Mantle Petrology: Field Observations and High Pressure Experimentation: A Tribute to Francis R. (Joe) Boyd
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Editors: Yingwei Fei, Constance M. Bertka, and Bjorn O. Mysen

Evolution of cratonic lithospheric mantle: an isotopic perspective

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Abstract—Radiogenic isotopes can be used both as petrogenetic tracers in lithospheric mantle rocks, to identify processes that may have formed and modified the lithospheric mantle, and also as chronometers to constrain over what time scales these processes operated. This can only be done after the effects of secondary processes have been properly identified and constrained. Here I focus on the information gained from studying radiogenic isotope systems in cratonic lithospheric mantle, mostly in the form of xenoliths erupted by kimberlites. Isotopic systematics in cratonic lithospheric mantle are complex, probably because of its antiquity, and the numerous processes that may have acted to generate and modify it over time. Cratonic lithospheric mantle is difficult to unequivocally distinguish using incompatible element based isotope systems, but these systems can be successfully used to identify the different processes that modify the lithospheric mantle over time by metasomatism. These processes include interaction with hydrous fluids, silicate melts and carbonate-rich fluids. Also, combinations of radiogenic and stable isotope systematics in eclogite suites have been used to argue for a derivation involving subduction of oceanic lithosphere. In contrast to incompatible element based isotope systems, the Re-Os isotope system uniquely defines ancient cratonic mantle as having the least radiogenic $^{187}Os/^{188}Os$ measured in any terrestrial geochemical reservoir. This should allow distinctive tracing of cratonic mantle contributions to magma sources permits ancient lithospheric mantle to be identified in different tectonic settings. Precise age estimates for the formation of cratonic mantle, and lithospheric mantle in general, are difficult to provide. This is both a function of the high ambient temperature of much of the lithospheric mantle, such that it is above most isotopic closure temperatures, and the multi-phase history of the lithospheric mantle, involving melt depletion and enrichment in many cases. Petrological models or cratonic peridotite suites are still being debated and this also induces some uncertainty in what event is being measured by parent-daughter isotopic fractionations. Os isotope systematics for cratonic peridotites appear to be dominantly influenced by the ancient differentiation events that caused them to separate from the convecting mantle whereas Sr-Nd isotope systematics record later enrichment events. Hence the different isotope systems provide complimentary information. The formation age of cratonic peridotites, as defined by Os isotope model ages, correlates well with the age of the major crustal forming event in a particular region, and is mid- to late-Archean throughout most of the cratonic lithospheric keel. Later addition of lithospheric mantle can be identified in certain localities *e.g.*, the Premier kimberlite pipe in S. Africa. The ages of circum-cratonic lithospheric mantle also appear to correlate with the generally younger age of the crust off-craton, implying long-term crust-mantle coupling both on and around cratons and indicating a possible genetic relationship between crust stabilisation and the formation of deep lithospheric mantle keels. The crust and lithospheric mantle beneath several cratons has been physically coupled for billions of years to depths of 150 km at least.

INTRODUCTION

Petrological and experimental studies of the type pioneered by JOE BOYD (BOYD, 1973; BOYD and NIXON, 1973), have made long lasting contributions to our understanding of the conditions of formation and equilibration of mantle derived xenoliths. This work has laid the essential ground for isotopic studies aimed at determining the age and evolution of these valuable fragments of mantle entrained by kimberlites and alkaline volcanics in general. Radiogenic isotopes provide the means to constrain the chronological framework for processes evident from petrological studies. A comprehensive historical perspective on these studies is provided by MENZIES (1990a).

The processes that create the continental and oceanic crust, mantle lithosphere and asthenosphere all act to fractionate parent-daughter isotope pairs in radiogenic isotope systems. This fractionation, together with the contrasting thermal regimes of these environments, combine to generate different time-integrated isotopic signatures that allow petrogenetic tracing of terrestrial reservoirs. The aim of this paper is to review the contribution made by radiogenic isotopes to the understanding of the age and origin of cratonic lithospheric mantle (CLM). Significant advancement in this field has recently taken place due to analytical developments allowing the more wide spread application of the Re-Os isotope system (SHIREY and WALKER, 1998). The contribution made by incompatible element-based radiogenic isotope systems to the understanding of continental lithosphere in general is summarised in MENZIES (1990a).

MANTLE XENOLITHS: THE NATURE OF THE SAMPLE

Since they were first mined it was evident that kimberlites contained a great diversity of constituents, many of which must be foreign bodies, unrelated to the host kimberlite.

Among this material, several lithologies, particularly eclogites (Bonney, 1897; Cohen, 1879), were recognised to be of high-pressure origin, due to the presence of diamonds within them. These rocks were conjectured to ultimately come from the Earth's mantle. It was some time before systematic study of these mantle xenoliths occurred (Nixon *et al.*, 1963). The lithologies represented by mantle xenoliths are very varied, but the most dominant, of the types sampled on cratons, comprise harzburgites, lherzolites, eclogites and assorted pyroxenite variants (see Nixon, 1987, for a full summary).

Xenoliths in alkali basalts are commonly 1 to 20 cm in diameter. In kimberlites, mantle xenoliths may reach over 70 cm in size. Even with xenoliths this large, it is clear that the xenolith sample provides only a vignette of the mantle, on a scale of 10's of cm to metres at most. Massif peridotites provide a view of the mantle on the order of 10's of km, and allow observation of lithological relationships in the field. Despite the patchwork nature of the xenolith view of the mantle, such samples have the great advantage that, in any one kimberlite, the xenoliths often originate from very varied depths and so may provide us with samples of the entire thickness of the lithospheric mantle (*e.g.,* Boyd, 1973; Finnerty and Boyd, 1987).

Another type of mantle fragment brought up by kimberlite, of much more commercial value, is diamond. Although diamonds themselves provide a wealth of information about the deep mantle and possible crust-mantle interactions (Gurney, 1989), it is the minerals included within diamonds that are sought by radiogenic isotope geochemists. The chemical and petrological character of these microscopic inclusions constrain aspects of diamond formation in the mantle and potentially provide us with material armoured from subsequent events since the formation of the diamond. Hence, they allow the possibility to examine the secular evolution of the mantle if we can determine their ages.

ISOTOPE SYSTEMS AND APPROACH

To study the evolution of a given terrestrial reservoir an isotope system must either be an effective geochronometer over much of the history of the Earth, or an effective tracer, or, ideally both. The range of systems used is geochemically varied and this has provided much complimentary information. In particular the contrast between isotopic systems where both parent and daughter isotopes are incompatible elements (*e.g.,* Rb-Sr and Sm-Nd) and those where there is significant contrast in compatibility (*e.g.,* U-Pb and Re-Os) provides us with a means of tracing a wide range of processes that affect different elements in different ways, for example melting and hydrous fluid metasomatism or infiltration.

Probably the most extensively used tracers for the lithospheric mantle are the Rb-Sr, Sm-Nd and Re-Os isotope systems and their differing time-integrated responses to mantle melting and re-enrichment are illustrated in Fig. 1. The differing behaviour of these systems and the varying degrees to which they fractionate during mantle melting are clearly evident, both diagramatically, and in the magnitude of the range in isotopic compositions observed for terrestrial reservoirs and mantle xenoliths (Fig. 1).

PRIMARY AND SECONDARY SIGNATURES

When ultramafic rocks first began to be investigated using Sr isotopes, bulk rocks were analysed (Hurley *et al.*, 1964; Lanphere, 1968; Roe, 1964; Stueber and Murthy, 1966). Such data led to numerous erroneous conclusions about the relationship between mantle samples and basalts due to the pervasive alteration suffered by many ultramafic rocks, enhancing the amount of radiogenic Sr present. Many subsequent studies have shown that acid-washed mineral separates, particularly diopside and garnet, are the most reliable means of obtaining the primary, unaltered isotopic composition of mantle material (Basu and Murthy, 1977; Basu and Tatsumoto, 1980; Bruekner, 1974; Jagoutz *et al.*, 1980; Menzies and Murthy, 1980a; Menzies and Murthy, 1980b; Zindler and Jagoutz, 1988). Even with apparently "clean" mineral separates from mantle rocks, detailed studies have shown that sequential acid leaching procedures are necessary for many minerals in order to obtain the primary (mantle) isotopic composition, unaffected by crustal contamination (Richardson *et al.*, 1985; Zindler and Jagoutz, 1988; Pearson *et al.*, 1993). In general, for isotopic analysis, mineral fragments are selected that are clear, as free of mineral and fluid inclusions as possible, and that are bounded by fresh fractures induced by sample preparation, i.e., avoiding grains that retain their primary margins.

In mantle xenoliths erupted by kimberlite pipes, both low-T secondary alteration and kimberlite contamination have been identified as major concerns to be addressed during the analysis of mineral separates (Richardson *et al.*, 1985). Acid washed mineral separates give considerably different Nd-Sr isotope compositions than their whole-rocks for both peridotites (Richardson *et al.*, 1985; Walker *et al.*, 1989a) and eclogites (Neal *et al.*, 1990; Fig. 2), the isotopic signature of the whole-rocks being dominated by small amounts of infiltrated host kimberlite. The whole-rock isotopic signatures of some samples, however, appear to be dominated by a component distinctly different to the host kimberlite (Figs. 2 and 3). This component usually is characterised by much more radiogenic Sr isotopes and appears to be due to the effects of addition of phlogopite mica, that may not be related to the host kimberlite (Fig. 3). Also, the nature of kimberlite/xenolith alteration often produces almost undetectable films of high-Sr material on mineral grain-boundaries and fractures that can dramatically affect the measured Sr isotope composition of a low-Sr mineral such as garnet if not properly removed, *e.g.,* dramatic shifts in Sr isotope composition of garnet observed for 0.2 % contamination of kimberlite or carbonate in Fig. 3.

The problem of discerning primary isotopic signatures does not only pertain to crustal alteration/syn-eruption metasomatism. Ireland *et al.*, (1994) noted that eclogitic minerals included within diamonds were much less enriched in incompatible elements than the minerals of the host eclogite xenoliths. This observation led Ireland *et al.*, (1994) to suggest that the xenolith minerals have been pervasively metasomatised by fluids and that only the host diamond inclusions retain the primary elemental signatures of the eclogite. These authors then suggest that because of this pervasive metasomatism, the isotopic compositions of the host rock minerals cannot be used to draw inferences about the long-term evolution of eclogites and their parent reservoirs as attempted by numerous authors (*e.g.,* McCulloch, 1989; Snyder *et al.*, 1993). It is not clear to what extent all eclogite suites are affected by such processes (Taylor *et al.*, 1996), but they must be properly identified before making inferences about evolutionary histories based on isotope and trace element measurements in xenoliths.

