

CHEMICAL AND ISOTOPIC SYSTEMATICS OF CONTINENTAL MANTLE.

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Peridotite xenoliths show systematic geochemical trends¹⁻³. These systematics are illustrated in Figure 1, where the sequence of elements along the x-axis reflects decreasing incompatible behaviour (from left to right). Patterns displayed by garnet and spinel bearing peridotite xenoliths (Figure 1), are consistent with a two stage history involving the extraction and later reintroduction of melts. These processes control peridotite geochemistry.

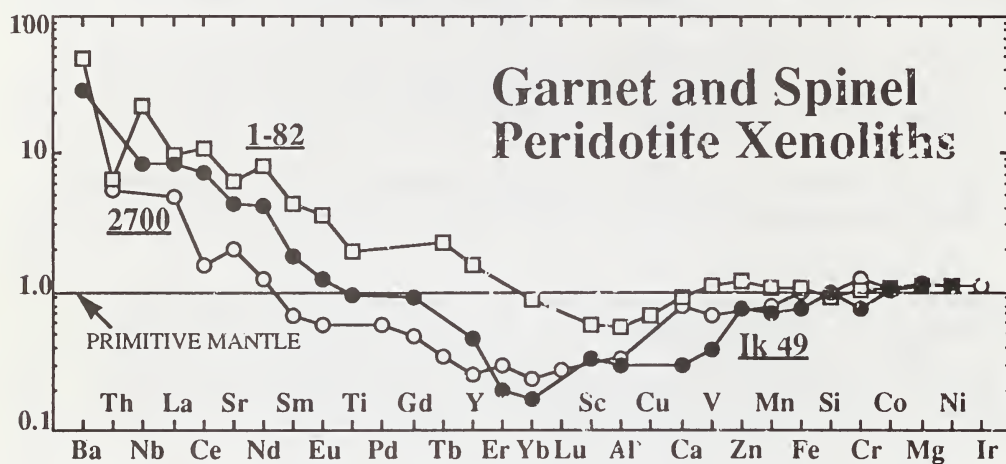


FIGURE 1. Mantle normalized diagram for typical peridotites from continents, including a garnet peridotite⁵ (filled symbol) and two spinel peridotites^{6, 7} (open symbols). Element abundances normalized to primitive mantle^{1, 19, 20}; order of elements is established by the enrichment factors observed in oceanic basalts.

These element systematics are typical of peridotites from non-cratonic and cratonic parts of the continents¹⁻⁸ and are schematically illustrated in Figure 2. Here elements are classified into Groups for the sake of further discussion. For most peridotites, the Group V elements (e.g., LREE, P, Sr, Ba, Nb, Ta, Mo, W, Tl, Cs, Rb, K, Th and U) and some of the Group IV elements (e.g., heavy to middle REE, Y, Ti, Na, Zr, Hf, Li, Sb, Sn and Pd) are enriched relative to Primitive Mantle. Members of Group V and IV elements included the highly incompatible and moderately incompatible trace elements, respectively. The Group III elements (e.g., Cu, Zn, Ca, Sc, Al, V, Lu, Yb, Re, Au and Cd), which included the mildly incompatible elements, are generally depleted relative to Primitive Mantle. This behaviour is in contrast to that shown by the Group IV and V elements. The Group I elements (e.g., Co, Cr, Mg, Ni, Rh, Ru, Ir and Os) which include the compatible trace elements and are consistently enriched by about 5% to 50% relative to the Primitive Mantle. Finally, the Group II elements (e.g., Si, Mn, Fe and Ge) show similar abundances in basalts and residual peridotites, indicating that these elements have distribution coefficients close to unity.

Enrichment of Group I elements and depletion of Group III-V elements occurred during an early melt extraction event, probably during the initial stages of lithospheric mantle development and stabilization^{3, 7, 9}. The seemingly contradictory enrichments of incompatible elements are due to a later metasomatic enrichment. This enrichment process may have occurred repeatedly, over long time scales and in association with tectonomagmatic reactivation of the lithosphere.

