

Foundered Lower Continental Crust in the Source of Group 2 Kimberlites

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Plate reconstructions link the 60-95 Ma group 1 kimberlites of southern Africa to the Shona hotspot in the southern Atlantic (Hartnady and le Roex, 1985). The group 2 kimberlites are older, between 105 and 200 Ma and plate reconstructions for this period are poorly constrained. Hargraves (1989) found a significant shift in the palaeomagnetic south pole of the group 1 and group 2 kimberlites. This data requires that the African plate migrated 1700 km southward from 105 to 95 Ma. The resultant track joins the group 2 kimberlite track (Skinner, 1989) to the Namibian kimberlites which Davies et al. (2001) link to the Discovery hotspot. Both group 1 and group 2 kimberlites can therefore be related to a mantle reservoir sampled by a mantle plume. Reservoirs considered below are the subcontinental lithosphere, the MORB source, the transition zone, lower continental crust, ancient recycled continental crust, and depleted lower mantle.

Subcontinental Lithosphere

Becker and le Roex (2006) regard the mantle plume as a source of heat only, and relate the distinct chemistry of group 1 and group 2 kimberlites to two distinct types of clinopyroxene found in the lithosphere, in metasomatised lithospheric peridotites. For example, type 1 clinopyroxenes have higher Nb/Th ratios than type 2 clinopyroxenes, matching the higher Nb/Th ratio of group 1 kimberlites relative to group 2 kimberlites (Fig. 1). Nb/Th ratios in the type 2 clinopyroxenes are 2 or less and are highly variable, while the Nb/Th ratio in group 2 kimberlites cluster around 4 and are more coherent. Similarly, Nb/Th ratios in group 1 kimberlites are far more tightly clustered than Nb/Th ratios in type 1 clinopyroxenes (Fig. 1). The same pattern is observed for Hf and Nd isotope ratios, where kimberlites form tight clusters which deviate by +4 to -16 $\Delta\epsilon_{\text{Hf}}$ units from the mantle array while Kaapvaal peridotites range to values above 100 $\Delta\epsilon_{\text{Hf}}$ units from the mantle array (Nowell et al., 2004). The variable and incoherent isotope chemistry of the subcontinental lithosphere led Nowell et al. (2004) to reject this reservoir as a significant contributor to kimberlite magmatism, and to seek for a deeper source.

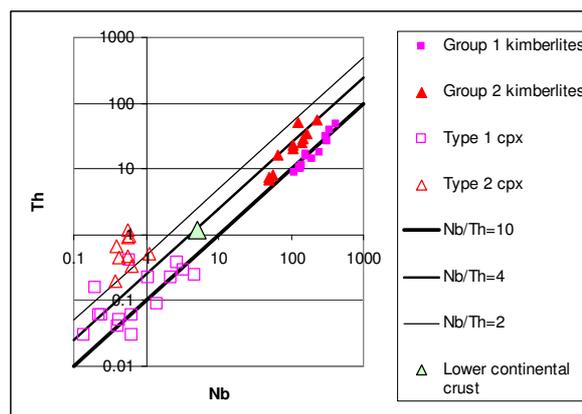


Fig. 1. Nb and Th contents of kimberlites, lithospheric clinopyroxenes and lower continental crust.

MORB source

The lithosphere is underlain by the asthenosphere which is connected to the source of Mid-Ocean Ridge Basalts. One characteristic of the MORB source is its low $^3\text{He}/^4\text{He}$ ratios, so the observation that some group 1 kimberlites have high $^3\text{He}/^4\text{He}$ ratios requires a yet deeper reservoir (Sumino et al., 2006; Tachibana et al., 2006).

In the standard model of two-layer mantle convection the base of the MORB source is at 660 km (Hofmann, 1997). Heat flow from the MORB source into the overlying lithosphere decreases as the thickness of the MORB source decreases, so that heat flow into thick continental lithosphere is lower than into thick continental lithosphere. The magnitude of this variation is large, too large to be accommodated by a MORB source with a base at 660 km. Instead the base of the MORB source must lie at 410 km, at the top of the transition zone (Hatton, 2008).

