

CHEMICAL AND ISOTOPIC SYSTEMATICS OF CONTINENTAL LITHOSPHERIC MANTLE

By

William F. McDonough¹

ABSTRACT

The compositions of garnet and spinel peridotite xenoliths from continental regions and massif peridotites reveal some generalized chemical systematics in the behavior of elements in the mantle. Most peridotite xenoliths and some massif peridotites have experienced early melt extraction and later incompatible element enrichment(s). The combination of these processes results in peridotite xenoliths having enrichments, relative to the Primitive Mantle, in the highly incompatible and compatible elements and depletions in elements with residue/melt distribution coefficients slightly less than one. The chemical systematics of these peridotite xenoliths constrain compositional models of the continental lithospheric mantle and its growth and evolution. These systematics also reveal some simple but important relationships in the parent/daughter ratios of the radiogenic isotope systems which with time evolve to distinctive fields in isotope space. The two stage history of most peridotite xenoliths and the variable behavior of Th-U-Pb, Rb-Sr, and Sm-Nd during melting and metasomatism cause dispersion in Pb-Sr-Nd isotope compositions. In contrast, Re/Os ratios in peridotite xenoliths are characteristically subchondritic, indicating that the Os isotope system does provide a distinct continental lithospheric mantle signature (Walker et al., 1989).

INTRODUCTION

The continental lithospheric mantle, that portion of the lithosphere underlying the crust and mechanically coupled to it, is considered to be more refractory than the surrounding and deeper mantle (Clark and Ringwood, 1964, Jordan, 1988). Knowledge of the continental lithospheric mantle is derived largely from studies of peridotite xenoliths, the only direct samples of this portion of the lithosphere, and from models based on geophysical and petrological data. Frey and Green (1974) showed that the major and trace element compositions of lherzolite and harzburgite xenoliths often reflect a two stage history, namely an initial melt extraction event followed by an enrichment event which introduced incompatible elements back into the rock. These observations have been further reinforced by geochemical studies on peridotite xenoliths over the past 18 years.

Kimberlites bring up both spinel and garnet peridotites, generally from older regions of the continental lithospheric mantle, whereas alkali basalts are usually restricted to non-cratonic portions of continents and typically carry only spinel peridotites, which are lower pressure facies of the continental lithospheric mantle (Nixon, 1987). The major element compositions of garnet and spinel peridotites (Table 1) are similar, with garnet peridotites having on average slightly more refractory characteristics (Maaløe and Aoki, 1977; Jordan, 1979; Boyd, 1989; McDonough, 1990). Most spinel and garnet peridotite xenoliths have significantly lower CaO, Al₂O₃, TiO₂ and Na₂O contents and higher MgO, Cr and Ni contents compared to the Primitive Mantle. These refractory major element characteristics are attributed to the early loss of a melt component, which in many cases was basaltic, but could have been a komatiitic in the case of some very refractory peridotites (Boyd, 1989; Hawkesworth et al., 1990).

In contrast, massif (or alpine) peridotites are large exposures of the upper mantle that provide information on the field relations of different lithologies. These ultramafic bodies represent slices of lithospheric mantle, although in a number of cases it is difficult (if not impossible) to determine whether a particular massif is derived from continental or oceanic lithospheric mantle. Relative to the xenolith samples, massif peridotites typically have more lherzolite than harzburgite. This is readily illustrated by their high CaO and Al₂O₃ contents (Table 1). Like peridotite xenoliths, massif peridotites have bulk rock compositions indicating they have lost a basaltic melt component.

Frey and Green (1974) were the first to observe that the majority of peridotite xenoliths nevertheless display LREE (light rare earth element)-enrichments. Numerous subsequent studies have confirmed their findings (see McDonough and Frey (1989) for a recent review). Typical REE patterns for spinel and garnet peridotite xenoliths are shown in Figure 1. Peridotite xenoliths depleted by prior partial melting events should have LREE-depleted, not enriched patterns, given that the LREE (being incompatible elements) are partitioned into the melt, and not the residue. Thus, Frey and Green (1974) argued that the presence of LREE-enriched compositions in refractory peridotite xenoliths required a metasomatic enrichment event post-dating an earlier melt extraction event.

(1) Research School of Earth Sciences, The Australian National University, GPO Box 4, Canberra ACT, 2601, Australia.