Peridotite xenoliths are samples of the continental mantle, albeit small. Based on a compilation of geochemical data for about a thousand peridotite xenoliths a compositional model for the continental mantle can be developed. The continental mantle in non-cratonic regions possesses a LREE-enriched pattern, with about 1.5 to 4 times the primitive mantle abundance for La, and a relatively flat HREE pattern, with Yb-Lu concentrations about a factor of 2 less than primitive mantle abundances³. This two fold decrease in Yb and Lu abundances is consistent with their average major element compositions^{3, 10-12}. Peridotite xenoliths (predominantly garnet-bearing) from cratons have on average more depleted major

element compositions¹⁰⁻¹² and likewise have more depleted HREE abundances than the non-cratonic (predominantly spinel-bearing) peridotite xenoliths³. This feature is consistent with cratonic peridotites being generated by the extraction of greater degrees of partial melt¹¹.

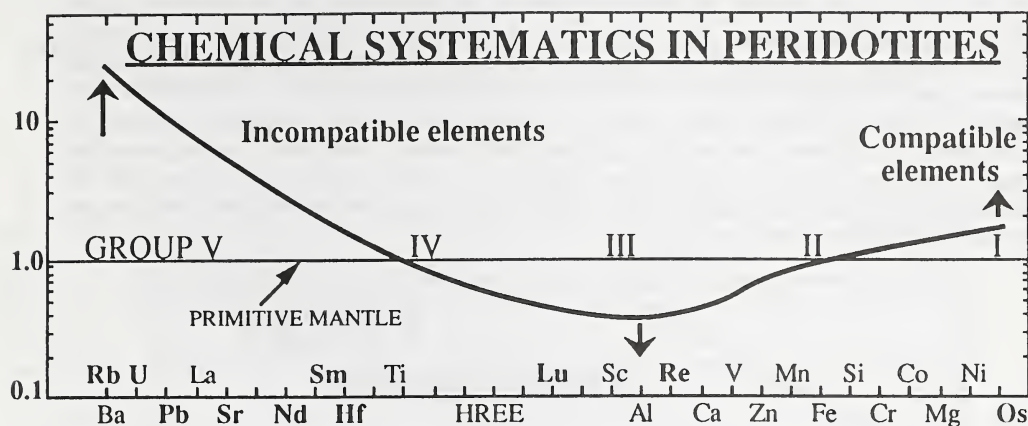


FIGURE 2. A schematic mantle normalized diagram illustrating the systematic geochemical behaviour of elements in garnet and spinel bearing peridotites.

These chemical systematics have important implications for the parent/daughter ratios (i.e., Rb/Sr, Sm/Nd, U(Th)/Pb, Lu/Hf and Re/Os) of the radiogenic isotope systems. Parent and daughter isotopes for the Sr, Nd and Pb isotope systems are incompatible and are therefore more strongly influenced by the early depletion and later enrichment processes. Thus, the age of the melting event, the time difference between this and later enrichment(s) and the composition of the added component will all greatly influence the resultant isotopic characteristics. Consequently, the Sr-Nd-Pb isotope systems are fairly complicated, as is readily shown by the broad spectrum of Sr and Nd isotopic compositions in peridotite xenoliths. In contrast, the parent isotopes ¹⁷⁶Lu and ¹⁸⁷Re are classified with the Group III elements and their daughter isotopes (¹⁷⁶Hf and ¹⁸⁷Os) are Group IV and Group I elements, respectively. Re/Os data for peridotite xenoliths¹³⁻¹⁵ are limited, however, most have subchondritic values (Figure 3). Rhenium tends not to be enriched during metasomatic enrichment events. Likewise, peridotite xenoliths with long term incompatible element enrichments should have low, subchondritic Sm/Nd and Lu/Hf values. Thus, time integrated evolution of these isotope systems in most cratonic and non-cratonic peridotites should be retarded with respect to the bulk earth, leading to distinctive Hf-Os isotopic compositions for the continental mantle (Figure 4). The limited amount of Os and Hf isotope data for continental peridotite xenoliths support this interpretation.

