Mantle plumes and other mail from the mantle

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Study of mantle plumes involves a myriad of disciplines ranging from geochemistry to seismic tomography to mineral physics to fluid dynamics modeling. Evidence from these fields is converging on the notion, put forth in 1980 by Hofmann and White, that plumes originate at the core/mantle boundary layer, fed by thermal activation of ancient subducted slab components. The Sr, Nd and Pb isotope tracer taxonomy of Zindler and Hart delineates four mantle 'species' – the uppermost depleted mantle which feeds spreading ridges (DMM), and three others which are transported to the surface at volcanic oceanic islands by upwelling mantle plumes (EM1, EM2 and HIMU). The distinct isotopic evolution of these four species has required 1–2 billion years, and each of the three 'plume' species shows up in pure form in at least two separate geographic regions (in other words, these species are not 'examples of one'; Hofmann, 1992). Figure 1 shows a global isotopic data set consisting of over 1000 analyses of MORB and OIB, with the four mantle species approximately located. Following Carlson (1994), the data are distinguished by hemisphere; the MORB and OIB from the southern hemisphere are far more variable than those from the northern hemisphere. The prevalence of enriched species (EM1 and EM2) in the southern hemisphere originally led to the delineation of the DUPAL ANOMALY belt (Dupre and Allegre, 1983; Hart, 1984). Later this belt was amended to include the HIMU species as well (Hart, 1988). The most extreme isotopic signatures seen in Figure 1 are clustered in two regions of the DUPAL belt one centered under the SW Pacific and one centered under the SW Indian Ocean. These features correlate very well (at low degree) with the two 'grand structures' delineated by seismic tomography in the deepest mantle the 'Equatorial Pacific Plume Group' and the 'Great African Plume' (Dziewonski *et al.*, 1991). This correspondence supports a lower mantle storage location for the DUPAL components.

Fluid dynamics modeling of ascending plumes shows that they can entrain significant quantities of the ambient mantle which they traverse. This occurs both within the initial plume head, and later as a steady state feature of the conduit itself. Plumes thus provide a mantle sampling device, though admittedly not a very tidy device!Hauri *et al.* (1994) modeled non-Newtonian plumes with depth-dependent properties and found that the fraction of entrained material could range from $<5\%$ for robust plumes to $>90\%$ for weaker plumes. In all cases, most of the entrained material is derived from the lower half of the region

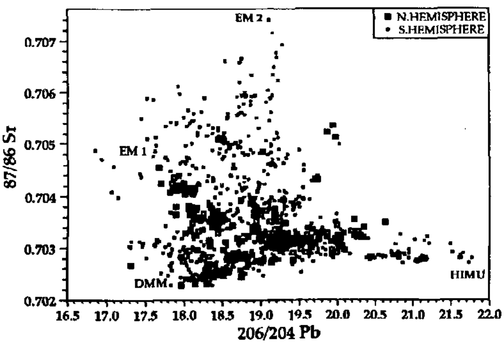

FIG. 1. $^{87}/^{86}$Sr versus $^{206}/^{204}$Pb for over 1000 samples of MORB and OIB; open and filled squares are northern and southern hemispheres, respectively. Data from various literature sources.

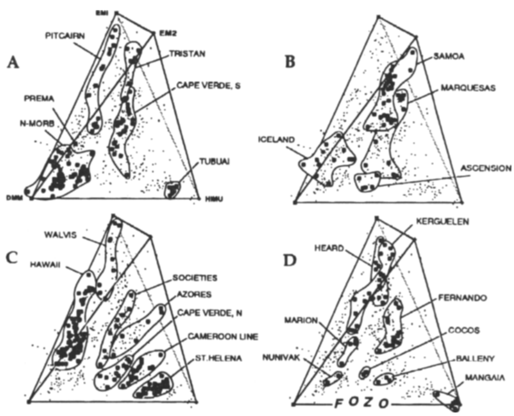

FIG. 2. Various MORB and OIB data plotted in $^{87/86}$Sr–$^{143/144}$Nd–$^{206/204}$Pb space, circumscribed by a tetrahedral volume defined by the four mantle end-member components DMM-EM1-EM2-HIMU (adapted from Hart *et al.*, 1992).