Table 1 — Composition of Xenolith and Massif Peridotites and the Primitive Mantle

	Primitive Mantle	Massif Peridotites	Spinel Peridotites	Garnet Peridotites
SiO ₂	44.8	45.1	44.1	45.5
TiO ₂	0.21	0.13	0.09	0.09
Al ₂ O ₃	4.45	2.89	2.20	1.23
Cr ₂ O ₃	0.38	0.37	0.39	0.35
FeO	8.40	8.05	8.19	7.26
MnO	0.14	0.13	0.14	0.11
MgO	37.2	40.2	41.2	44.2
NiO	0.24	0.26	0.27	0.27
CaO	3.60	2.52	2.20	0.90
Na ₂ O	0.34	0.20	0.21	0.08
K ₂ O	0.028	0.010	0.028	0.050
P ₂ O ₅	0.022	0.020	0.030	0.020
Ca/Al	1.09	1.18	1.35	0.99
Mg#	88.8	89.9	90.0	91.6
Ir (ppb)	3.3	3.5	3.7	3.8
Co (ppm)	105	110	111	101
Ga	3.9	2.5	2.4	2.3
V	82	70	53	31
Sc	17.3	14.1	12.0	6.0
Sr	21	7.0	20	29
La	0.708	0.101	0.77	2.05
Ce	1.83	0.420	2.08	4.12
Nd	1.37	0.478	1.10	1.74
Sm	0.444	0.192	0.25	0.37
Eu	0.168	0.081	0.10	0.11
Gd	0.595	0.304	0.31	0.35
Tb	0.108	0.061	0.056	0.050
Yb	0.481	0.354	0.27	0.085
Lu	0.074	0.055	0.045	0.011

Compositions reported are median values; these values provide a better estimate of the abundances of the incompatible elements in these mantle reservoirs than averages (see McDonough (1991) for a discussion on the differences between median and average values).

Massif peridotites, in comparison, commonly have LREE-depleted patterns which are consistent with their major element compositions having experienced the loss of

a partial melt. There are, however, examples of LREE-enriched patterns in some massif peridotites (McDonough and Frey, 1989) which have also been attributed to second stage melt enrichment processes (Bodinier et al., 1990; Vasseur et al., 1991).

The use of the terms compatible and incompatible elements as proposed by Ringwood (1966) is a convenient means of describing the relative partition behavior between crystal and melt. These terms, however, are applied to minor and trace elements and not to major elements. To facilitate discussion, a generalized classification of elements is presented below, which is based on the relative enrichment of elements between melt and residual peridotite. Elements are divided into five groups (I-V). This classification is dependent on the residual mineralogy of the peridotite and some variation in the grouping of elements will occur under different melting conditions.

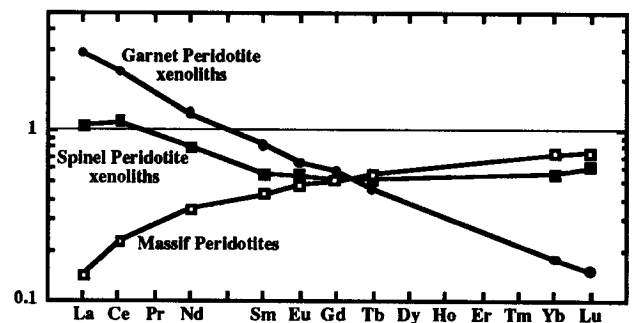


Figure 1 - A Primitive Mantle normalized REE diagram for garnet and spinel bearing peridotite xenoliths and massif peridotites. The values for the REE are reported in Table 1.

CHEMICAL SYSTEMATICS IN PERIDOTITES

Group I elements (e.g., Co, Mg, Ni, Rh, Ru, Ir and Os) are enriched in the peridotite residue after melting (i.e. elements with distribution coefficients greater than unity). These elements generally behave coherently and thus ratios of these elements in the residual peridotite will often reflect their initial relative compositions. This feature is clearly illustrated by the constant MgO/Ni ratios in garnet and spinel bearing peridotite xenoliths and massif peridotites (Fig. 2). Similarly, a small variation is also found in the Ni/Ir ratio (Fig. 3), although there are substantially fewer data available. A constant ratio for Ni/Os (given a constant Os/Ir ratio of ~1.0 in peridotites) would be expected. Overall, element ratios involving Group I elements generally show about 15-20% total variation in peridotites (Table 2).

Group II elements (e.g., Si, Mn, Fe, Ge and ± Cr) have melt concentrations comparable to concentrations in the source and distribution coefficients close to unity. Because of this, many of these elements have near constant ratios in a wide variety of peridotites. This point is highlighted in Figure 2 where the ratios of Fe/Mn, Fe/Cr and Mn/Cr are