The use of negative thermal ionisation mass spectrometry for Re and Os isotope analysis (Creaser *et al.*, 1991; Volkening *et al.*, 1991) has led to a proliferation of Re-Os isotopic studies of mantle xenoliths. The attraction of this

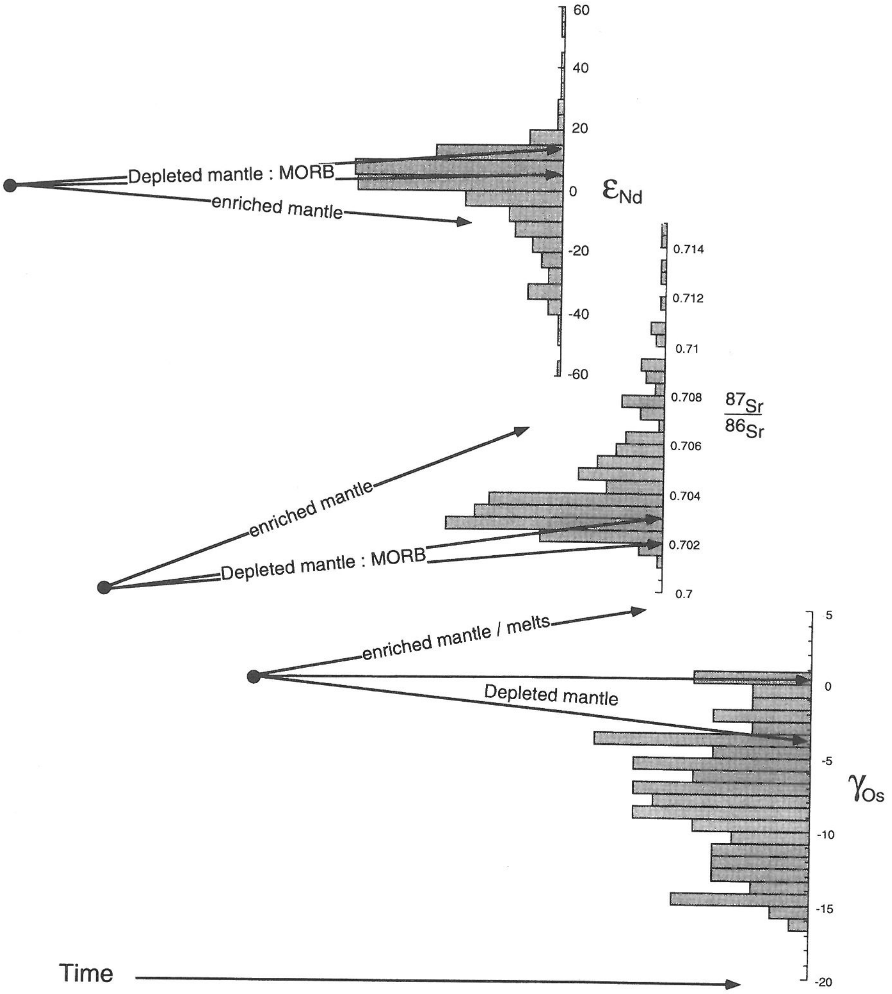

FIG. 1. Isotope evolution of the Rb-Sr, Sm-Nd and Re-Os isotope systems in response to mantle melting and enrichment events. Data for cratonic and non-cratonic peridotites are plotted as histograms on the right hand axis, arrows illustrate the expected isotopic evolution of enriched and depleted mantle in a single stage model over 1 Ga. Mineral separate data only plotted for Rb-Sr and Sm-Nd systems, wholerock and mineral data plotted for Re-Os. For data sources see MENZIES (1990b), CARLSON and IRVING (1994), DENG and MCDOUGALL (1992), GUNTHER and JAGOUTZ (1994), GUNTHER and JAGOUTZ (1997), HASLER and SHIMIZU (1998), HAURI *et al.* (1993), IONOV *et al.* (1993), JACOB *et al.* (1998b), MEISEL *et al.* (1996), PEARSON *et al.* (1995a), PEARSON *et al.* (1995b), PEARSON *et al.* (1995c), REISBERG and LORAND (1995), WALKER *et al.* (1989a), ZHURAVLEV *et al.* (1991)

system is multi-fold. Firstly, the large fractionation of Re from Os during moderate to large degrees of mantle melting removes a large proportion of the Re from a residual peridotite, causing rapid divergence of its Os isotopic evolution curve from the convecting mantle evolution curve (Fig. 4). This rapidly creates large, easily measurable differences in isotopic composition between the two reservoirs, *e.g.,* in 10's of Ma. Secondly, in contrast Sr and Nd isotopes, Os contents of the magmas that host lithospheric xenoliths are usually much lower (in the case of alkali basalts) or close to those of the peridotite xenoliths themselves. This means that whereas a small amount of kimberlite interaction with diopside from a xenolith (modeled as bulk mixing) will result in a large change in Nd isotopic composition, such interaction will produce only a small change in the Os isotope composition of the bulk rock (Fig. 5). The Re-Os system is thus much more robust to host-rock interaction, even when whole-rocks are analysed. If melt addition occurred 100's of Ma before kimberlite eruption, Re added from the metasomatising agent will generate radiogenic Os and hence will have a more noticeable effect on the Os isotope composition of the xenolith than recent metasomatism by the host rock (Fig. 5). In addition, studies of sulfide inclusions in diamonds have revealed that some mantle melts are capable of disturbing sulfide grains very high in Os (PEARSON *et al.*, 1998c; PEARSON *et al.*, 1998d). Thus, even though the

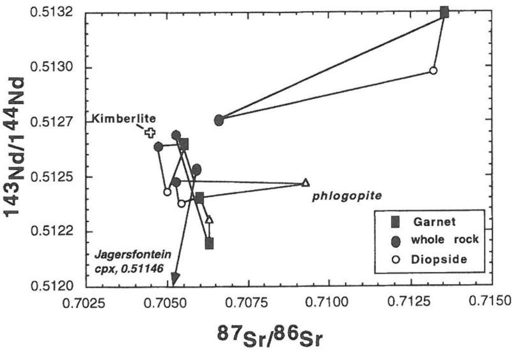

FIG. 2. Whole-rock vs. mineral separate Nd-Sr isotopic compositions for kimberlite derived xenoliths from Bultfontein (RICHARDSON *et al.*, 1985) and one sample from Jagersfontein (WALKER *et al.*, 1989a). Lines connect coexisitng phases/whole-rocks. Initial isotopic composition of the Bultfontein kimberlite is also plotted. Jagersfontein CPX plots well off scale on Nd axis.

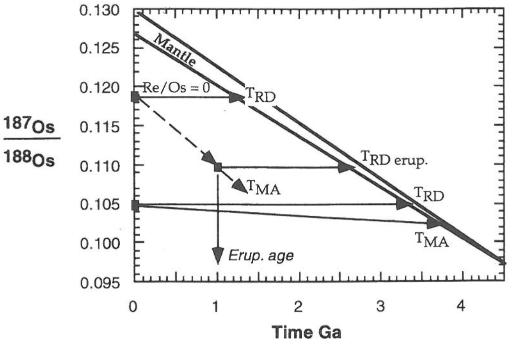

FIG. 4. Os isotope evolution diagram illustrating the evolution of melts and residues. The relationship between T_{RD} age and T_{MA} age is indicated for residues where the ages closely agree and where they are discrepant, probably due to later Re addition. T_{RD} ages assume a Re/Os of zero. T_{MA} ages use the measured Re/Os for the model age calculation (see WALKER *et al.*, 1989b). Also shown is the effect of correcting for possible Re addition during kimberlite eruption/alteration on a T_{RD} age.

Re-Os system is substantially more robust to mantle metasomatism than isotope systems based on incompatible element isotope systems such as Rb-Sr and Sm-Nd, it is not immune to its modifying effects, especially when metasomatism occurred a long time ago. Another feature of mantle xenoliths that can potentially disturb their Re/Os systematics is the breakdown of sulfides during low-T secondary oxyhydration during eruption. This process has been shown to reduce S levels in bulk peridotite xenoliths compared to orogenic peridotites (LORAND, 1990) and may lead to fractionation of Re/Os from original values. The above processes make application of standard model age calculations for Os in mantle xenoliths questionable. For this reason widespread use has been made of Re-depletion model ages in xenolith studies.

The principle behind Re depletion or T_{RD} model ages is the assumption that, at large degrees of melting, most of the Re in a peridotite is removed, effectively freezing in the Os isotopic composition at that time (Fig. 4 and caption). The measured Re content thus represents the integration of secondary processes such as metasomatism or low-T alteration that may introduce Re. A minimum age for a xenolith with subchondritic $^{187}Os/^{188}Os$ can therefore be obtained by extrapolating the measured Os isotope ratio of the sample back to the mantle evolution line with a Re/Os of zero, *e.g.,* Fig. 4 (WALKER *et al.*, 1989a). For xenoliths erupted in the Proterozoic, such as those recovered from the Premier kimberlite, South Africa, additional correction can be made for syn-post eruption Re addition by calculating the T_{RD} age using the initial $^{187}Os/^{188}Os$ at the time of eruption, Fig. 4 (PEARSON *et al.*, 1995a). The justification behind the T_{RD} approach is that numerous samples give meaningless model ages if calculated the standard way using the measured Re/Os of the xenolith. It is to be stressed that the T_{RD} model ages are minima and should be interpreted as such.

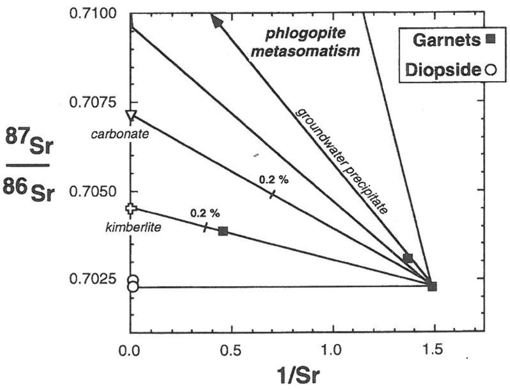

FIG. 3. Sr isotope and abundance systematics of "pure" and altered/metasomatised garnet separates from the Bultfontein kimberlite (after RICHARDSON *et al.*, 1985). Shaded region indicates the area defined by phlogopite addition. Tick marks on mixing lines illustrate % of component added.

Although "meaningless" model ages may be obtained for whole-rock xenoliths when the Re/Os ratio is used in the model age calculation, this result provides us with information on the possible relative timing of Re addition. The most obvious type of disruption of the Re/Os isotope systematics in xenoliths is Re addition, in most cases accompanied by relatively low $^{187}Os/^{188}Os$, suggesting Re gain at, or close to the time of the kimberlite eruption event. This implies that, in contrast to the Rb-Sr and Sm-Nd isotope systems, most mantle processes preceding the kimberlite entrainment event are relatively ineffectual at disturbing peridotite Re-Os systematics.

It is possible to try to minimise the effects of post-crystallisation Re/Os fractionation by analysing phases with very high Os, or phases capable of armouring hosts for Re and Os from later, post-magmatic interaction. Analysis of chromite from peridotite xenoliths has shown this phase to sometimes contain very high Os, but low Re contents which makes the mineral useful in recording close to the initial Os isotopic composition of the system where the bulk rock may have suffered substantial new Os or Re addition, reducing T_{RD} model ages (CHESLEY and RUDNICK, 1996; NAGLER *et*

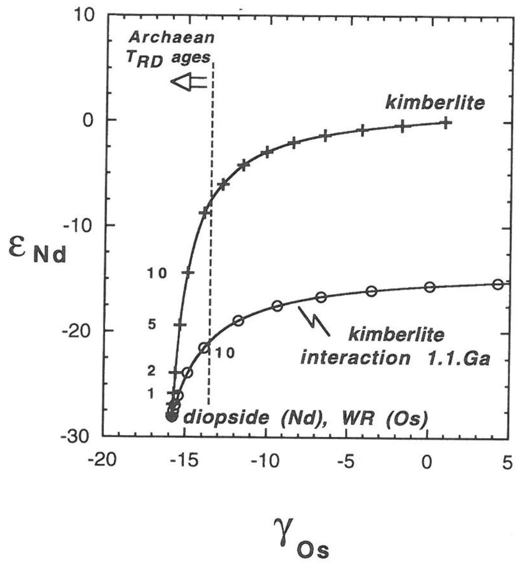

FIG. 5. Illustration of the effects of simple mixing of a peridotite xenolith and host kimberlite magma on the Os isotope composition of the bulk-rock xenolith and the Nd isotope composition of diopside from the xenolith (the bulk-rock is usually measured for Os isotopes and a diopside or garnet separate measured for the Nd isotope composition). The effects of older interaction, at 1.1 Ga, the age of the Premier kimberlite, followed by time-integrated ingrowth of radiogenic Os from introduced Re is also modeled. The vertical line illustrates the point at which an Archaean model T_{RD} age in the xenolith is overprinted by infiltration.

al., 1997). It is not understood whether the high Os contents of chromites are due to micro-inclusions of sulfides (*e.g.*, THALHAMMER *et al.*, 1990). Results of experimental partitioning studies have led to the suggestion that that Os may be compatible in the spinel structure (CAPOBIANCO and DRAKE, 1990), but those experiments were performed in the absence of sulfide. The presence of sulfide coexisting with chromite would preferentially partition Os into the sulfide, hence high Os partition coefficients for chromites crystallised in the absence of sulfide may not be geologically relevant. Measurements of aluminous spinel from peridotite xenoliths (PEARSON *et al.*, unpublished) show low Os contents and relatively radiogenic Os isotope compositions. If sulfide inclusions are the main cause of high Os contents within chromites, once enclosed, the chromite grain will be effective in protecting the sulfide grains against further interaction with metasomatic agents. It is not presently clear how widely applicable the use of chromites will be for Re-Os analyses of mantle rocks but they are of obvious benefit if they happen to be of the high Os variety.

