Carbonatites and mantle evolution: a review

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Introduction

Carbonatites (igneous rocks containing > 50% by volume carbonate minerals) are ideal for monitoring the evolution of the sub-continental upper mantle (SCUM). The reasons for this are as follow: 1) carbonatites are rich in Sr (average 7000 ppm) and the *REE*s (more abundant than any other igneous rocks: average Nd = 250 ppm) and in some cases Pb (up to 118 ppm) and hence the eftects of crustal contamination of the mantle signatures should be reduced; 2) carbonatitic melts are thought to rise rapidly to the surface because of their low density and low viscosity, thus minimizing available reaction time between continental crust and melt; 3) carbonatitic bodies range in age from 2.68 Ga to recent, and hence provide information of SCUM from late Archaean to present; 4) carbonatites, although volumetrically insignificant are found on most continents, and 5) carbonatitic melts or their parents sample large mantle volumes, and thus provide an average isotopic composition for the mantle source. Phase equilibrium studies, stable oxygen isotope compositions, along with the radiogenic isotopic compositions of Nd, Sr and Pb clearly indicate that carbonatites are derived from a mantle source. Whether all carbonatite magmas are the products of primary carbonatitic melts, or whether they are derived from a carbonated nephelinitic parent by crystal fractionation or liquid immiscibility or a combination of both, is still under debate.

Discussion

The advantage of carbonatites over oceanic basalts is that they can be used to monitor the secular evolution of the mantle over a considerable part of the Earth's history. Isotopic studies of carbonatites from the Canadian Shield indicate derivation of melts from a depleted mantle, that differentiated about 3.0 Ga ago (Bell *et al.*, 1982; Bell and Blenkinsop 1987a; Kwon *et al.*, 1989; Tilton and Bell, in press). Isotopic data from 2.68 Ga, 1.9 Ga, 1.1 Ga, 600 Ma and 110 Ma carbonatite-alkalic complexes (Bell and Blenkinsop 1987a) indicate a source with a constant Rb/Sr ratio of 0.020 ± 0.002, considerably lower than that of bulk Earth, and a present-day $^{87}Sr/^{86}Sr$ ratio of 0.70342 ± 0.00008 (ε_{Sr}(O) = -15.3 ± -0.5). The initial Pb ratios from the 1.9 Ga and 110 Ma carbonatites lie well below crustal evolution curves, supporting the idea of a LIL-depleted source for the magmas (Kwon *et al.*, 1989). ε_{Nd}(T) values, although variable, generally increase with corresponding decrease in age (Bell and Blenkinsop. 1987a). Values range from +1.6 for the 1.9 Ga carbonatite to +5.3 for the 110 Ma carbonatite (parameters for bulk Earth are: present day $^{87}Sr/^{86}Sr$ 0.7045, initial ratio 0.69898, $^{87}Rb/^{86}Sr$ = 0.0827, age of Earth = 4.55 Ga). Two Archean carbonatites (Lac Shortt, and Dolodau, Quebec) with ages of 2.68 Ga have Sr (ε_{Sr}(T) = $-0.3 \pm$ 0. 3) and Pb isotopic signatures similar to 0.9 those estimated for 'bulk silicate Earth' at 2.68 Ga, although their ε_{Nd}(T)˜Nd˜) values of $+2.8 \pm 0.3$ indicate an earlier mantle depletion event (Tilton and Bell in press). The absence of any HIMU or EM 1 signature in these Archean carbonatites was used by Tilton and Bell (in press) to argue for a major change in mantle differentiation processes about 3 Ga ago.

Although the approach taken using Canadian carbonatites has yet to be tried elsewhere, there is a considerable amount of isotopic information from young (< 200 Ma) carbonatites and hence comparisons can be made to the data from OIBs. On the basis of Nd, Pb and Sr isotope ratios of young carbonatites from five continents, the most important findings are:

1) almost all have Nd, Pb and Sr isotopic signatures similar to those from OIBs (Basu and Tatsumoto, 1980; Bell *et al.*, 1982; Nelson *et al.*, 1988; Kwon *et al.*, 1989; Simonetti and Bell, in press; Tilton and Bell, in press). Nd and Sr isotopic data from most young carbonatites fall within the depleted quadrant of the anti-correlation plot (Bell and Blenkinsop, 1987b) and Pb ratios follow the oceanic regression line based on MORB and OIB data, and most lie to the right of the geochron (Kwon *et al.*, 1989)

2) most isotope ratio diagrams show patterns consistent with mixing between HIMLU and EM 1 (Bell and Blenkinsop, 1987b; Tilton and Bell, in press). Negative correlations occur between $^{87}Sr/^{86}Sr$ *vs.* $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ *vs.* $^{87}Sr/^{86}Sr$, and linear relationships suggest that

the Sr/Nd and Sr/Pb ratios are the same in both end members.

Data from young carbonatites from East Africa, including the only known active carbonatite volcano, Oldoinyo Lengai, lie along a straight line with a slope of -0.28 ± 0.02. The samples are uniformly distributed between HIMU and EM 1, and mimic the LoNd array of Hart *et al.* (1986) defined by isotopic data from St. Helena and Tubuaii for HIMU, and the Walvis Ridge for EM 1. Mixing of HIMU and EM 1 components is widespread in the sub-continental mantle below Kenya, Tanzania and Uganda.

Sr and Nd isotopic ratios from both silicate rocks, (nephelinites and phonolites) and natrocarbonatites from one single volcano, Oldoinyo Lengai, cover almost two thirds of the length of the East African Carbonatite Line (Bell and Dawson, in press) suggesting that the sources of the HIMU and EM 1 components are in close spatial relationship. A linear array of $\varepsilon_{Nd}(T)$ and $\varepsilon_{Sr}(T)$ for 380–360 Ma carbonatites (Kramm, 1993) from the Kola alkali province, Russia, is also interpreted in terms of the mixing of two end-members, considered to be of mantle origin. The slope of Kola carbonatite line is thought by Kramm (1993) to be significantly different from that of the EACL.

Conclusions

The isotopic systematics of carbonatites are extremely similar to those associated with some OIB's, suggesting involvement with the same sources, or sources that have undergone similar differentiation histories. Most young carbonatites are best considered as mixtures of two mantle components with isotope characteristics similar to HIMU and EM 1. Any model proposed for the evolution of the mantle and the generation of carbonatites must take into account the following features: 1) the close association of many carbonatites with nephelinites (supposedly derived from an amphibole-bearing peridotite); 2) intermittent carbonatitic magmatism over many millions of years at restricted parts of the Earth's crust (e.g. Greenland, Canada); 3) the confinement of most carbonatites to continental settings; 4) the similarity in isotope composition between OIBs and carbonatites, and 5) a fundamental change in mantle differentiation processes at about 3.0 Ga.

The high abundances of Nd and Sr, and sometimes Pb, in carbonatites provide a unique probe into the upper mantle, a probe that rarely becomes tarnished by interaction with continental crust.

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