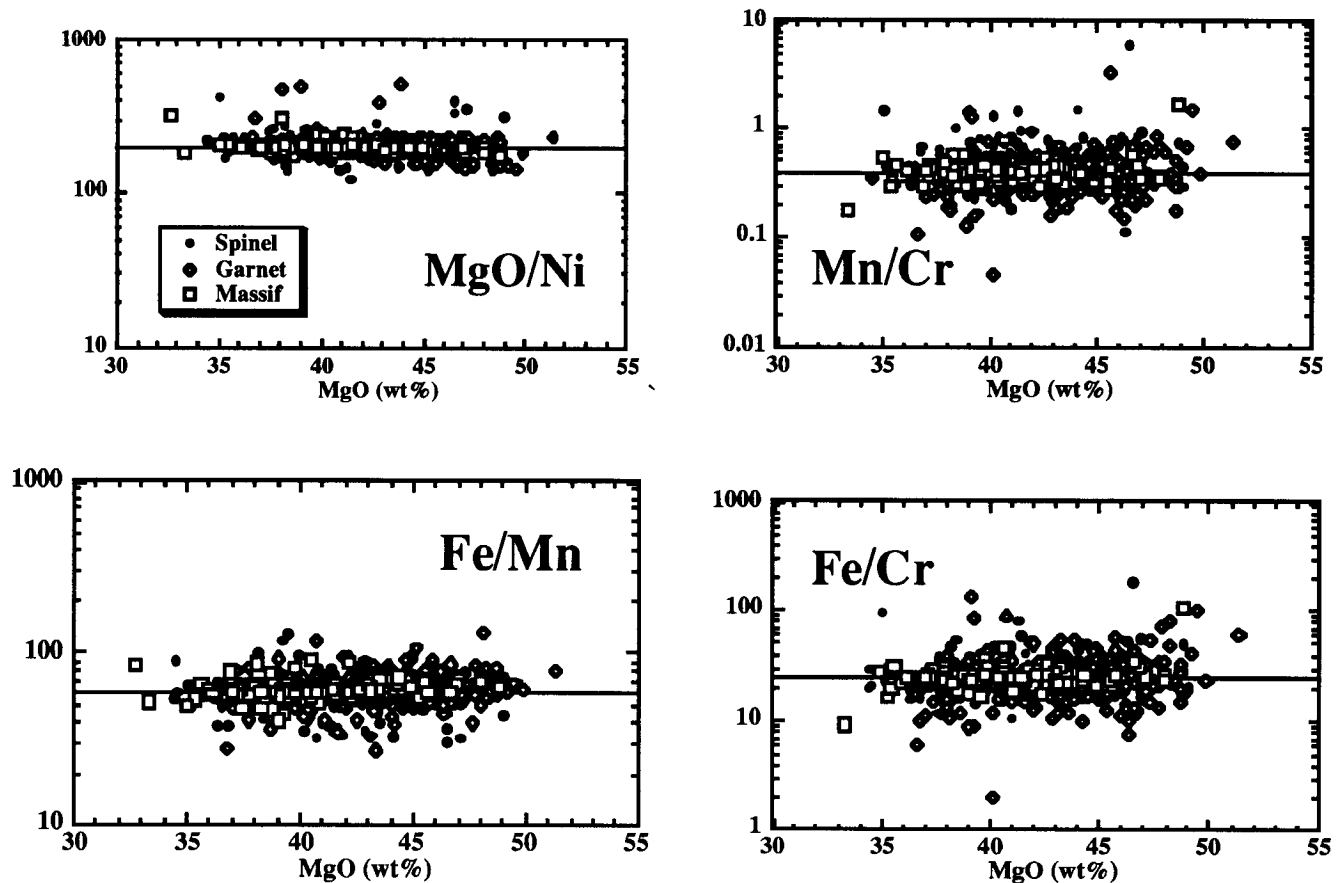


Figure 2 - MgO/Ni, Fe/Mn, Fe/Cr and Mn/Cr versus MgO content for garnet and spinel bearing peridotite xenoliths from continental regions and for massif peridotites.

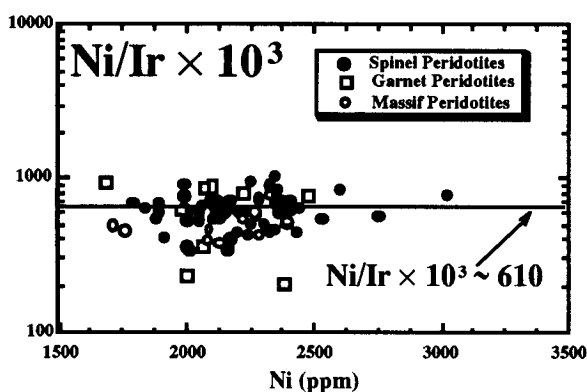


Figure 3 - Ni/Ir versus Ni (ppm) content for garnet and spinel bearing peridotite xenoliths from continental regions and for massif peridotites. Data from a number of sources including BVSP (1981), Spettel et al (1991) and references therein.

plotted against MgO content for garnet and spinel-bearing peridotite xenoliths and massif peridotites. The range of

MgO contents covers the compositional spectrum from fertile to most depleted peridotite. In comparison to Group I elements, ratios involving Group II elements show greater total variation in peridotites (Table 2).