ISOTOPIC CHARACTERISATION OF CONTINENTAL LITHOSPHERIC MANTLE (CLM)

Peridotites

Various reasons exist for trying to fingerprint lithospheric mantle isotopically. Perhaps foremost amongst these is the ongoing attempt to identify lithospheric input to magma sources and evaluate the input of lithosphere to mantle dynamics in general (see HOFMANN, 1997 for a recent review). As will be shown below, this is not a simple task.

The major element compositions of many lithosphere to peridotites are frequently interpreted to indicate an origin as residues of partial melting of the mantle (*e.g.*, NIXON and BOYD, 1973; MAALOE and AOKI, 1977). However, a compilation of the Sr and Nd isotope compositions of their diopsides (or garnet if they contain no diopside) indicates that very few samples retain the expected signatures of residues of partial melting from normal depleted mantle (Fig. 1a,b). This makes CLM in general very difficult to identify convincingly using Sr-Nd isotopes. Combined Nd-Sr systematics (Fig. 6) show that although the CLM is vastly more heterogeneous than the oceanic mantle, CLM shows almost total overlap with continental crust, and probably has more isotopic variation when the very high ϵ_{Nd} signatures of some peridotites and eclogites are taken into account (Fig. 6). Measurements of Pb-isotopes are fewer but show essentially the same phenomena (KRAMERS, 1979; STOLZ and DAVIES, 1988; WALKER *et al.*, 1989a). It is possible to find samples showing any of the postulated mantle "end-members" defined in isotope space by ZINDLER and HART (1986) within samples clearly belonging to the lithosphere. One aspect of the lithospheric mantle that is clear from Fig. 6 is that xenolith samples erupted through cratonic areas show considerably more isotopic heterogeneity than those erupted through non-cratonic areas. This indicates isolation of CLM for longer periods than that beneath

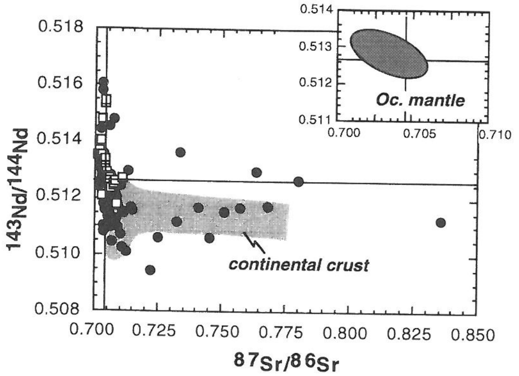

FIG. 6. Sr-Nd isotope compositions of diopsides or garnets (in cases where garnet is the only Ca-Al-rich phase) for lithospheric peridotites compared to oceanic mantle (ZINDLER and HART, 1986) and continental crust. Cratonic mantle peridotites solid symbols, non-cratonic peridotites open symbols. Peridotite data from references listed Fig. 1.

off-craton areas and is a direct indication of crust-mantle coupling to the extent that ancient lithosphere generally underlies ancient crust. Although we can distinguish between cratonic- and non-cratonic lithospheric mantle, it is difficult unambiguously to identify lithospheric mantle in general as a terrestrial reservoir, or a potential magma source reservoir using incompatible-element based isotope systems, largely because of overlap between crustal and lithospheric mantle isotopic compositions. This is no surprise as it is likely that some of the extreme signatures observed in the lithospheric mantle are the product of metasomatism by subducted sediment-derived fluids. One of the incompatible element isotope signatures thought to be more characteristic of lithospheric mantle is that of the so-called EM-1 component (Zindler and Hart, 1986), most clearly defined by Nd-^{206}Pb/^{204}Pb isotopes. However, there are few reliable data for Pb-Nd isotopes in lithospheric xenoliths, and of these, less than $^{1}/_{4}$ have clearly defined EM-1 type characteristics (see Fig. 5 of Carlson, 1995).

In contrast to their variety of Sr and Nd isotopic compositions, most lithospheric peridotites of widely varying age have Os isotope signatures indicative of low-Re/Os environments, as might be expected for residues of partial melting (Fig. 1c). In fact, no other terrestrial reservoir retains the very unradiogenic Os isotope compositions of average cratonic lithospheric mantle ($\gamma_{Os} \sim -10$). Thus, the Re-Os isotope system on its own has the ability to define uniquely CLM whereas other systems, even in multi-isotope space, are not distinctive. Very unradiogenic, low γ_{Os} peridotites are found in the Kaapvaal, Siberian and Wyoming cratons (Fig. 7), showing this feature to be ubiquitous amongst the cratons studied so far. Furthermore, the Re-Os system appears to discriminate clearly between mantle underlying cratonic crust and that lying beneath circum-cratonic crust, of Proterozoic age (Pearson *et al.*, 1994; Pearson *et al.*, 1998a). Studies of peridotite suites from Namibia and East Griqualand, surrounding the Kaapvaal craton, have shown that they are petrologically distinct from peridotites erupted through the craton (Boyd and Nixon, 1979; Boyd *et al.*, 1994); this distinction is apparent in a comparison of average mg-numbers of the various suites (Fig. 8) and is clearly evident in their Os-isotope compositions. Cratonic peridotites such as those from Kaapvaal range to considerably less radiogenic γ_{Os} values than circum-cratonic xenoliths from Namibia or East Griqualand (Fig. 9). The East Griqualand kimberlites are within 100 km of the probable boundary of the Kaapvaal craton and show no evidence of any Archaean Os. The East Griqualand peridotites range to slightly lower γ_{Os}

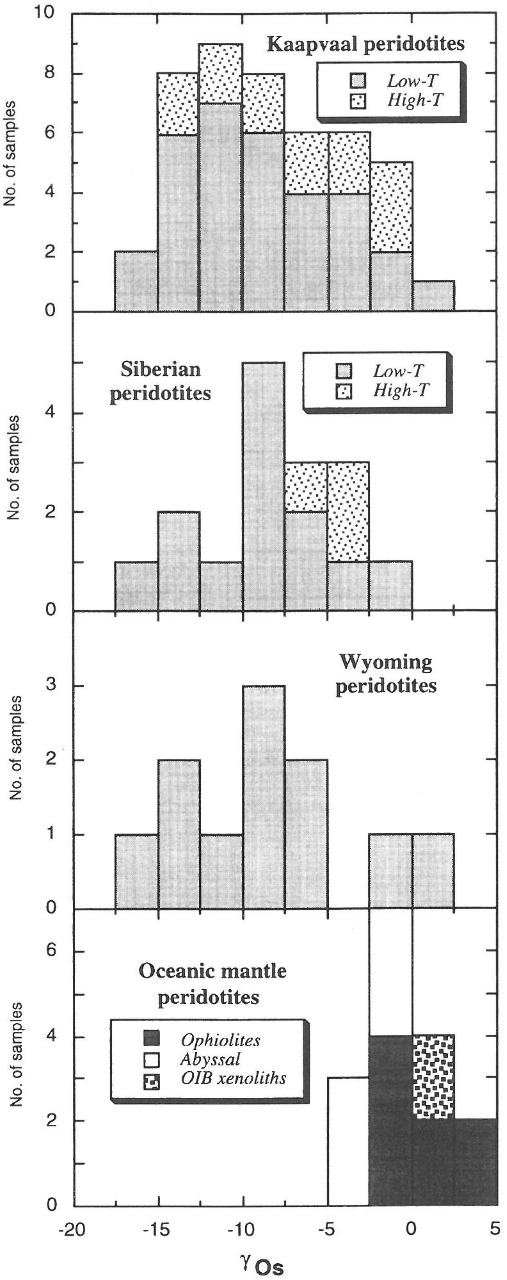

Fig. 7. Histograms of Os isotopic compositions of cratonic peridotite xenoliths expressed as initial γ_{Os} values, at the time of kimberlite eruption, (Carlson and Irving, 1994; Pearson *et al.*, 1995a; Pearson *et al.*, 1995c; Walker *et al.*, 1989a and Pearson, unpublished) compared to those for oceanic mantle (Martin, 1991; Snow and Reisberg, 1995; Hauri *et al.*, 1993); where:

$$\gamma_{Os(t)} = [(^{187}Os/^{188}Os_{sample(t)})/(^{187}Os/^{188}Os_{chondrite(t)})] \times 100$$

values than Namibian peridotites, but none have obviously Archaean isotopic signatures (see below). The distinct petrological and Os isotopic signatures of circum-cratonic lithospheric peridotites indicates that the Archaean/Proterozoic boundary in the lithospheric mantle must be as abrupt as it appears on the surface.

One surprise resulting from Re-Os isotope studies of cratonic xenolith suites is the discovery that peridotites with high equilibration temperatures and relatively fertile mg-numbers (high-T lherzolites of NIXON and BOYD, 1973), thought to represent recently accreted asthenospheric material, or subducted oceanic lithosphere (BOYD and GURNEY, 1986; BOYD and MERTZMAN, 1987; NIXON and BOYD, 1973; RICHARDSON *et al.*, 1985) have γ_{Os} values spanning a similar range to the low-T peridotites (Fig. 7; PEARSON *et al.*, 1995a; WALKER *et al.*, 1989a). The very unradiogenic Os isotopic signatures of some of these samples indicate that they appear to have been part of the cratonic keel since Archaean times and this observation must be considered in any model for their genesis.

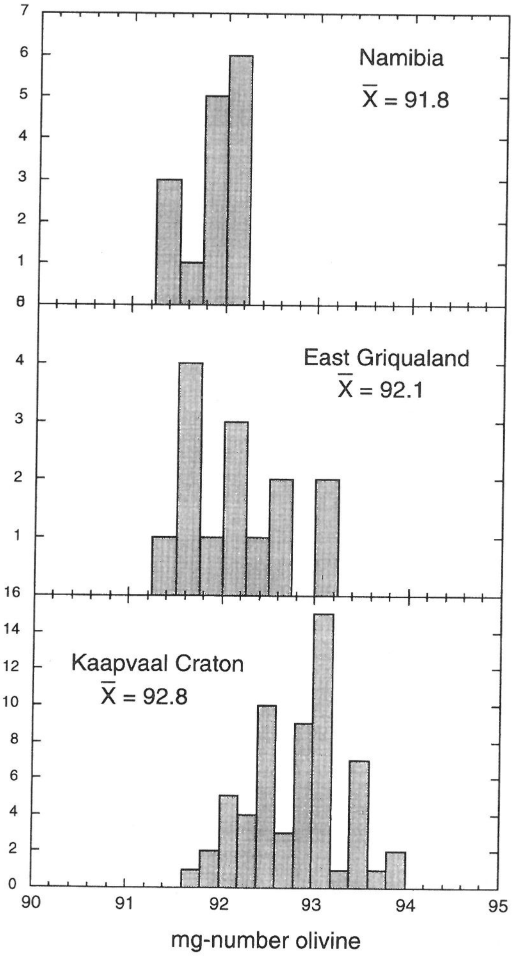

FIG. 8. Comparison of olivine mg-numbers for circum-cratonic peridotite xenoliths from East Griqualand and Namibia compared with Kaapvaal peridotites. Data source: BOYD and NIXON (1979), NIXON (1987b) and F. R. BOYD (unpublished data).

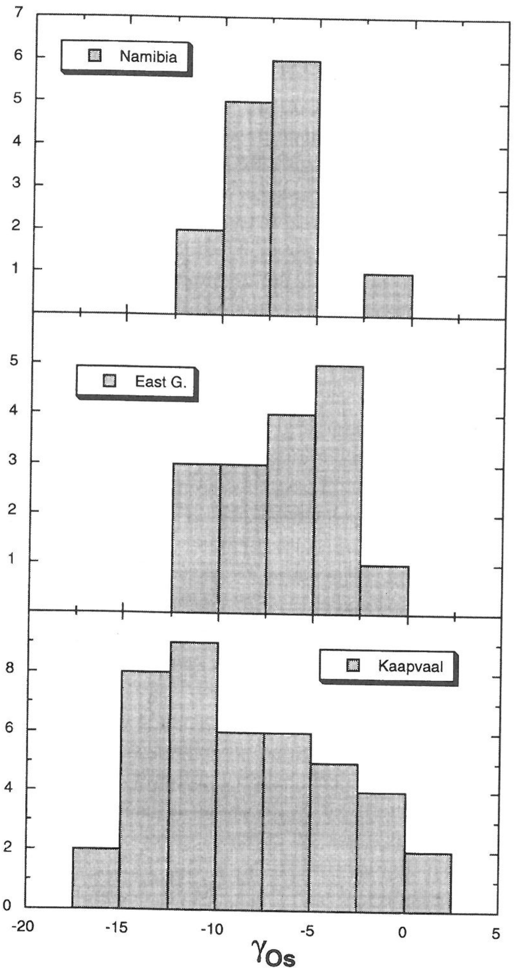

FIG. 9. Histograms of Os isotopic compositions of circum-cratonic peridotite xenoliths expressed as initial γ_{Os} values compared to Kaapvaal cratonic peridotites. Data from PEARSON *et al.* (1994, 1995a, 1998a), WALKER *et al.* (1989a), and PEARSON (unpublished data).