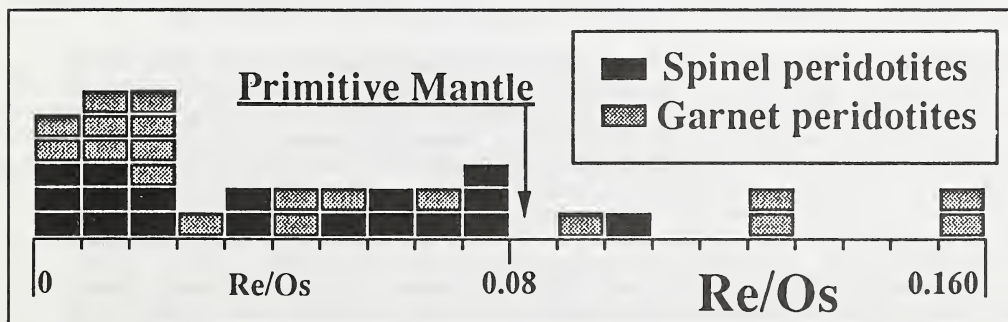


FIGURE 3. A histogram of Re/Os ratios for peridotite xenoliths from continents. Most peridotites have subchondritic (i.e., subprimitive mantle) Re/Os ratios. Samples contaminated by kimberlitic magmas¹³ were not included in this histogram. Other garnet peridotites with high Re/Os (shown here) may also have been contaminated.

These chemical and isotopic systematics for the continental mantle can constrain source models for different types of magmas. Sr, Nd, Pb and Os isotope data for southern Africa

kimberlites^{13, 16} are consistent with incompatible element-enriched regions of the continental mantle as a source for Group II kimberlites, whereas Group I kimberlites may be derived from similar or deeper mantle sources. The abundant Sr, Nd and Pb isotope data for continental flood basalts are consistent with, but do not require, an incompatible element-enriched source region in the continental mantle. This isotope data in combination with the scant amount of Os and Hf isotope data^{17, 18}, however, do not support the hypothesis that continental flood basalts are derived from incompatible element-enriched continental mantle sources. Assuming the bulk composition of the continental mantle possess an incompatible element-enriched composition, then the former should have low Sm/Nd Lu/Hf and Re/Os ratios. Over time this region evolves to negative ϵ_{Nd} , ϵ_{Hf} and γ_{Os} compositions (Figure 4). The available Os isotope data for continental flood basalts are similar to the crust ($+\gamma_{Os}$)¹⁸ and are inconsistent with source models invoking the continental mantle.