A comparison of transition element ratios in the Primitive Mantle, peridotite xenoliths, massif peridotites and primitive lavas is given in Table 2. Garnet peridotite xenoliths show the largest deviation from Primitive Mantle values in transition element ratios, which is consistent with these xenoliths having lost the greatest amount of a melt component. In contrast, many of these ratios in the massif peridotites are close to Primitive Mantle values, reflecting the less depleted character of the massif sample. For many of these element ratios primitive mafic to ultramafic lavas have complementary ratios to those seen in the peridotite samples.

The final three groups of elements are enriched in the melt and depleted in the residual peridotite after melting. Group III elements (e.g., Cu, Zn, Ca, Sc, Al, V, Lu, Yb, Re, Au and Cd) are compatible in some mantle minerals (e.g., Al, Sc, V in pyroxenes, spinels and garnets), but are depleted in the bulk peridotite after melting. Many Group III elements are enriched in basalts by factors of only 2 to 6 over their concentrations in the source region. In contrast,

Table 2. Transition element ratios in Peridotites, primitive Mafic/Ultramafic Lavas and the Primitive Mantle

	Primitive Mantle	Massif Peridotites	Spinel Peridotites	Garnet Peridotites	Komatiite	Basalt
MgO/Ni	197	196 ±17	191 ±33	199 ±44	210	350
Ni/Ir * 10 ³	570	515 ±120	600 ±140	630 ±290	1000	1500
Fe/Mn	61	62 ±7	60 ±10	63 ±11	56	55
Fe/Cr	25	25 ±7	26 ±9	29 ±9	32	145
Fe/Co	620	570 ±50	580 ±66	510 ±99	830	1300
Fe/Ni	35	31 ±4	31 ±8	26 ±9	75	230
Ni/Co	18	19 ±1.3	20 ±4	21 ±4	12	6
Ni/Cr	0.72	0.82 ±0.35	0.86 ±0.31	1.08 ±0.62	0.5	0.6

Group IV elements are more enriched in a melt relative to Group III elements (i.e., they have low distribution coefficients (~0.1~0.005) and include the heavy to middle REE, Y, Ti, Na, Zr, Hf, Li, Sb, Sn and Pd. Group V elements (e.g., LREE, P, Sr, Ba, Nb, Ta, Mo, W, Tl, Cs, Rb, K, Th and U) are highly incompatible elements that are strongly partitioned into melts and have very low distribution coefficients (<0.005).

The REE and other incompatible elements (e.g., Ti, P, Sr, Zr, Hf, Y) often behave systematically in oceanic basalts (Sun and McDonough, 1989). This allows non-REE incompatible trace element behavior to be linked to a REE. For example, during mantle melting the partition behavior of Ti is closely matched to that of Eu, leading to constant Ti/Eu in primitive basalts from a variety of oceanic settings. Other element pairs involving REE (e.g., Y-Ho, P-Nd, Sm-Zr-Hf and Sr-Nd) show similar coherent behavior (Sun and McDonough, 1989). Peridotite xenoliths also show similar patterns (McDonough and Frey, 1989; Jochum et al., 1989; McDonough, 1990). Additionally, the Group I elements display systematic behavior according to their relative compatibility, and are present in high concentrations in refractory peridotite xenoliths, relative to Primitive Mantle. These systematics are illustrated in Figure 4, where the sequence of elements along the x-axis reflects decreasing incompatible behavior (from left to right). Patterns displayed by peridotite xenoliths (Fig. 4), are consistent with extraction and reintroduction of melts which are the controlling factor in peridotite geochemistry.

The element systematics described above are typical of peridotite xenoliths from both non-cratonic and cratonic parts of the continents (Frey and Green, 1974; Stosch and Seck, 1980; Nixon et al., 1981; Erlank et al., 1987; Menzies et al., 1987; McDonough and Frey, 1989; McDonough, 1990). In general, peridotite xenoliths show depletions in Group III and some of the IV elements and are enriched in Group V elements relative to Primitive Mantle. At the same time, the compatible elements are enriched by

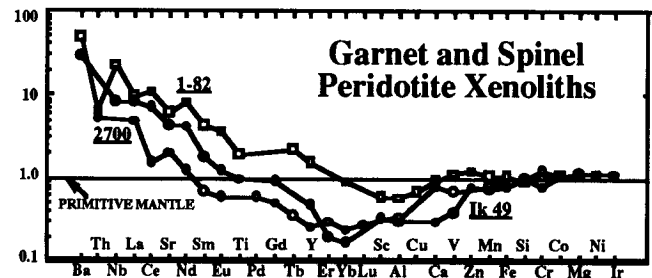


Figure 4 - A mantle normalized diagram for incompatible element-enriched peridotite xenoliths from continental regions. Examples include a typical garnet peridotite (Erlank et al., 1987) (filled symbol) and spinel peridotites (Frey and Green, 1974, Menzies et al., 1987) (open symbols), normalized to Primitive Mantle abundances (Sun, 1982, Sun and McDonough, 1989, McDonough and Frey, 1989). The order of elements is established by the enrichment factors observed in oceanic basalts.