The clear distinction between cratonic or even Proterozoic lithospheric mantle and recently accreted continental, or the oceanic lithosphere makes the Re-Os isotope system a powerful tectonic discriminant. HASLER and SHIMIZU (1998) inferred the presence of old continental mantle beneath the Kerguelan Plateau from the unradiogenic Os isotope compositions of peridotite xenoliths erupted by alkali basalts. Handler *et al.* (1997) found evidence for the persistence of fragments of Proterozoic (c. 2 Ga) mantle beneath Paleozoic cover in S.E. Australia based on the unradiogenic Os isotope signatures of some peridotites in a suite of peridotite xenoliths erupted there. In the same region, Pearson *et al.* (1998b) used low γ_{Os} values and Proterozoic to Archaean Re-Os model ages of sulfide inclusions in alluvial E. Australian diamonds to infer that the diamonds may have been sourced from an adjacent craton, prior to continental breakup.

It is apparent that for incompatible element isotope systems such as Rb-Sr and Sm-Nd, in cratonic peridotites, their integrated isotopic signature is dominated by enrichment events in the sense that they do not preserve isotopic compositions expected for ancient residual/depleted mantle (Figs. 1 and 6). In contrast, Os isotopes are dominated by the effects of Re depletion, which may be equivalent to melt depletion in specific cases. This means that combined isotopic studies of peridotites have the potential to constrain both the formation, and post-formation metasomatic history of lithospheric mantle. The Os-Nd isotope characteristics of CLM samples with very depleted Os isotope signatures yet highly enriched Nd isotopes are very difficult to model in terms of simple mixing between a melt residue and any reasonable amount of metasomatic agent, such as carbonatite (Fig. 10). To this extent the incompatible element isotope systems in CLM are decoupled from the Re-Os system and we are clearly some way from fully understanding the details of lithospheric enrichment processes.

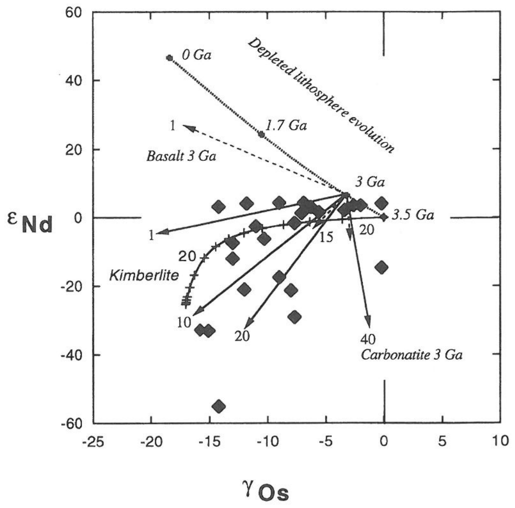

Fig. 10. Nd-Os isotope compositions of Kaapvaal and Siberian peridotites (Nd—mineral data; Os—bulk rock data, data sources as for Fig. 1). Negative trending curve (no arrow) is a modeled depleted mantle separated from the convecting mantle at 3.5 Ga. Arrows at the end of solid lines represent the present-day, time-integrated isotopic compositions of mixing between a carbonatite-like metasomatic agent and depleted mantle peridotite at 3 Ga. Numbers next to arrows represent percent metasomatic agent. Dashed lines with arrows represent interaction of peridotite with a basaltic magma at 3 Ga. Also illustrated is a mixing curve between peridotite and host-kimberlite at the time of kimberlite eruption.

Beyond characterisation of lithospheric mantle in general terms, Menzies (1990a) and Hawkesworth *et al.* (1990) have found that cratonic mantle can be distinguished in some instances from non-cratonic mantle on the basis of combined Nd-Sr isotope systematics, and more recent data augment this distinction (Fig. 6). The development of extremely low ϵ_{Nd} values at variable $^{87}Sr/^{86}Sr$ appears to be unique to cratonic samples, the most extreme ϵ_{Nd} values in particular being shown by low-Ca "subcalcic" garnets of the type found in diamonds of peridotite-suite paragenesis and diamond-bearing peridotites (Fig. 11). This is ironic in that garnet is usually characterised by high Sm/Nd and hence radiogenic Nd isotopes. Jacob *et al.* (1998b) have shown that subcalcic garnets from an individual kimberlite (Udachnaya) are extremely heterogeneous in their Nd-Sr isotope compositions on a single grain basis, with a range in initial ϵ_{Nd} of 42 units between grains. The total range for low-Ca garnets, as composites (Pearson *et al.*, 1995d) or single grains from the Udachnaya kimberlite is over 60 epsilon units for Nd (Fig. 11), i.e., about 3 times the range found in the convecting mantle, emphasising the extreme isotopic heterogeneity shown by CLM.

Some intra-cratonic distinctions can also be made on the basis of Sr-Nd isotope systematics that reflect differing extents and styles of lithospheric enrichment processes. Peridotites from the Kaapvaal and Wyoming lithospheric roots have Sr isotope compositions that range up to very radiogenic compositions (Fig. 12). Probably the most extreme Sr isotope composition of a mantle rock to date comes from a Tanzanian peridotite ($^{87}Sr/^{86}Sr$ = 0.836: Cohen *et al.*, 1984), but an insufficient number of Tanzanian samples have been analysed to make comparisons meaningful. In contrast to the Kaapvaal and Wyoming cratons, minerals within Siberian peridotites rarely have $^{87}Sr/^{86}Sr$ over 0.720, with most below 0.710 (Fig. 12). This feature correlates with a general paucity of phlogopite in Siberian peridotites (Boyd *et al.*, 1997), possibly indicating that hydrous-fluid-dominated metasomatism has not been as extensive in the Siberian lithosphere. The range in ϵ_{Nd} for Siberian peridotites is comparable to that of Kaapvaal

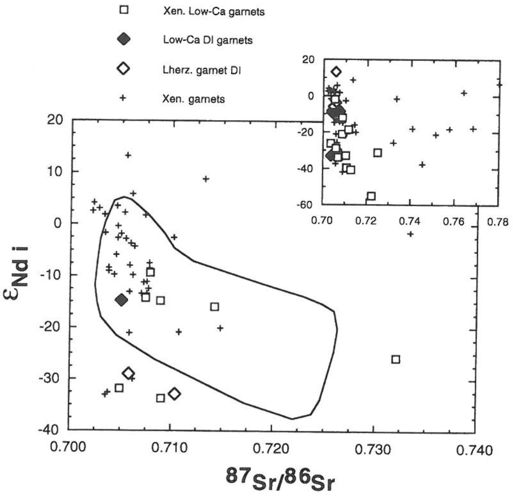

FIG. 11. Sr-Nd isotope composition of subcalcic garnets (RICHARDSON *et al.*, 1984; RICHARDSON *et al.*, 1993; PEARSON *et al.*, 1995c; JACOB *et al.*, 1998b) compared to minerals from cratonic peridotites and oceanic mantle (see Fig. 1 for data sources). Solid symbols are data for individual crystals from concentrate of a single kimberlite pipe (JACOB *et al.*, 1998b).

peridotites, reflecting both ancient LREE depletion and enrichment. This behaviour is also displayed by peridotite/pyroxenite xenoliths from Loch Roag, Scotland, erupted at the margin of the N. Atlantic craton (MENZIES and HALLIDAY, 1988). LREE enrichment without marked increase of Rb/Sr is thought to be a characteristic of carbonatite metasomatism, and appears to be a clearly identifiable signature in xenoliths from various cratons. Peridotites from Tanzania even have clear petrographic and mineral chemical indications of carbonatite metasomatism (RUDNICK *et al.*, 1993). This type of metasomatism is not restricted to cratonic lithosphere, and has also been clearly identified in post-Archaean continental lithosphere (IONOV *et al.*, 1993) and oceanic lithosphere (HAURI *et al.*, 1993), but its isotopic manifestation in cratonic lithosphere is much more extreme.

The Wyoming peridotites analysed by CARLSON and IRVING (1994) have consistently very low ϵ_{Nd} and radiogenic Sr with a distinct sub-horizontal trend (Fig. 12). Other Wyoming peridotites plot on the steep main lithospheric "array" in Sr-Nd isotope space. This common radiogenic Sr signature in the Wyoming peridotites is partly a reflection of their slightly unusual petrography compared to the normal lherzolite-harzburgite suites from Kaapvaal and Siberia, and is thought to be the result of shallow slab-derived fluid fluxing during the Archaean, soon after their formation (CARLSON and IRVING, 1994).

From the diversity of observed isotopic compositions a number of different metasomatic processes can be seen to produce shifts of Nd-Sr isotope systematics in distinct directions (HAWKESWORTH *et al.*, 1984, 1990; MENZIES and CHAZOT, 1995; Fig. 12). Three main enrichment processes are probably most readily identifiable isotopically, and have been shown to take place in the lithospheric mantle on the basis of petrographic, trace element and isotopic evidence. Firstly melt addition, which may take the form of normal silicate melts, or kimberlitic/lamproitic melts. The effect of this type of metasomatism might be to increase Rb/Sr and decrease Sm/Nd in such a way that with time, the metasomatic products move approximately down the mantle "array" to more radiogenic Sr and less radiogenic Nd isotope compositions compared to Bulk Earth. A physical manifestation of kimberlitic metasomatism is thought to be the formation of the MARID assemblage within veins in the lithospheric mantle (SWEENEY *et al.* 1993; HAMILTON *et al.* 1998). A second metasomatic process readily identifiable is H_2O-fluid-rich metasomatism which may result in phlogopite/amphibole metasomatism. Where phlogopite is the dominant product, the effect in terms of Sr-Nd isotopes will be to create sub-horizontal trajectories on Sr-Nd isotope diagrams, i.e., the high Rb/Sr of phlogopite rapidly creates radiogenic Sr in the metasomatised product whereas the low Sm and Nd concentrations of mica mean that Nd isotope systematics are relatively unchanged. Carbonatite metasomatism is the third "end-member" metasomatic process. This typically

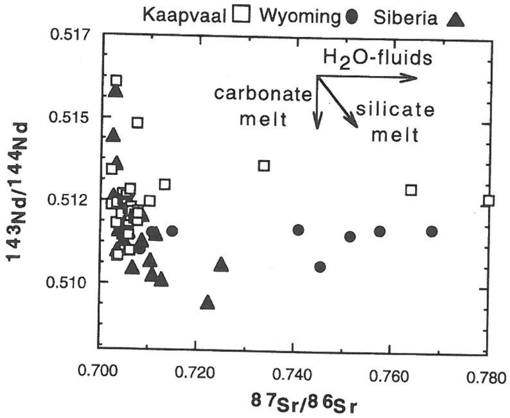

FIG. 12. Sr-Nd isotope variation for xenolith minerals from cratonic peridotites from Kaapvaal-, Siberian- and Wyoming-craton xenoliths. Data sources from CARLSON and IRVING (1994), GUNTHER and JAGOUTZ (1994, PEARSON *et al.*, (1995c), RICHARDSON *et al.*, (1985), WALKER *et al.* (1989a), and ZHURAVLEV *et al.* (1991). Arrows indicate approximate direction of isotopic evolution resulting from metasomatism by the agents indicated.

produces metasomatic products that have low Rb/Sr and low Sm/Nd such that sub-vertical arrays may be generated on Sr-Nd isotope diagrams. Another characteristic chemical feature of carbonatite metasomatism is that it produces pronounced high-field-strength element anomalies in the products and fractionation of element ratios such as Zr/Hf. Details of these effects and processes have been thoroughly documented and/or reviewed by Hawkesworth *et al.* (1984, 1990), Menzies and Hawkesworth (1987), Ionov *et al.* (1993), Rudnick *et al.* (1993), and Menzies and Chazot (1995); see also Fig. 12. The longevity of CLM means that it is likely that more than one process may have influenced a particular peridotite.