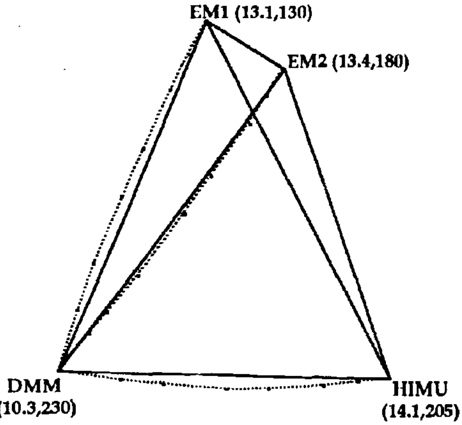

FIG. 3. Mantle tetrahedron with mixing lines drawn between DMM and the other three corners. The numbers in parentheses are the Sr/Nd and Sr/Pb concentration ratios used for the four mantle end members; these are derived from average N-MORB and from the end-member basalts from Pitcairn, Samoa-Tahaa and Mangaia-Tubuai.

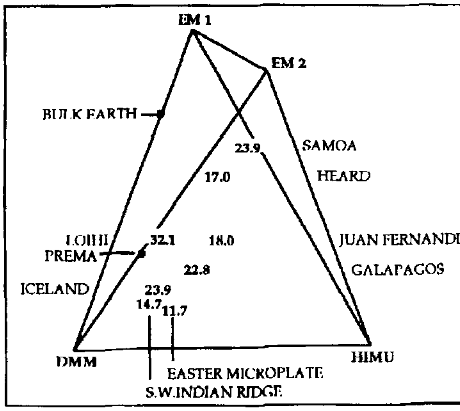

FIG. 4. Mantle tetrahedron (Sr-Nd-Pb isotopic space) showing the position of the highest $^3He/^4He$ ratio in basalts from each of 8 OIB and MORB localities. Data from various literature sources.

traversed by the plume. If plumes originate from the base of the upper mantle, they should entrain only upper mantle (DMM). Isotopic arrays for various plumes should then indicate DMM as a mixing end-member. Figure 2 shows a sampling of oceanic plume arrays (plotted in the 4 component mantle tetrahedron), and very few of the arrays 'point' toward DMM. Most converge on a region we term FOZO (focus zone), with the exception of two near-ridge plumes which clearly contain a large DMM component (Galapagos and Iceland).

Mixing arrays in Sr-Nd-Pb isotopic space are not significantly curved, so the apparent lack of convergence on DMM cannot be circumvented by postulating strong (but unsampled) curvature. This can be modeled by observing the actual Sr/Nd/Pb concentration ratios in basalts from the end-member species, and arguing that the partial melting process will act to maximize, not minimize, the relative concentration variations in basalts relative to their mantle source. Mixing arrays are shown in Figure 3 between DMM and EM1, EM2, HIMU, and the curvature is nil.Further evidence against entrainment of upper mantle (DMM) comes from the $^3He/^4He$ isotope data on OIB. The DMM and HIMU mantle components both have $^3He/^4He$ ratios of 7-9 times atmospheric (Ra), yet many plumes which plot in the lower part of the mantle tetrahedron show high to very high $^3He/^4He$ (Fig. 4); other plume arrays such as Samoa don't reach very far south in the tetrahedron, yet their $^3He/^4He$ nevertheless increases in that direction. Several MORB suites dredged from ridge segments near plumes (SW Indian ridge - Bouvet; Easter microplate) show high $^3He/^4He$ ratios due to contamination by the plume. We associate the high $^3He/^4He$ with the new FOZO component, which is in turn identified with lower mantle. The exact isotopic character of FOZO is not well defined by Figures 2 or 4, but it clearly cannot be 'bulk earth'; it might be close to the PREMA component of Zindler and Hart (1986).

Future studies of He isotopes combined with Sr, Nd and Pb isotopes should help define the position of the highest $^3He/^4He$ component in the mantle tetrahedron, and ascertain whether this location is also consistent with the FOZO region where the many OIB arrays appear to converge. We also appear poised to finally understand the evolutionary history of the three mantle plume species, with the high $^{187}Os/^{186}Os$ isotope signature of HIMU supporting an ancient recycled ocean crust origin, and the heavy $\delta^{18}O$ signature of EM1 and EM2 (Woodhead *et al.*, 1993) pointing strongly to a recycled sedimentary component in these species.

The input from many colleagues will be obvious, and especially that from E. Hauri, J. Whitehead and J. Blusztajn.