5-50% relative to the Primitive Mantle. For the most part the massif peridotites tend only to display depletions in Group II through V elements and small enrichments in Group I elements. Those massif peridotites with LREE-enriched patterns typically show geochemical characteristics like those commonly found in peridotite xenoliths.

A generalized pattern of depletion and enrichment of elements in peridotite xenoliths is presented in Figure 5. The enrichment of Group I elements and depletion of Group III-V elements occurred during an early melt extraction stage, probably during the initial stages of lithospheric mantle development and stabilization (Frey and Green, 1974; Ringwood, 1982; McDonough, 1990). The seemingly contradictory enrichments of incompatible elements are attributed to later metasomatic enrichment. This enrichment process may have occurred repeatedly over long time scales in association with tectonomagmatic

reactivation of the lithosphere.

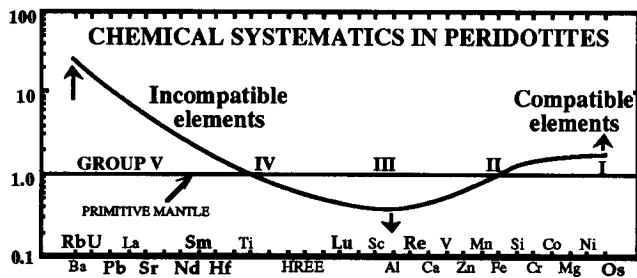


Figure 5 - Stylized geochemical signature for peridotite xenoliths, illustrating the systematic behavior typical of incompatible element-enriched continental lithospheric mantle. The radiogenic isotope systems are indicated in bold symbols, with the parent isotope above and the daughter isotope below the x-axis. The arrows indicate that the curvature of the pattern is more extreme in refractory peridotites. Fe and Mn in some metasomatized peridotite xenoliths are enriched during some incompatible element enrichment processes. Other details as in Fig. 1.

Frey and Green (1974) initially drew attention to the fact that samples with the lowest CaO and Al₂O₃ contents (i.e., the most refractory peridotites) also had the highest LREE/HREE enrichments and lowest Yb and Lu concentrations. Thus, as peridotites become more refractory, there is an increased tendency to develop a more convex pattern, with the highly incompatible and Group I elements being more enriched relative to other elements (Fig. 5). The processes responsible for this remarkable feature are still poorly understood (McDonough and Frey, 1989).

A compositional model for the continental lithospheric mantle can be developed using these chemical systematics and the compilation of geochemical data for several hundred xenoliths. The continental lithospheric 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 abundances (McDonough, 1990). This two-fold decrease in Yb and Lu abundances is consistent with the low CaO and Al₂O₃ contents of average peridotite xenoliths (Maaløe and Aoki, 1977; Jordan, 1979; Boyd, 1989; McDonough, 1990). Peridotite xenoliths (predominantly garnet-bearing) from cratons have lower CaO and Al₂O₃ contents (Maaløe and Aoki, 1977; Jordan, 1979; Boyd, 1989). These peridotite xenoliths are more depleted in HREE abundances than the non-cratonic (predominantly spinel-bearing) peridotite xenoliths but show similar enrichments of the LREE (McDonough, 1990).

An alternative compositional model for the continental lithospheric mantle can be derived from the geochemical data for several hundred samples of Massif peridotite. In this example the continental lithospheric mantle would

possesses a LREE-depleted pattern, with about 0.1 times the Primitive Mantle abundance for La, and a relatively flat HREE pattern, with Yb-Lu concentrations about 0.7 times the abundances of the Primitive Mantle (Table 1). Again the lower Yb and Lu abundances are consistent with the lower CaO and Al₂O₃ contents of average Massif peridotites when compared to the Primitive Mantle composition.