In addition to identifying processes on the basis of isotope systematics, the predominance of one process over another in different localities means that it is also possible to identify isotopically distinct domains that exist within regions and between cratons (Menzies, 1989; 1990a; 1990b). However, as more analyses reveal ever greater isotopic diversity in the CLM, it is appears unlikely that particular mantle isotopic "endmembers" can be unequivocally identified in different domains. In particular it is seems unwise to expect clearly distinguishable isotopic signatures of lithospheric mantle contributions to magma genesis in particular regions.

Eclogites

Eclogites (garnet plus high-jadeite clinopyroxene) occur in numerous kimberlite pipes intruding cratonic regions. At some pipes, *e.g.*, Roberts Victor, they are especially abundant and predominate over peridotites in the xenolith suite. Assessing their relative importance in the lithosphere has not been easy due to considerations of preferential dissaggregation of certain types of xenoliths (Schulze, 1989).

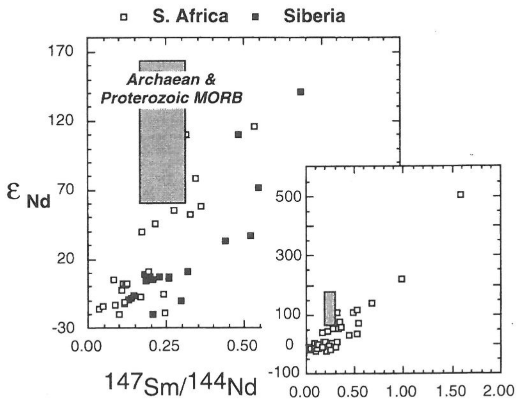

FIG. 13. Sm-Nd isotope compositions of eclogite xenoliths from kimberlites compared to the range expected for ancient MORB and crustal eclogites from orogenic areas (Stosh and Lugmair, 1990). Data sources (Jacob *et al.*, 1994; Jagoutz, 1988; Jagoutz *et al.*, 1984; Neal *et al.*, 1990; Pearson *et al.*, 1995c; Snyder *et al.*, 1993).

These rocks form integral parts of cratonic roots and may contain information critical to understanding the processes of craton formation and evolution. If data from eclogites are combined with peridotites, the total Nd isotopic variation shown by CLM samples, and cratonic xenoliths in particular, far exceeds any terrestrial reservoir that we know of (Fig. 13). Eclogites alone are highly isotopically variable and some samples have the most radiogenic Nd isotopes of any rocks yet measured (Fig. 13), with ϵ_{Nd} values in excess of 500 for garnets (Jagoutz *et al.*, 1984), and differences of over 200 epsilon units between coexisting garnet-pyroxene pairs (Jagoutz, 1988; Jagoutz *et al.*, 1984). The high $^{143}Nd/^{144}Nd$ of these samples far exceeds that expected for ancient samples of MORB (Fig. 13). The very radiogenic Nd is supported by high Sm/Nd that is unmatched by either MORB magmas, or komatiites. The only rocks with similar Sm/Nd to those of high Sm/Nd eclogites are garnetiferous pyroxenites from the Beni Bousera orogenic peridotite (Pearson *et al.*, 1993), Fig. 14. Crustal eclogites exhumed in orogenic zones do not have extreme Sm/Nd, or very radiogenic Nd isotopes and very often contain quartz. Although quartz (as coesite) has been recorded in eclogite xenoliths in kimberlites, its occurrence is rare (*e.g.*, Sobolev, 1977).

Jacob *et al.* (1994) found Sr-Nd and O isotopes and mineralogical compositions of a suite of eclogites from the Udachnaya kimberlite that were best explained by derivation from altered Archaean ocean floor. Snyder *et al.* (1997) have emphasised the great petrological and geochemical diversity shown by eclogites in general that make their precise evolution difficult to constrain, however, a crustal origin for some of these rocks seems clear (MacGregor and Manton, 1986; Neal *et al.*, 1990; Jacob *et al.*, 1994)

In addition to having the most radiogenic Nd isotopic compositions of any mantle rocks, eclogites commonly have very radiogenic Os isotope signatures (Menzies *et al.*, 1998; Pearson *et al.*, 1995d; Shirey *et al.*, 1998), in marked contrast to the unradiogenic signatures observed in peridotites (Fig. 15). Initial γ_{Os} values range from close to chondritic up to 6700 and are similar to Archaean basalts and komatiites (*e.g.*, Walker *et al.*, 1989b). The large spread in $^{187}Os/^{188}Os$ and Re/Os within eclogite suites from the same kimberlite makes them amenable to dating using this system. The very radiogenic Os in many of

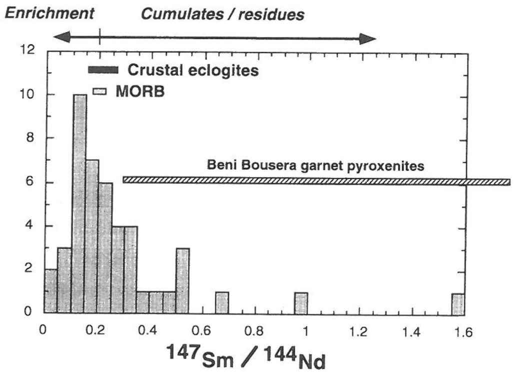

FIG. 14. Histogram of $^{147}Sm/^{144}Nd$ for eclogite xenoliths (data sources as in Fig. 13) compared to MORB, crustal eclogites from orogenic areas (STOSCH and LUGMAIR, 1990) and garnet-bearing pyroxenites from the Beni Bousera peridotite massif (PEARSON *et al.*, 1993).

these mafic fragments of the lithosphere mean that they will severely disturb the isotopic signature of any magma that interacts with them.

Diamond inclusions

The first precise isotopic measurements on inclusions in diamond were made by KRAMERS (1979) on sulfides of uncertain paragenesis. The analyses revealed variable Pb isotope compositions, some with ancient isotopic signatures. Application of the Sm-Nd system to composites of silicate inclusions obtained from many different diamonds gave unradiogenic Nd isotope ratios indicative of diamond formation in old, LREE enriched lithospheric mantle (RICHARDSON *et al.*, 1984). These inclusions were sub-calcic, high-Cr garnets. The Sm-Nd model ages of the garnet composites were 3.3 Ga and taken to be indicative of the crystallisation age of the diamonds (Fig. 16). Subsequent analyses of lherzolitic garnet inclusion composites (RICHARDSON *et al.*, 1993) produced isochronous relationships interpreted to reflect later diamond formation. The Sr isotope compositions of sub-calcic, high-Cr garnet inclusions are radiogenic and frequently unsupported by their measured Rb contents. Although apparently shielded from mantle processes since their encapsulation, silicate diamond inclusions show a similar range in Nd isotopic compositions to the minerals in mantle xenoliths (Fig. 11). However, minerals within xenoliths (mostly diopsides) show a much greater range in Sr isotopes than the diamond inclusions so far measured (Fig. 11). This difference may simply be due to a sampling problem considering the low numbers of diamond inclusions so far analysed. A greater number of inclusions in diamonds have been analysed for trace elements and very few show evidence for very high Rb/Sr that would lead to some of the high $^{87}Sr/^{86}Sr$ values seen in xenolith minerals.

Recent advances in Re-Os analytical chemistry have enabled analysis of single sulfide inclusions within diamond, and even analyses of different sulfides from within the same diamond, permitting, for the first time, the possibility of obtaining an isochron age from a single diamond (PEARSON *et al.*, 1998c; PEARSON *et al.*, 1998d). Sulfide inclusions belonging to the peridotite paragenesis from Siberia have so far shown unradiogenic Os isotope compositions that are characteristic of the least radiogenic, diamondiferous peridotite xenoliths from Siberia (Fig. 17; PEARSON *et al.*, 1995c). These unradiogenic Os isotope compo-

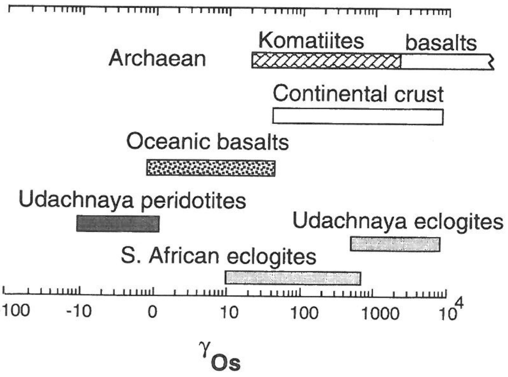

FIG. 15. Comparison of present-day Os isotopic compositions of eclogite xenoliths from Siberia (PEARSON *et al.*, 1995d) and S. Africa (MENZIES *et al.*, 1998; PEARSON *et al.*, 1992; SHIREY *et al.* 1998) with continental crust (MARTIN *et al.* 1991), oceanic basalts (see review in SHIREY and WALKER, 1998), and Archaean komatiites and basalts (WALKER *et al.* 1989b; WALKER *et al.* 1988).

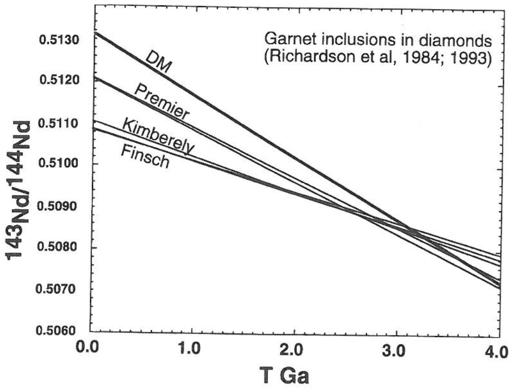

FIG. 16. Nd isotope evolution diagram illustrating diamond inclusion model age relationships for subcalcic garnet composites from Finsch & Kimberley (RICHARDSON *et al.*, 1984) and Premier (RICHARDSON *et al.*, 1993).

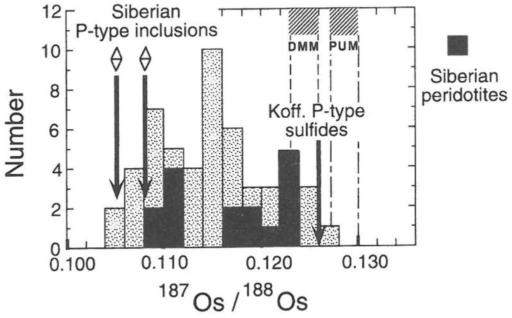

FIG. 17. Histogram showing Os isotope compositions of Kaapvaal (shaded) and Siberian (black) cratonic peridotites compared to sulfide inclusions from Siberian diamonds. P-type sulfides belong to the peridotitic paragenesis and data are shown from Koffiefontein, S. Africa, and Siberia (Udachnaya pipe). Estimated ranges for the primitive upper mantle (PUM) and depleted mantle (DMM end-members of ZINDLER and HART (1986) are shown. Data sources as in Fig. 7 and (PEARSON *et al.* 1998c).

sitions are supported by low Re contents, giving Re-Os model ages as old as 3.5 ± 0.3 Ga. We interpret these results to indicate that the sulfide has remained isolated since diamond crystallisation, 3.5 Ga ago. The concurrence of the low γ_{Os} values found in sulfide inclusions in diamonds and the least radiogenic Siberian peridotite xenoliths suggests that Re-Os systematics in some peridotite xenoliths have remained relatively undisturbed since the mid Archaean.

AGE DETERMINATION

The isochron approach

The response of isotope systems to cessation of inter-mineral diffusive equilibria in rock systems enables precise isochrons to be obtained on many crustal rocks (see review by SHIREY, 1991). In mantle rocks, their high equilibration temperatures are frequently above the blocking temperature of most isotope systems and so the use of the isochron approach has been very limited. Frequently, multi-mineral analyses from xenoliths have closely approximated the eruption age of the volcanic pipe that brought them rapidly to the surface. One of the first studies to show this was performed on Kilbourne Hole spinel lherzolites (JAGOUTZ *et al.*, 1980). Equilibrated Nd isotopes in orthopyroxene and diopside separates defined essentially zero age isochrons, consistent with the very recent eruption age of the host volcanic. Subsequent studies that have obtained mineral isochrons defining the approximate age of kimberlite eruption include garnet lherzolites (PEARSON *et al.*, 1995a; PEARSON *et al.*, 1995c; RICHARDSON *et al.*, 1985; WALKER *et al.*, 1989a) and eclogites (PEARSON *et al.*, 1995c; SNYDER *et al.*, 1993). Two-point garnet-cpx isochrons from eclogites in particular are very variable and not generally a good way to estimate the kimberlite eruption age. Despite the fact that mineral isochrons from ancient peridotite xenoliths can be used to constrain the age of the volcanic eruption as precisely as some other kimberlite dating techniques (PEARSON *et al.*, 1995a), the frequent observation of inter-mineral dis-equilibria in peridotites, and the labour intensive analytical methods required, means that this method is not a viable way to approach the dating of kimberlites.

