curves of the garnet and spinel stability field. All measured trace elements of garnets resp. clinopyroxenes were normalized to Vitim 313-105.

This peridotite is very close to a primitive mantle composition. The comparison of mineral compositions will show relative changes caused by depletion and reenrichment.

The Sm and Nd contents of the σ minerals were very low after depletion and their present abundances must stem mostly from metasomatism. The Sm-Nd contents of the Δ

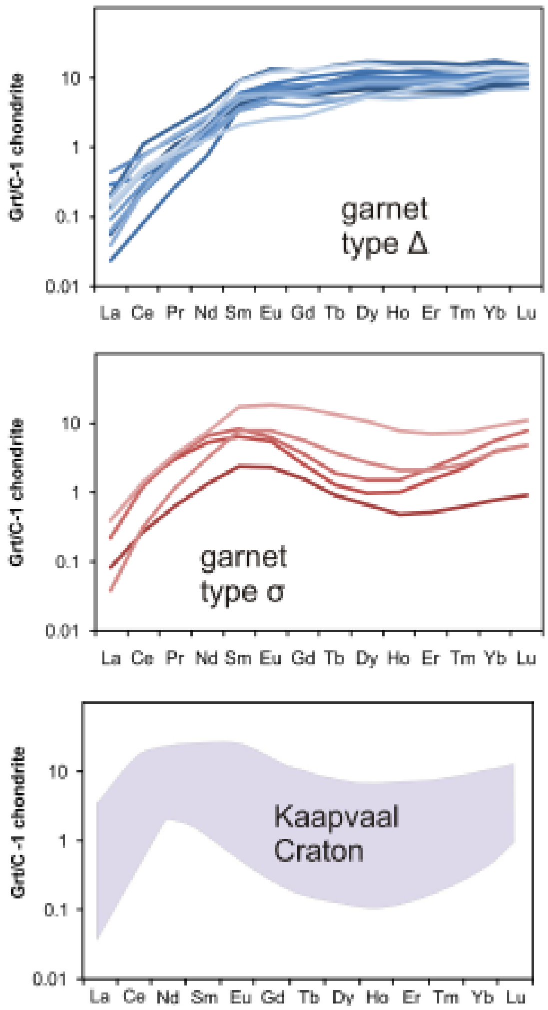

Fig.3. Averaged REE patterns of garnets from peridotites from the Hanaus and Gibeon Townsland kimberlite pipes in comparison to REE patterns of garnets from the Kaapvaal craton (after Lazarov et al. (2009), Fig.3c). Garnets for samples with LREE depleted garnet patterns (type Δ) are shown in Fig. 1A and for samples with sigmoidal garnet patterns (type s) in Fig. 1B.

samples are a mix of residual and reintroduced components and their isotope systematics will give a mixed signal.

The Sm-Nd system may provide information on the timing of metasomatism. Equally, some of the Hf seems to be reintroduced and the Lu-Hf isotope system may provide even better age constraints on metasomatism.

Based on the relative proportions of garnet and clinopyroxene, whole rock $^{176}Lu/^{177}Hf$ and $^{176}Hf/^{177}Hf$ ratios were calculated and plotted in an isochron diagram (Fig. 4).

Four samples from the Δ peridotites yield an age of 810 ± 51 Ma (+ up to 38 for orthopyroxene) with an initial of 0.282365 (εHf_{CHUR} = + 3.3) and MWSD = 2.8. Three σ garnets yield an age of 1852 Ma ± 100 Ma (+ up to 86 for orthopyroxene) and an initial of 0.28243 (εHf_{CHUR} = + 29.4) and MWSD = 3.1. Partial melting in the ó peridotites was probably significantly higher than in the Ä peridotites and only very little Sm and Nd was left. Metasomatism may have overprinted this completely and the three σ garnets may yield a realistic age of metasomatism at around 458 ± 32 Ma.

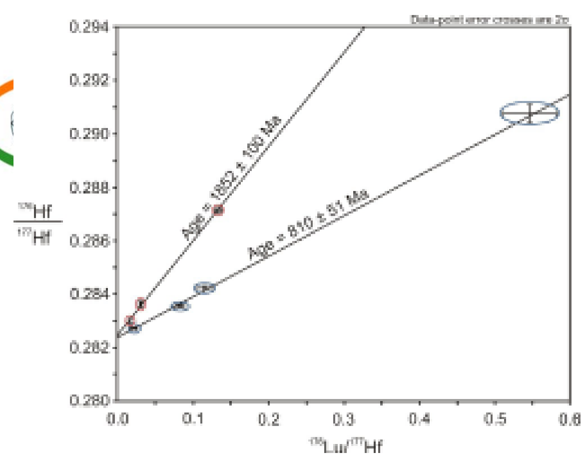

Fig.4. Calculated whole rock isochrons for the Lu-Hf system. This system yields an isochron age of 810 Ma for the Ä peridotites and 1852 Ma for the ó peridotites (from garnets only for the latter because of diminishingly small amounts of clinopyroxene in the samples). Both isochrons are interpreted as enrichment ages because Hafnium was reintroduced into the Samples.