IMPLICATIONS

The chemical systematics described here 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 (Fig. 5). Both the 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 and the time difference between this and later enrichment(s) will control the resultant isotopic characteristics. This leads to the broad spectrum of Sr and Nd isotopic compositions in peridotite xenoliths (Hawkesworth et al., 1990). 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 (Fig. 5). (The Os isotope system is the only one in which the parent isotope is incompatible and the daughter isotope is compatible under most mantle melting conditions.) The available Re/Os data for peridotite xenoliths are limited (BVSP, 1981; Nonaka, 1982; Walker et al., 1989), however, most have subchondritic (i.e., subPrimitive Mantle) values (Fig. 6), indicating that Re, a Group III element, tends not to be enriched during metasomatic enrichment events. (Only rarely do garnet and spinel peridotite xenoliths, with incompatible element enrichments, display Group III element abundances greater than the Primitive Mantle.) Likewise, peridotite xenoliths with long term incompatible element enrichments should have low, subchondritic Sm/Nd and Lu/Hf values. Thus, the time integrated evolution of these isotope systems should be retarded with respect to the bulk earth, leading to distinctive Hf-Os (and possibly Nd-Os) isotopic compositions for the continental lithospheric mantle (Fig. 7). The limited amount of Os isotope data for continental peridotite xenoliths support this interpretation, but there are currently no Hf isotope data for peridotite xenoliths. It is anticipated that recent technical advances will allow for such measurements in the near future.

An incompatible element-enriched continental lithospheric mantle is often invoked as a source for different types of magmas (e.g., kimberlites, ultrapotassics, and flood basalts) (Carlson, 1984; Nelson et al., 1986; Walker et al., 1989). The chemical systematics and expected isotopic compositions for the continental lithospheric mantle provide some useful constraints on models of this kind. The Sr, Nd, Pb and Os isotope data for

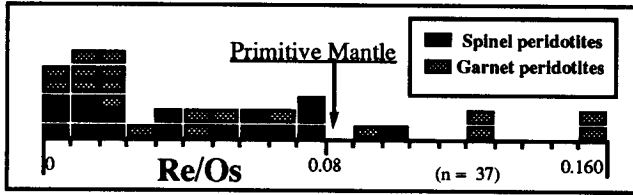


Figure 6 - Histogram of Re/Os ratios for peridotite xenoliths from continental regions. The majority of peridotite xenolith data have subchondritic (i.e., subPrimitive Mantle) values. Samples contaminated by kimberlitic magmas were not included (Walker et al., 1989). Other kimberlite-hosted garnet peridotites with high Re/Os may also have been contaminated.

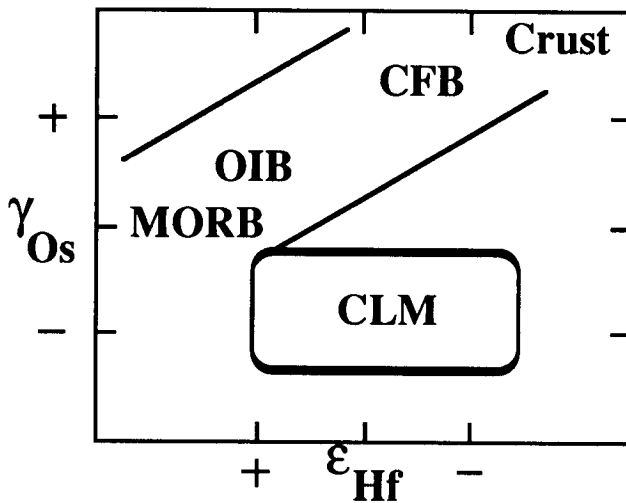


Figure 7 - Idealized Hf-Os isotope systematics for mid-ocean ridge basalts (MORB), ocean island basalts (OIB), continental flood basalts (CFB), continental crust (CRUST) and the continental lithospheric mantle (CLM). This diagram has been constructed from the few available data for Hf and Os isotopes and from predictions on the continental lithospheric mantle based on the chemical systematics of peridotite xenoliths. The isotopic composition of the continental lithospheric mantle as predicted by this exercise would not be a suitable source for most continental flood basalts. The terms ϵ_{Hf} and γ_{Os} are convenient notations for expressing differences in parts to the 10^4 and 10^3 , respectively, from a chondritic value.

southern Africa kimberlites (Smith, 1983; Walker et al., 1989) are consistent with incompatible element-enriched regions of the continental lithospheric 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 lithospheric mantle. The scant amount of Hf

isotope data (Liew et al., 1986) are consistent with crustal contamination and do not substantiate source models invoking the continental lithospheric mantle. On the other hand, the limited amount of Os isotope data for continental flood basalts (Pegram and Allègre, 1989; Ellam et al., 1991) present a more enigmatic picture. The strongly positive γ_{Os} compositions for the Mesozoic Appalachian tholeiites (Pegram and Allègre, 1989) are consistent with some amount of crustal contamination. In contrast, γ_{Os} values near bulk Earth in the Karoo picrites (Ellam et al., 1991) and the positive correlation between ϵ_{Nd} and γ_{Os} are suggestive of a continental lithospheric mantle source. However, derivation of such large degree of partial melts from the lithospheric mantle is at odds with the information available for the lithospheric mantle in this region. Firstly, the cool geotherm recorded in the peridotites carried by the Mesozoic kimberlites of the Kaapvaal craton (Finnerty and Boyd, 1987; Brey, 1991) is in marked contrast to the higher temperatures required to generate picrites. Secondly, the chemical composition of Kaapvaal peridotites, particularly their incompatible trace element signatures, are markedly different from those of the Karoo picrites.