More ancient mineral isochrons, significantly in excess of eruption ages, have been determined for diopside-garnet pairs in cratonic peridotites (GUNTHER and JAGOUTZ, 1997; MCCULLOCH, 1989; PEARSON *et al.*, 1995a; PEARSON *et al.*, 1995c; WALKER *et al.*, 1989a; ZHURAVLEV *et al.*, 1991) and eclogites (JACOB *et al.*, 1994; JAGOUTZ, 1988; JAGOUTZ *et al.*, 1984; SNYDER *et al.*, 1993). Two point peridotite mineral isochrons from a single kimberlite pipe can vary widely in slope, giving apparent ages hundreds of Ma different. The geochronological information provided by these isochrons is unclear. The wide variations in isochron ages from a single kimberlite are unlikely to represent closure ages in similar lithologies (PEARSON *et al.*, 1995c). Contamination by the host kimberlite can alter peridotite mineral isochrons and this can usually be identified (GUNTHER and JAGOUTZ, 1997). GUNTHER and JAGOUTZ (1997) proposed that the oldest mineral isochrons in Siberian peridotites, of c. 2 Ga, represent closure ages. Younger ages represent partial closure/re-equilibration during either lithospheric residence or during eruption. In-situ trace element measurements of minerals from some of these rocks provide a different perspective. The frequent presence of both fine-scale (100 μm) zonation, and non-equilibrium partitioning behaviour for REE between many garnets and clinopyroxenes from Siberian peridotites (SHIMIZU *et al.*, 1997 and SHIMIZU, this volume) have two possible implications. One is the probable recent disruption of isotope systematics in many peridotite minerals due to recent growth, and the other is their non-equilibrium features, such that plotting them on an isochron diagram is not even a valid procedure. A good example of the type of isotopic complexity that this can lead to is shown by reversed mineral "isochrons" in some cratonic peridotites (Fig. 18). The Sm-Nd isotope systematics of garnet-orthopyroxene-clinopyroxene clusters in Kimberley peridotites show distinctly more radiogenic Nd for both pyroxenes compared to the garnet, despite much higher Sm/Nd of the garnet (Fig. 18). This feature has been ob-

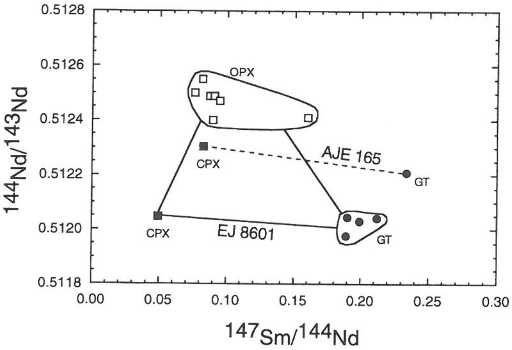

FIG. 18. Sm-Nd isotope systematics of minerals from Kimberley peridotites (Gunther and Jagoutz, 1994; Richardson *et al.* 1985).

served in other Kaapvaal low-T peridotites (Fig. 18) and suggests recent garnet growth from a LREE enriched precursor (Gunther and Jagoutz, 1994).

Some, albeit post-Archaean lithospheric peridotites can show reasonable isochronous relationships. For example, Deng and McDougall (1992) obtained a 1.64 ± 0.01 Ga isochron from clinopyroxene separates obtained from spinel lherzolites from Inner Mongolia. They interpreted this age to reflect the time of local lithospheric differentiation, an interpretation that is consistent with the generally radiogenic Nd in these rocks. In contrast, Carlson and Irving (1994) found correlated Sm-Nd systematics in minerals from Wyoming peridotites that scatter around a 1.8 Ga reference isochron. The Nd in these cratonic samples is consistently very unradiogenic compared to primitive upper mantle, with an initial ϵ_{Nd} of -9, indicative of an ancient metasomatic pre-history. The Sm-Nd age agrees well with U-Th-Pb ages for zircon and monazite metasomatic phases in the Wyoming peridotite suite and must clearly reflect the time of major, regional metasomatic enrichment in the lithosphere (Carlson and Irving, 1994). This study, and others make a clear case for multiple post-formation enrichment events in the evolution of CLM.

Given the severe disruption often caused even to mineral isochrons, it is perhaps surprising that wholerock Re-Os isochrons have been produced for eclogite suites from Siberia (Pearson *et al.*, 1995d) and the Kaapvaal craton (from the Newlands kimberlite pipe; Menzies *et al.*, 1998) that yield Archaean ages. The 3.5 ± 0.7 Ga isochron for Newlands eclogites obtained by Menzies *et al.* (1998) is consistent with the oldest Re depletion ages of Kaapvaal peridotite xenoliths (Pearson *et al.*, 1995a). The 2.9 ± 0.4 Ga isochron for Udachnaya eclogites analysed by Pearson *et al.* (1995d) is within error of the oldest Re depletion ages of Udachnaya peridotites (Pearson *et al.*, 1995c). Moreover, this age agrees well with the 2.51 ± 0.12 Ga secondary Pb isochron on clinopyroxenes from Udachnaya eclogites obtained by Jacob *et al.* (submitted). The Re-Os system in this case appears quite robust against the effects of post-formation metasomatism and host-rock interaction.

Shirey *et al.* (1998) have pointed out that only diamondiferous eclogites appear to retain good isochron systematics. He found that of a suite of 8 Roberts Victor eclogites, the two diamondiferous samples appear to plot along the 3.5 Ga isochron line of Menzies *et al.* (1998). The non-diamondiferous Roberts Victor eclogites from Roberts Victor define a poor correlation with a slope equivalent to an age of 2.7 Ga on an isochron diagram, consistent with the Sm-Nd results of Jagoutz (1984). This means that either the diamondiferous and non-diamondiferous eclogites at Roberts Victor have different ages, or that one of the lines may be a mixing line. In this respect, the fact that the diamondiferous eclogites from Roberts Victor generally have elevated Sr isotope compositions and do not plot on the Sm-Nd isochron of Jagoutz (1984) appears to indicate that the non-diamondiferous eclogites are less disturbed in their Sr-Nd isotope systematics than the diamondiferous ones (see Jacob *et al.*, 1995). This contrasts with Shirey *et al.*'s (1998) observation that in terms of Re-Os systematics, the diamondiferous samples appear less disturbed, and illustrates the difficulties in drawing clear-cut conclusions from isotope data in many eclogite suites.

This conclusion supports an Archaean age for the diamonds that they contain, and raises the possibility that a process deleterious to diamond preservation may have caused disruption of the Re-Os systematics.

Model ages

The model age approach requires a number of assumptions about the rocks being studied. Foremost is the maintenance of a closed system since the event being dated. It has been shown above that this is rarely the case with cratonic peridotite xenoliths. This causes severe problems for the Rb-Sr and Sm-Nd systems in cratonic peridotites because their antiquity makes them likely to have experienced multiple enrichment events, possibly separated by large time intervals. So, although enrichment model ages can be calculated, for Nd, for example, their significance is very dubious. This problem is well illustrated by a plot of Nd isotope evolution for single, low-Ca garnet crystals, with very similar major element chemistry, from the Udachnaya kimberlite (Fig. 19; Jacob *et al.*, 1998b). Model ages, calculated from a depleted mantle reservoir, range from <1 to >3 Ga. This large

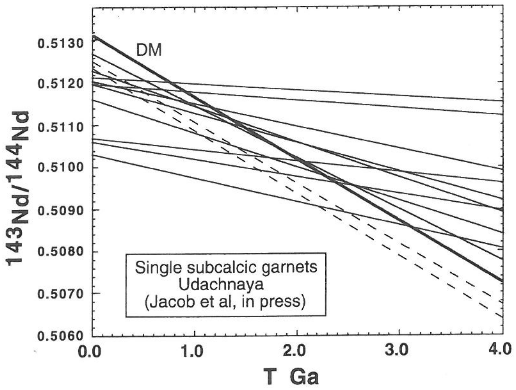

FIG. 19. Nd model ages for single subcalcic garnet crystals from the Udachnaya kimberlite (Jacob *et al.*, 1998b). DM is the depleted mantle evolution curve.

range in model ages for single crystals may be due to metasomatic reaction at different times, to varying extents subsequent to garnet crystallisation (Jacob *et al.*, 1998b), or, relatively recent growth of garnet, with individual crystals achieving varying degrees of equilibrium in their trace element partitioning. Whatever the explanation, it is clearly dangerous to rely on such model ages for accurate chronological information, particularly in cratonic xenoliths. Some systematic Rb-Sr and Sm/Nd model ages have been obtained for non-cratonic xenoliths (Deng and McDougall, 1992; Ionov and Jagoutz, 1989), but in general, most suites do not produce systematic, reliable model ages that correlate clearly with other geological parameters.

In cratonic peridotites, the Re-Os system is also prone to disturbance by metasomatic reaction with melts, especially when interaction preceded eruption by large time intervals. This complication is due to the high Re content of typical mantle melts compared to peridotites, but there is also evidence that Os can be dramatically disturbed (Chesley and Rudnick, 1996; Pearson *et al.*, 1998d). Re depletion models ages, or T_{RD} ages are used to try to overcome the problems of post-formation Re addition or loss in peridotite xenoliths (see above). For very depleted xenoliths with low Re, the T_{RD} age is often within 200 Ma of the model ages calculated using the measured parent-daughter ratio (T_{MA} age; see Fig. 4). For relatively fertile xenoliths, or those that have experienced substantial Re addition, T_{RD} ages represent minimum age estimates only. The philosophy behind this approach, and its applicability, is discussed at more length by Pearson *et al.* (1995a) and Shirey (1998). An additional source of error for both T_{RD} and T_{MA} Re-Os model ages is the uncertainty in both the Bulk Earth and Depleted Mantle evolution curves. The problem with the Bulk Earth evolution curve becomes less severe further back in time because of the precisely determined, most primitive initial $^{187}Os/^{188}Os$ defined for early Solar System materials (IIIA irons; $^{187}Os/^{188}Os = 0.09531 \pm 11$; Smoliar *et al.*, 1996). However, considerable debate exists concerning the present day Bulk Earth. The mantle has been found to have a generally chondritic Os isotope composition (*e.g.*, Luck and Allègre, 1983) but the exact value is somewhat uncertain. Chondrites have been shown to be heterogeneous in terms of their Os isotope compositions. Current estimates varying from mean carbonaceous chondrite values of $^{187}Os/^{188}Os$ values of ~ 0.127 (Luck and Allègre, 1983; Walker *et al.*, 1989a) to 0.129 or higher, characteristic of the OIB source, or more akin to enstatite-chondrites (Martin, 1991; Meisel *et al.*, 1996). Fortunately, the ancient ages of cratonic rocks generally minimise these problems. Despite the above caveats, which should always be borne in mind, remarkable success has been achieved understanding the evolution of cratonic mantle using simplistic, single-stage T_{RD} model ages.

The ground-breaking study of Walker *et al.* (1989a) showed that Kaapvaal peridotites were characterised by very unradiogenic Os isotope ratios which translated into ancient T_{RD} ages extending into the Archaean. This initial finding has been confirmed and extended by subsequent studies on more Kaapvaal peridotites, with the oldest Re depletion ages being 3.3 to 3.5 Ga (Pearson *et al.*, 1995a). Moreover, studies of other lithosphere peridotites from the Wyoming (Carlson and Irving, 1994) and Siberian cratons (Pearson *et al.*, 1995c) indicate that most intact cratonic lithosphere began to stabilise in the mid-Archaean (Fig. 20). Chromites from ultramafic rocks analysed by Nagler *et al.* (1997) indicate that stabilisation of cratonic lithosphere beneath the Zimbabwe craton began perhaps 3.8 Ga ago, but no direct samples of the lithospheric mantle from this craton have yet been dated.