Transition zone

In isotope ratio arrays ocean island basalt converge to a focus zone, or FOZO, which is thought to represent the depleted lower mantle (Hart et al., 1992). The high $^3\text{He}/^4\text{He}$ source, referred to as C (Hanan and Graham, 1996) has average $^{143}\text{Nd}/^{144}\text{Nd}$ isotope ratios near 0.5129, representing mantle which is distinctly less depleted than FOZO, where the average value is

0.5131 (Hofmann, 1997). A reasonable location for C is therefore in the transition zone above the depleted lower mantle and below the MORB source. The Sr and Nd isotope ratios of C lie within the carbonatite box of Harmer and Gittins (1998) and are similar to the HIMU component which Smith (1983) associated with group 1 kimberlites. C is therefore a suitable source for group 1 kimberlite magmatism. Group 2 kimberlites have an enriched mantle, or EM signature (Smith, 1983) and must contain a contribution from another reservoir.

Lower continental crust

The enriched mantle signature in basalts of the Indian Ocean is referred to as the DUPAL anomaly, and has been linked to the delamination of lower continental crust during Gondwana breakup (Escrigo et al., 2004). The track of the group 2 kimberlites places the Discovery hotspot at the site of Gondwana breakup at 188 Ma so this is an attractive hypothesis. Delaminated lower continental crust may have contaminated the Discovery hotspot. This hypothesis receives support from the observation that lower continental crust has a Nb/Th ratio of 4, similar to that of group 2 kimberlites. Eclogites in the group 2 Roberts Victor kimberlite have bulk TiO₂ contents which are too low for recycled oceanic crust (Hatton, 1978) and they could be samples of lower continental crust returned to surface via the Discovery hotspot.

Oxygen isotopes in Roberts Victor eclogites range from $\delta^{18}\text{O}$ of 2 to 8 (Garlick et al., 1971). In the lower crust the range is from $\delta^{18}\text{O}$ of 5 to 13 (Kempton and Harmon, 1992). By contrast low-chrome garnets associated with group 2 kimberlites have a restricted $\delta^{18}\text{O}$ value of 5.59 ± 0.18 (Schulze et al., 2001). As is the case for the lithosphere, the variation in the isotope chemistry of lower continental crust is too great for this reservoir to be a significant contributor to kimberlite magmatism. A further problem is that the oldest group 2 kimberlite, Dokolwayo, was emplaced at 200 ± 5 Ma (Allsopp and Roddick, 1984). Gondwana breakup commenced at least 20 to 40 million years after this (Duncan et al., 1997) so it is difficult to appeal to crustal delamination in explaining the enriched mantle signature of this particular kimberlite.

Ancient recycled continental crust

The $\delta^{18}\text{O}$ value of 5.59 ± 0.18 that is associated with group 2 kimberlites (Schulze et al., 2001) falls within the range of 5.4 to 6.1 found in EM2 ocean island basalts (Eiler et al., 1997). The EM2 component is usually related to whole mantle convection which carries components from the continental crust to the deep mantle (Jackson et al., 2007). Continuous whole mantle convection cannot be reconciled with the strongly layered mantle proposed here. Whole mantle

convection may have been a feature of the early earth only.

Boyet and Carlson (2005) demonstrated that an early enriched reservoir formed before 4.53 Ga, but after 4.5 Ga this reservoir was isolated. Isolation of this reservoir may be linked to the cessation of vigorous whole mantle convection. Terrestrial lead isotope evolution probably began at 4.45 Ga (Rudnick and Goldstein, 1990) and this dates the end of vigorous whole mantle convection.

During vigorous whole mantle convection the mantle degassed and the outer layers of early earth were anhydrous. The current budget of volatile elements and noble elements is widely considered to have been added in a late veneer. The transition zone contains the water-rich minerals wadsleyite and ringwoodite, and hosts a large proportion of the earth's water. Once water was retained in the earth the transition zone became a discrete and separate reservoir, abruptly curtailing whole mantle convection.

The enriched mantle component in group 2 kimberlites is therefore ultimately related to continental crust which formed in the Hadean earth and accumulated at the base of the mantle. A large, very low velocity anomaly at the core-mantle boundary marks the site where this component is currently entrained in rising diapirs (Wen, 2006). These diapirs rise up to the transition zone, producing secondary diapirs.

The Cretaceous Group 1 kimberlites of southern Africa contain only a minor component of the deep enriched mantle. Their isotope chemistry is dominated by the C signature of the transition zone. By contrast the isotope chemistry of lamproites is dominated by the enriched mantle signature (Bell, 2006). Group 2 kimberlites are intermediate, with contributions from the enriched mantle reservoir at the base of the mantle and from the transition zone reservoir.

While the deep mantle reservoirs are the ultimate sources of kimberlite magmatism, it is the secondary diapirs rising from the transition zone that produce the hotspot tracks associated with particular kimberlite clusters, and it is the interaction between these secondary diapirs and the base of the lithosphere that yields the economic concentrations of diamonds that are associated with kimberlites.

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