It is now well established that there is a clear link between hotspots, mantle plumes and flood basalt volcanism (Duncan and Richards, 1991) indicating that in many cases the generation of flood basalt is due to upwelling mantle plumes. Thus, it is expected that the base of the continental lithospheric mantle will be involved, to some extent, in the production of continental flood basalts. A model of the interactions between an upwelling mantle plume and the base of the lithospheric mantle is given in McDonough et al (1985); this model highlights the role of lithospheric mantle melting during plume related magmatism in an oceanic and continental setting. However, the extent of involvement of the lithospheric mantle in influencing the composition of the melts is, at present, difficult to constrain. Further Os and Hf isotopic studies, together with other geochemical and isotopic data, on continental flood basalts will help greatly in our understanding of the role of the lithospheric mantle during melt generation.

ACKNOWLEDGMENTS

I thank Drs. I. Campbell, J. Hergt, E. Jagoutz, S. E. Kesson, L. Reisburg, D. G. Pearson, A. E. Ringwood, R. L. Rudnick and S. S. Sun for discussion and comments on the paper. I thank Marilyn Holloway for her help and patience with the final preparation of this paper.

REFERENCES

- BODINIER, J. L., VASSEUR, G., VERIERES, J., DUPUY, C and FABRIES, J.** (1990) Mechanisms of mantle metasomatism: geochemical evidence from the Lherz orogenic peridotite. *Journal of Petrology* 31, 597-628.
- BOYD, F. R.** (1989) Compositional distinction between oceanic and cratonic lithosphere. *Earth and Planetary Science Letters* 96, 15-26.
- BREY, G. P.** (1991) Fictive geotherms beneath the Kaapvaal craton. (Extended abstract-5th International Kimberlite Conference), CPRM Special Publication 2/91. Brasilia, 23.25.
- BVSP** (1981) Basaltic Volcanism on the Terrestrial Planets. Pergamon Press.
- CARLSON, R. W.** (1984) Isotopic constraints on Columbia River flood basalt genesis and the nature of the subcontinental mantle. *Geochimica Cosmochimica Acta* 48, 2357-2372.
- CLARK, S. P. and RINGWOOD, A. E.** (1964) Density distribution and constitution of the mantle. *Reviews of Geophysics* 2, 35-88.
- DUNCAN, R. A. and RICHARDS, M. A.** (1991) Hotspots, mantle plumes, flood basalts and true polar wander. *Reviews of Geophysics* 29, 31-50.
- ELLAM, R. M., CARLSON, R. W. and SHIREY, S. B.** (1991) Re-Os isotope constraints on flood basalt genesis. *EOS* 72, 579.
- ERLANK, A. J., WATERS, F. G., HAWKESWORTH, C. J., HAGGERTY, S. E., ALLSOPP, H. L., RICHARD, R. S. and MENZIES, M. A.** (1987) Evidence for mantle metasomatism in peridotite nodules from the Kimberley pipes, South Africa. In: M. A. Menzies and C. J. Hawkesworth; editors. *Mantle Metasomatism*, 221-312. Academic Press, London.
- FINNERTY, A. A. and BOYD, F. R.** (1987) Thermobarometry for garnet peridotites: basis for the determination of thermal and compositional structure of the upper mantle. In: P. H. Nixon; editor. *Mantle Xenoliths*, 381-402. John Wiley and Sons.
- FREY, F. A. and GREEN, D. H.** (1974) The mineralogy, geochemistry and origin of lherzolite inclusions in Victorian basanites. *Geochimica Cosmochimica Acta* 38, 1023-1059.
- HAWKESWORTH, C. J., KEMPTON, P. D., ROGERS, N. W., ELLAM, R. M. and VAN CALSTEREN, P. W.** (1990) Continental mantle lithosphere, and shallow level enrichment processes in the Earth's mantle. *Earth and Planetary Science Letters* 96, 256-268.
- JOCHUM, K. P., McDONOUGH, W. F., PALME, H. and SPETTEL, B.** (1989) Compositional constraints on the continental lithospheric mantle from trace elements in spinel peridotite xenoliths. *Nature* 340, 548-550.
- JORDAN, T. H.** (1988) Structure and formation of the continental lithosphere. *Journal of Petrology Special Lithosphere Issue*, 11-37.
- JORDAN, T. H.** (1979) Mineralogies, densities and seismic velocities of garnet lherzolites and their geophysical implications. In: F. R. Boyd and H. O. A. Meyer; editors. *The mantle sample: Inclusions in kimberlites and other volcanics*, pp. 1-14. AGU, Washington, D. C.
- LIEW, T. C., COX, K. G., HAWKESWORTH, C. J. and HOFMANN, A. W.** (1986) Behaviour of Hf isotopes in the continental crust: two case studies. *Terra cognita* 6, 234-235.
- MAALØE, S. and AOKI, K. I.** (1977) The major element composition of the upper mantle estimated from the composition of lherzolites. *Contributions to Mineralogy and Petrology* 63, 161-173.
- McDONOUGH, W. F.** (1990) Constraints on the composition of the continental lithospheric mantle. *Earth and Planetary Science Letters* 101, 1-18.
- McDONOUGH, W. F., McCULLOCH, M. T. and SUN, S. S.** (1985) Isotopic and geochemical systematics in Tertiary-Recent basalts from southeastern Australia and implications for the evolution of the sub-continental lithosphere. *Geochimica Cosmochimica Acta* 49, 2051-2067.
- McDONOUGH, W. F. and FREY, F. A.** (1989) REE in upper mantle rocks. In: B. Lipin and G. R. McKay; editors. *Geochemistry and Mineralogy of Rare Earth Elements*, 99-145. Mineralogical Society of America, Washington, D. C.
- MENZIES, M. A., ROGERS, N., TINDLE, A. and HAWKESWORTH, C. J.** (1987) Metasomatic and enrichment processes in lithospheric peridotites, an effect of asthenosphere-lithosphere interaction. In: M. A. Menzies and C. J. Hawkesworth, editors. *Mantle Metasomatism*, 313-361. Academic Press, London.
- NELSON, D. R., McCULLOCH, M. T. and SUN, S.-S.** (1986) The origins of ultrapotassic rocks as inferred from Sr, Nd and Pb isotopes. *Geochimica Cosmochimica Acta* 50, 231-245.
- NIXON, P. H.** (1987) *Mantle Xenoliths*. J. Wiley and Sons, Chichester.
- NIXON, P. H., ROGERS, N. W., GIBSON, I. L. and GREY, A.** (1981) Depleted and fertile mantle xenoliths from southern African kimberlites. *Annual Reviews of Earth and Planetary Science* 9, 285-309.
- NONAKA, J.** (1982) Über die Häufigkeit von bisher wenig untersuchten Elementen im Erdmantel. PhD dissertation, Universität Mainz.
- PEGRAM, W. J. and ALLEGRE, C. J.** (1989) Osmium isotopic compositions and abundances from basalts. *Terra abstracts* 1, 343.
- RINGWOOD, A. E.** (1982) Phase transformations and differentiation in subducted lithosphere: Implications for mantle dynamics, basalt petrogenesis, and crustal evolution. *Journal of Geology* 90, 611-643.
- RINGWOOD, A. E.** (1966) The chemical composition and origin of the Earth. In: P. M. Hurley; editor.