An obvious feature of the age histograms presented in Fig. 20 is the large spread in T_{RD} ages. This spread has been explained largely in terms of post-crystallisation Re addition (Pearson *et al.*, 1995a; Pearson *et al.*, 1995c; Walker *et al.*, 1989a), although direct alteration of Os contents and isotope ratios is clearly possible (Chesley and Rudnick, 1996) especially considering the high Os content of diamond inclusion sulfides, some of which appear to have crystallised in the lithosphere recently (Pearson *et al.*, 1998d). If the data for cratonic peridotites that show no sign of patent metasomatism (no post-differentiation introduction of metasomatic phases)

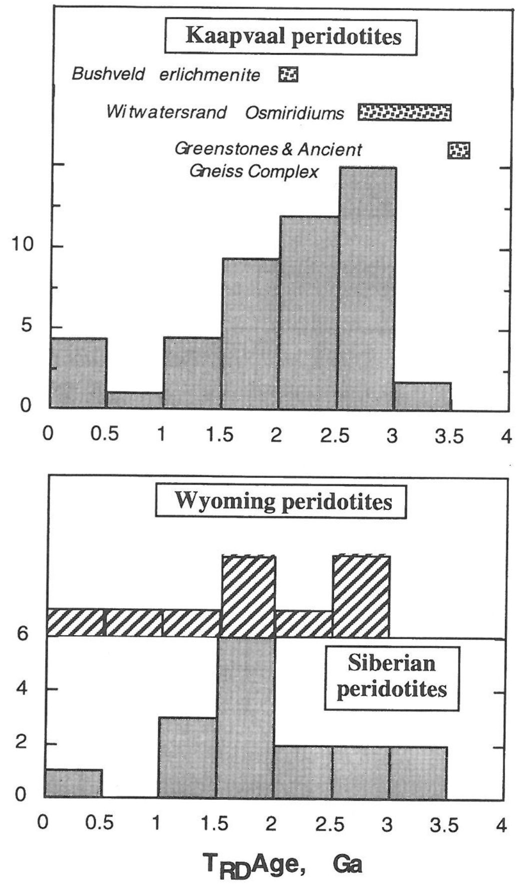

FIG. 20. T_{RD} model ages for cratonic peridotite xenoliths. Data sources as in Fig. 7.

are plotted on a Re-Os isochron diagram (Fig. 21), clear indications of Re addition are seen. Samples that differentiated by variable degrees of Re depletion, from mantle of chondritic composition, should lie on lines connecting them to present day Bulk Earth, the slope of these lines yielding the age of differentiation. The data clearly require more complex explanation than this simple one-stage model. Numerous samples have Re/Os values much higher than Bulk Earth, yet fairly unradiogenic Os, suggesting recent Re addition. The shaded field on Fig. 21 shows the area that would be occupied by samples that had experienced simple mixing with the variety of compositions shown by southern African kimberlites (PEARSON *et al.*, 1996). Numerous samples plot within this field and could be a product of host-kimberlite interaction plus the time-integrated effects of more ancient melt enrichment. Other samples have elevated Re/Os but retain unradiogenic Os. These samples could reflect recent interaction with carbonate-rich fluids which tend to have very low Os but high Re (*e.g.*, PEARSON *et al.*, 1995c; Fig. 21). It is possible that some of the samples lying to the left hand side of the isochron diagram have experienced Re loss, possibly due to breakdown and alteration of sulfides during eruption (LORAND, 1990), but this suggestion is difficult to verify.

The oldest T_{RD} ages for cratonic peridotites are predominantly from those with the lowest measured Re, well below the 260 ppt value suggested by MORGAN (1986) for fertile mantle (SHIREY and WALKER, 1998). The oldest T_{RD} ages are taken to approximate the age of craton stabilisation and this is supported by the similarity in the oldest T_{RD} ages for peridotites from 3 different cratons (Fig. 21, PEARSON *et al.*, 1995a). Samples from the Premier kimberlite, South Africa, consistently give post-Archaean ages of c. 2 Ga (PEARSON *et al.*, 1995a; CARLSON *et al.*, 1998). The Premier kimberlite erupted through the outcrop ring of the large Bushveld intrusion that formed close to 2 Ga and it seems likely that a major new addition to the lithosphere occurred beneath this region at this time (CARLSON *et al.*, 1998). This possibility is supported by the occurrence of Bushveld erlichmenites

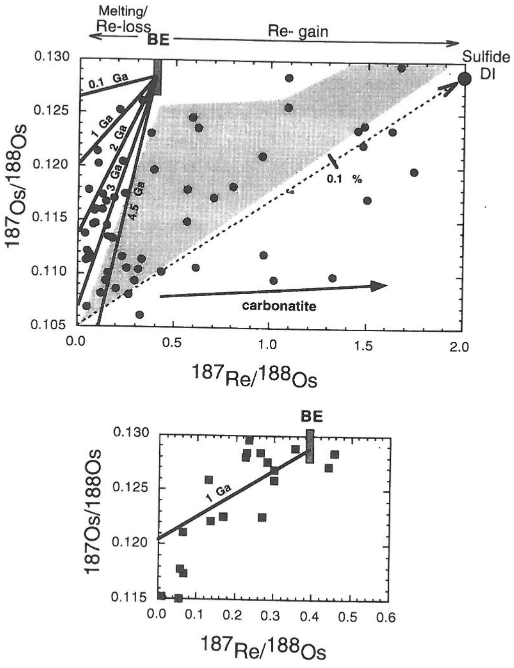

FIG. 21. Re-Os isotope systematics of cratonic peridotites. Isochrons for single-stage differentiates of a chondritic reservoir at various times (in Ga) are illustrated. Also shown is the field for peridotite interaction with kimberlites and the effect of mixing with a high Re-Os sulfide component similar to some sulfide inclusions in diamonds (PEARSON *et al.*, 1998d).

(Hart and Kinloch, 1990) with $^{187}Os/^{188}Os$ in the range of the Premier peridotites that show evidence of having formed at 2 Ga. The Os isotope composition of these grains presumably reflects that of the dominant component contributing to Bushveld magmatism in this period. In contrast, osmiridiums, laurites and erlichmenites from the Witwatersrand basin show evidence of grains as old as 3.3 Ga, the same age as the postulated maximum lithospheric mantle age in the main Kaapvaal craton root (Pearson *et al.*, 1995a). Further studies are on-going, aimed at characterising possible lateral variations in lithospheric age across the Kaapvaal craton (Carlson *et al.*, 1998).

The same approach of using T_{RD} ages to estimate the age of lithospheric mantle stabilisation can be applied to circum-craton xenolith suites. Peridotite suites from Namibia and East Griqualand, surrounding the Kaapvaal craton, show oldest T_{RD} ages that are early Proterozoic, c. 2.1 to 2.3 Ga (Pearson *et al.*, 1994; Pearson *et al.*, 1998a), much younger than the oldest ages from on-craton suites (Fig. 22). The mean T_{RD} age for the 2 circum-cratonic suite is 1.6 ± 0.4 Ga compared to 2.5 Ga ± 0.5 Ga for on craton xenoliths (Fig. 22). A large range of isotopic compositions is again evident. The isotopic variability does not clearly correlate with degree of melt removal as defined by major element parameters (if these peridotites represent residues), suggesting similar disturbance of Os isotope signatures. The oldest T_{TD} ages for circum-cratonic rocks appear to correlate with the age of the oldest crustal basement in these regions and indicate that the craton root does not extend beneath Proterozoic cover in these areas.

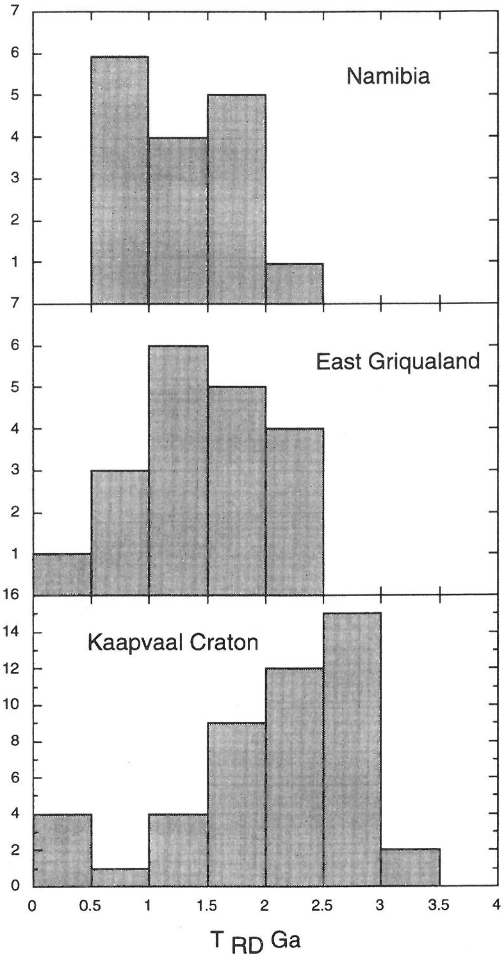

FIG. 22. T_{RD} model ages for circum-cratonic xenolith suites from Namibia and East Griqualand compared to Kaapvaal craton peridotites. Data sources as in Fig. 9.

Lithospheric stratigraphy

Depths of origin can be determined via thermobarometry for many cratonic peridotites and hence we can potentially examine the stratigraphy of the lithospheric mantle (Pearson *et al.*, 1995a). The most comprehensive data available in this regard is from southern Africa, where both on-craton (Pearson *et al.*, 1995a,c; Walker *et al.*, 1989a) and off-craton (Pearson *et al.*, 1994; Pearson *et al.*, 1998a) localities have been analysed. Examination of the depth versus age relationships in Fig. 23 reveals two important features: (a) Strong correlation between the age of the oldest major crust-building period and the oldest T_{RD} ages of the underlying lithospheric mantle, both on- and off-craton; (b) Lack of an obvious relationship between age versus depth in the lithosphere. Closer scrutiny shows that, of the present data, the oldest T_{RD} ages occur both in shallow, and deep mantle, and this observation has been used to argue for relatively rapid accretion of cratonic lithosphere, possibly from plume-driven melting (Pearson *et al.*, 1995a). One possible problem with this interpretation is that although the Os isotopes are recording ancient processes, the mineral equilibria upon which the P-T estimates are based, only record conditions immediately before sampling by the kimberlite. As such, it is possible that much later tectonic-stacking has produced the age-depth relationships observed in Fig. 23.

The oldest T_{RD} ages for 3 cratons are in the range of the period of major crust building for these regions. This observation leads to the suggestion of a causal link between either crust-building and stabilisation of lithospheric mantle, or the preservation of crust, once a protective deep lithospheric keel has been stabilised. On the basis of very limited xenolith

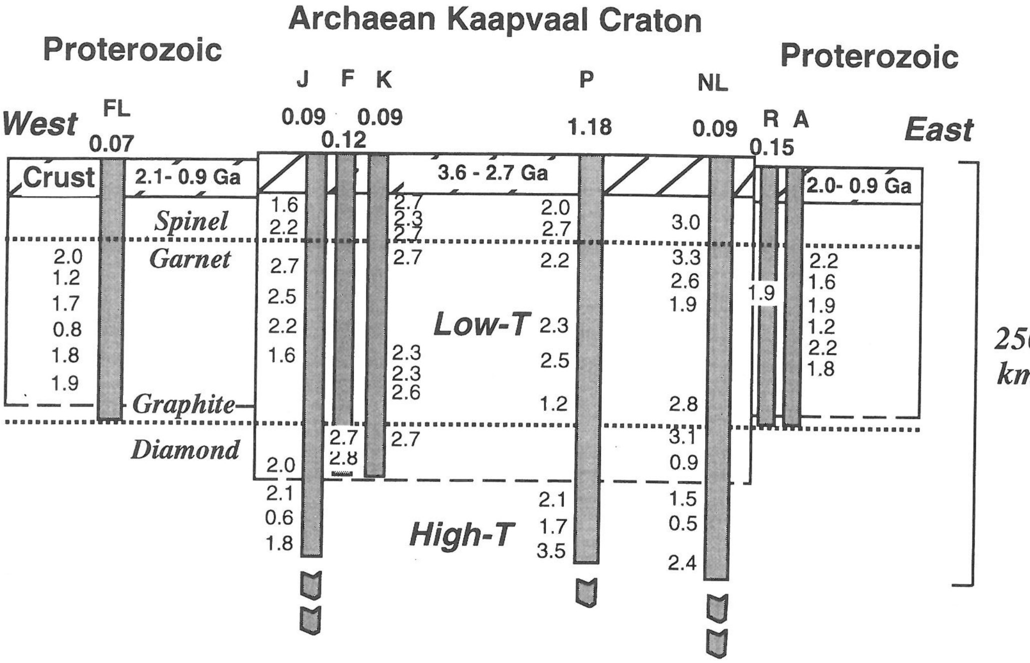

FIG. 23. Depth (from mineral thermobarometry) vs. T_{TD} model age plot of peridotite xenoliths from a section across southern Africa, after (PEARSON *et al.*, 1998A). Localities are: FL—Farm Louwrencia; J—Jagersfontain; F—Finsch; K—Kimberley; P—Premier; NL—North Lesotho; R—Ramatseliso; A— Abottsford.

data, this relationship appears to be the case for the Superior province (PEARSON *et al.*, 1995b). Studies of more localities may clarify the relationship between the formation of the cratonic crust and lithospheric mantle.