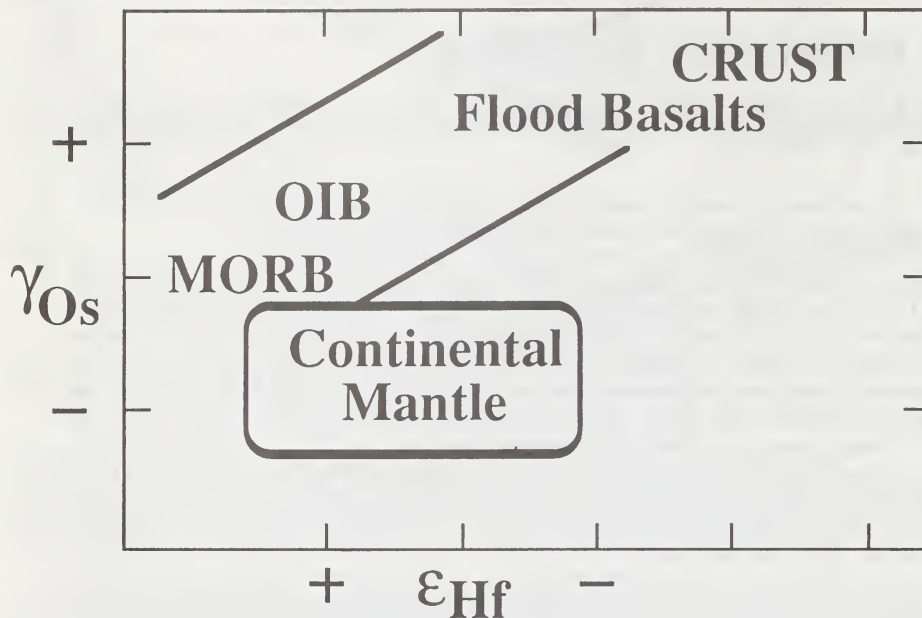


FIGURE 4. Idealized Hf-Os isotope systematics for oceanic basalts (MORB and OIB), flood basalts, continental crust (CRUST) and the continental mantle. This diagram has been constructed from the few available data for Hf and Os isotopes and from predictions on the continental mantle based on the chemical systematics of peridotite xenoliths. The continental mantle is not predicted to be a suitable source for continental flood basalts. ϵ_{Hf} and γ_{Os} express differences in parts to the 10^4 and 10^3 , respectively, from a chondritic value.

- REFERENCES:** 1. McDonough, W.F. & Frey, F.A. in *Geochemistry and Mineralogy of Rare Earth Elements* (eds. Lipin, B. & McKay, G.R.) 99-145 (Mineralogical Society of America, Chelsea, Michigan, 1989). 2. Jochum, K.P., McDonough, W.F., Palme, H. & Spettel, B. *Nature* **340**, 548-550 (1989). 3. McDonough, W.F. *Earth Planet. Sci. Lett.* **101**, 1-18 (1990). 4. Nixon, P.H., Rogers, N.W., Gibson, I.L. & Grey, A. *Ann. Rev. Earth Planet. Sci.* **9**, 285-309 (1981). 5. Erlank, A.J., et al. in *Mantle Metasomatism* (eds. Menzies, M.A. & Hawkesworth, C.J.) 221-312 (Academic Press Inc., London, 1987). 6. Menzies, M.A., Rogers, N., Tindle, A. & Hawkesworth, C.J. in *Mantle Metasomatism* (eds. Menzies, M.A. & Hawkesworth, C.J.) 313-361 (Academic Press Inc., London, 1987). 7. Frey, F.A. & Green, D.H. *Geochim. Cosmochim. Acta* **38**, 1023-1059 (1974). 8. Stosch, H.-G. & Seck, H.A. *Geochim. Cosmochim. Acta* **44**, 457-470 (1980). 9. Ringwood, A.E. *J. Geology* **90**, 611-643 (1982). 10. Maaløe, S. & Aoki, K.I. *Contrib. Mineral. Petrol.* **63**, 161-173 (1977). 11. Boyd, F.R. *Earth Planet. Sci. Lett.* **96**, 15-26 (1989). 12. Jordan, T.H. in *The mantle sample: Inclusions in kimberlites and other volcanics* (eds. Boyd, F.R. & Meyer, H.O.A.) 1-14 (AGU, Washington, D.C., 1979). 13. Walker, R.J., Carlson, R.W., Shirey, S.B. & Boyd, F.R. *Geochim. Cosmochim. Acta* **53**, 1583-1595 (1989). 14. BVSP. *Basaltic Volcanism on the Terrestrial Planets* 1-1286 (Pergamon Press Inc., New York, 1981). 15. Nonaka, J. *Über die Häufigkeit von bisher wenig untersuchten Elementen im Erdmantel* (Universität Mainz, 1982). 16. Smith, C.B. *Nature* **304**, 51-54 (1983). 17. Liew, T.C., Cox, K.G., Hawkesworth, C.J. & Hofmann, A.W. *Terra cognita* **6**, 234-235 (1986). 18. Pegram, W.J. & Allègre, C.J. *Terra abstracts* **1**, 343 (1989). 19. Sun, S.-s. *Geochim. Cosmochim. Acta* **46**, 179-192 (1982). 20. Sun, S.-s. & McDonough, W.F. in *Magmatism in the ocean basins* (eds. Saunders, A.D. & Norry, M.J.) 313-345 (Geol. Soc. Lond. Spec. Pub., 1989).