- Advances in Earth Sciences 287-356. MIT Press, Cambridge.
- SMITH, C. B.** (1983) Pb, Sr and Nd isotopic evidence for sources of southern African Cretaceous kimberlites. *Nature* 304, 51-54.
- SPETTEL, B., PALME, H., IONOV, D. A. and KOGARKO, L. N.** (1991) Variation in the Iridium content of the upper mantle of the Earth. Lunar and Planetary Science Conference Abstracts XXII, 1301-1302.
- STOSCH, H.-G. and SECK, H. A.** (1980) Geochemistry and mineralogy of two spinel peridotite suites from Dreiser Weiher, West Germany. *Geochimica Cosmochimica Acta* 44, 457-470.
- SUN, S.-S.** (1982) Chemical composition and origin of the earth's primitive mantle. *Geochimica Cosmochimica Acta* 46, 179-192.
- SUN, S.-S. and McDONOUGH, W. F.** (1989) Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: A. D. Saunders and M. J. Norry; editors. *Magmatism in the ocean basins*, 313-345. Geol. Soc. Lond. Spec. Pub No. 42.
- VASSEUR, G., VERNIERS, J. and BODNIER, J. L.** (1991) Modelling of trace element transfer between mantle melt and heterogranular peridotite matrix. *Journal of Petrology Special Lherzolite Issue*, 41-54.
- WALKER, R. J., CARLSON, R. W., SHIREY, S. B. and BOYD F. R.** (1989) Os, Sr, Nd and Pb isotope systematics of southern African peridotite xenoliths: implications for the chemical evolution of subcontinental mantle. *Geochimica Cosmochimica Acta* 53, 1583-1595.