ENRICHMENT AND DEPLETION

The comparison between of whole rock patterns with non modal fractional melting curves indicates for the Δ peridotites moderate degrees of partial melting between 5 and 15 % in the spinel stability field.

We interpret the comparison for the ó peridotites as a succession of partial melting at low pressures, followed by subduction and subsequent melting in the garnet stability in analogy to a scenario developed by Lazarov (Unpublished results) for the Finsch peridotites on the Kaapvaal craton with the difference of lower degrees of partial melting for the Gibeon ó peridotites.

Both Lu-Hf whole rock ages have to be considered as enrichment ages because Hf was reintroduced into already depleted peridotites (positive εHf initials) and probably reset the Lu-Hf system. Introduction of melts or fluids may also be the trigger of further partial of an already depleted mantle as it occurs in mantle wedges above subduction zones.

We examined the Louwrensia Re-Os data of Pearson et al. (2004) in the light of our Lu-Hf results and implemented these ages into a Re-Os diagram (see Fig. 2). We found a close correspondence of Re-Os data subsets with these ages and suggest the existence of a third isochron.

The enrichment age of 810 (+ up to 38 for orthopyroxene) Ma for the Δ peridotites closely correlates with the three data points with $^{187}Re/^{188}Os$ higher than bulk silicate Earth. Trace element data are not available for Louwrensia and the correspondence with the LREE depleted Δ peridotites is inferred from the age.

A further conspicuous coincidence is the overlap of four data points with intermediate $^{187}Re/^{188}Os$ ratios with the age of the σ peridotites (1852 (+ up to 86 for orthopyroxene) Ma). In the lack of trace element data the correspondence of these Louwrensia samples to the σ peridotites is also only inferred from the age.

We distinguish a third correlation of four data points at the almost lowest $^{187}Re/^{188}Os$ range with an age of 2885 ± 51 Ma, an $^{187}Os/^{188}Os$ initial of 0.10984 ± 0.00014 (γOs_{CHUR} = 2.44 based on a chondritic Earth model).

In view of the uncertainties and variabilities attached to the PUM and the chondrite values we interpret the 2.9 Ga age as recording the first partial melting of a primitive upper mantle and relate it to the residual ó periotites. Melting in the Archean within the circum cratonic mantle is supported by three TRD ages of around 2.6 Ga in other off- craton areas (Janney et al., 2010). Further support comes from Archean crustal ages of the Rehoboth province (Cornell et al., 2011; Van Schijndel et al., 2011).

DEVELOPMENT IN TIME

At the time of collision of the Kaapvaal E- and W- blocks at 2.9 Ga the first mantle segments of the lithospheric mantle of the Rehoboth terrane were created by partial melting at relatively shallow levels in the spinel stability field.

Segments of the Rehoboth crust (probably independent of the Kaapvaal craton) existed at that time and residual spinel peridotite was placed underneath this crust by subduction or a similar process to be transformed into garnet peridotite.

Attachment of the Rehoboth terraine occurred somewhere around 2 Ga which is around the time of reenrichment at about 1.9 Ga of the ó peridotites. Sigmoidal garnets were formed in a similar way as in the Archean Kaapvaal peridotites and, also similar, orthopyroxene enrichment may have occurred. This may have been in a mantle wedge setting and may have been simoultaneously connected with second stage partial melting.

Without having any age constraints we assume that the partial melting from a primitive mantle of the Δ peridotites occurred at these middle to early Proterocoic times in a low pressure setting and that these residua were subducted into the preexisting mantle also at these times or during the Namaquan orogenesis from 0.9 to 1.3 Ga. This mantle portion was reenriched at the end of this period at around 850 Ma years ago.

A common thermal history and lithosphere thickness was established across the block consisting of the Rehoboth province, the Kheis Magondi belt and the Kaapvaal craton until the Mesozoic when first, the lower parts of Kaapvaal lithosphere between 170 and 200 km were thermally disturbed and partly eroded sometime around about 150 Ma and second, the part of the Rehoboth lithosphere below about 140 km was removed and the mantle section between 120 and 140 km thermally overprinted (Bell et al., 2003; Boyd et al., 2004; Janney et al., 2010; Mather et al., 2011). This must have happened in the realm and at the beginning of the break-up of Gondwana and the opening of the Atlantic.

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