Orogenic peridotite massifs have been widely utilised in the study of post-Archaean lithosphere formation. Re-Os isotope studies of such massifs have also revealed evidence for Re disturbance but several massifs exhibit remarkably good correlations between bulk rock Al_2O_3 and $^{187}Os/^{188}Os$ (BURNHAM *et al.*, 1998; REISBERG and LORAND, 1995). Due to the apparent similarity in bulk distribution coefficients of Re and Al during mantle melting, REISBERG and LORAND (1995) proposed that this correlation represents an isochron analogue and used the y-axis intercept (on a plot of $^{187}Os/^{188}Os$ vs. Al_2O_3) to calculate a T_{RD} model age for the formation of the lithosphere beneath the Betics and the Pyrenees. BURNHAM *et al.*, (1998) have shown that this approach is much more appropriate for correlations between $^{187}Os/^{188}Os$ and either S, or Re, as these components may be totally depleted in a peridotite at high degrees of melting, whereas this is not the case for Al_2O_3 in the range of melting experienced by Orogenic peridotite massifs. Hence, lithosphere formation ages based on intercept values of $^{187}Os/^{188}Os$ vs. Al_2O_3 correlations are likely to be over-estimates (BURNHAM *et al.*, 1998). Correlations of $^{187}Os/^{188}Os$ vs. Al_2O_3 have been observed for some xenolith suites from alkali-basalts (COHEN *et al.*, 1996) but such correlations are absent or very poor in suites of cratonic and circum-cratonic kimberlite-borne peridotite xenoliths. Whether this represents a fundamental difference in the mode of origin of these different peridotite suites is not yet certain, but the general approach has not been found useful in cratonic xenolith suites.

SUMMARY: ISOTOPIC CONSTRAINTS ON THE ORIGIN AND EVOLUTION OF CRATONIC LITHOSPHERE

Origins of eclogites

The origin of eclogites erupted by kimberlites provides potential constraints on the tectonics associated with craton formation (JACOB *et al.*, 1994; JACOB *et al.*, 1998a; SNYDER *et al.*, 1997). Their antiquity has been shown using U-Pb, Sm-Nd and Re-Os isotope systematics. At issue is whether all kimberlite-derived eclogites are of crustal derivation, representing deeply subducted and metamorphosed Archaean ocean floor, or whether they are products solely of mantle processes. SNYDER *et al.* (1997) have stated that there are no unequivocal mantle signatures in eclogite xenoliths. In terms of isotopic signatures this is possibly correct, but other characteristics may be more indicative. Eclogites have a very large spread in Sm/Nd. Although the mean is close to values seen in MORB and crustal eclogites occurring in metamorphic belts, numerous eclogites have very high Sm/Nd, far above that observed for crustal rocks. Eclogites have been proposed as residues from slab melting (IRELAND *et al.*, 1994), and this process might elevate Sm/Nd in a residual eclogite although this is difficult to model without appropriate partition coefficients. The only analogous very high Sm/Nd signatures are seen in garnet pyroxenites from orogenic peridotite massifs, of clear mantle derivation (Fig. 14), suggesting that a mantle signature can be seen in some kimberlite-borne eclogite xenoliths. The very high Sm/Nd of some eclogite xenoliths suggests that they originated as high-pressure cumulates. This observation does not deny an origin from subducted protoliths for these very high Sm/Nd eclogites, indeed several have extreme oxygen isotope compositions (JAGOUTZ *et al.*, 1984), but they appear to have experienced high-pressure crystal-liquid equilibria involving garnet fractionation. Hence, high Sm/Nd eclogites might be another variant of eclogites, possibly produced by high pressure crystal fractionation of slab derived melts, either as cumulates or by crystal plating. The low Re/Os signatures of some eclogites (MENZIES *et al.*, 1998; PEARSON *et al.*, 1992; SHIREY *et al.*, 1998) may be explicable in terms of a cumulate origin. The Archaean age established for several eclogite suites, together with the clear crustal signatures in some suites strongly suggest that plate-tectonics involving subduction operated in the late Archaean (JACOB *et al.*, 1994; PEARSON *et al.*, 1995d).

Origin of cratonic peridotites

Radiogenic isotope systematics in cratonic peridotites testify to the diverse processes they have experienced. Incompatible element isotope systematics, in particular Sr-Nd isotopes, predominantly reflect enrichment by a variety of melts and H_2O-CO_2 rich fluids, probably during multiple events. The timing of some of this enrichment must have been ancient (Archaean) to produce the very unradiogenic Nd isotopes observed in both peridotites and diamond inclusions.

Re-Os isotopes provide clear evidence for an Archaean formation age for cratonic peridotites from three different cratons. New data are revealing evidence for substantial later additions to the CLM in some localities (CARLSON *et al.*, 1998). The Re-Os system uniquely fingerprints the CLM, and Re depletion model ages show excellent coherence with tectonic settings defined from crustal rocks; thus a systematic shift occurs in the mean T_{RD} ages of peridotites from Archons, Protons and Tectons (Fig. 24). The distinctive Os isotopic characteristics of CLM are proving very useful for identifying ancient lithospheric fragments in tectonically complex areas.

The oldest Re depletion ages of CLM xenoliths show excellent correspondence with the age of major crust building on craton. Furthermore, circum-cratonic peridotites mirror this relationship, with Proterozoic crustal basement underlain by Proterozoic mantle (Fig. 24). This observation is powerful evidence that the deep roots of continents move coherently with their crust during continental drift and tectonic activity and are not easily removed.

Many theories have been advanced to explain the origin of CLM, in particular, the Si-enriched peridotite xenoliths erupted through the Kaapvaal and Siberian cratons by kimberlites (BOYD, 1989; BOYD *et al.* , 1997; HERZBERG, 1993; KELEMAN *et al.*, 1992; KELEMAN *et al.*, in press; RUDNICK *et al.*, 1994). The lack of discernible difference in differentiation ages between shallow and deeply derived peridotites has

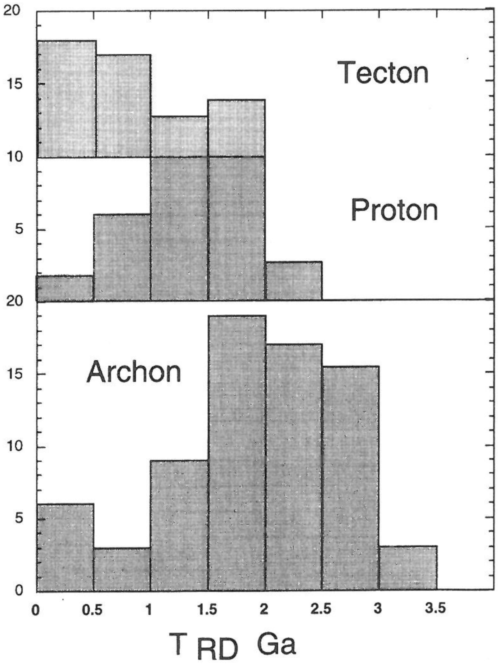

FIG. 24. Histograms of T_{RD} model ages for peridotite xenoliths from different tectonic settings (terminology from JANSE, 1994). Archon & Proton data sources as in Figs. 7 and 9. Tecton data from HANDLER *et al.* (1997) and PEARSON *et al.* (1998a).

been cited as evidence to support formation of CLM in a plume environment (PEARSON *et al.*, 1995a). However, recent models invoking shallow, ridge melting, followed by interaction with slab-derived melts in subduction zones (KELEMAN *et al.*, in press; RUDNICK *et al.*, 1994), and then tectonic stacking, are equally viable in producing the observed age versus depth relationships in CLM . The attraction of these models is several fold. They incorporate a mechanism for producing overlying crust of similar age to the mantle keel. The processes of polybaric melting together with melt-solid interaction would combine to produce many of the scattered geochemical relationships observed in cratonic peridotites. In addition, the subduction zone environment provides a means of generating eclogites of similar age (MENZIES *et al.*, 1998; PEARSON *et al.*, 1995d; SHIREY and WALKER, 1998) to the cratonic peridotites, interleaved with them in the craton root. Despite this, there are a number of features of such models that are problematic. One is the large amount of viscous SiO_2-rich melt required to interact with residual peridotite. It is not clear whether such melts could be effective at percolating through residual peridotite, and if they did, we might expect to see a clearer chemical signal of their effect. A second problem is that the positive correlation between Ni content of olivine versus modal orthopyroxene content in the Premier peridotite suite, which is used to support the melt-rock reaction model (KELEMAN *et al.*, in press) is not observed in other peridotite suites thus far analysed (BOYD, 1997). Clearly, much work is yet to be done if we are to fully understand the origin of cratonic peridotites.

Finally, a first-order implication of the persistence of ancient ages throughout the depth of cratonic lithosphere is that slow, thermal or tectonic accretion over large timescales seems unlikely. However these cratonic keels were put together, it appears to have happened mostly in Archaean times.

Acknowledgments—It is a great pleasure to contribute to a volume in honour of the work of Joe Boyd who has been responsible for educating me on many aspects of mantle xenoliths and for several years of friendship. Geoff Nowell, Dorit Jacob, Rick Carlson and Bjorn Mysen are thanked for providing helpful reviews and unpublished manuscripts.

REFERENCES

BASU A. R. and MURTHY V. R. (1977) Ancient lithospheric lherzolite xenoliths in alkali basalt from Baja California. *Earth Planet. Sci. Lett.* **35,** 239–246.

BASU A. R. and TATSUMOTO M. (1980) Nd-isotopes in selected mantle-derived rocks and minerals and their implications for mantle evolution. *Contrib. Mineral. Petrol.* **75,** 43–54.

BONNEY T. G. (1897) On some rock specimens from Kimberley, South Africa. *Geol. Mag.* **4,** 448–502.

BOYD F. R. (1973) A pyroxene geotherm. *Geochim. Cosmochim. Acta* **37,** 2533–2546.

BOYD F. R. (1987) High- and low temperature garnet peridotite xenoliths and their possible relation to the lithosphere-asthenosphere boundary beneath southern Africa. In *Mantle Xenoliths* (ed. P. H. NIXON), pp. 403–412. John Wiley & Sons.

BOYD F. R. (1989) Compositional distinction between oceanic and cratonic lithosphere. *Earth Planet. Sci. Lett.* **96,** 15–26.

BOYD F. R. (1997) Correlation of orthopyroxene abundance with the Ni-content of coexisting olivine in cratonic peridotites. *Eos, Trans. Amer. Geophys. U.* **78,** 746.

BOYD F. R. and GURNEY J. J. (1986) Diamonds and the African lithosphere. *Science* **232,** 472–477.

BOYD F. R. and NIXON P. H. (1979) Garnet lherzolite xenoliths from the kimberlites of East Griqualand, southern Africa. *Carnegie Inst. Washington Year Book* **80,** 328–336.

BOYD F. R., PEARSON D. G., OLSON H. K. E., and HOAL B. G. (1994) Composition and age of Namibian peridotite xenoliths; a comparison of cratonic and non cratonic lithosphere. *Eos, Transactions, American Geophysical Union* **75**(16, Suppl.), 192.

BOYD F. R., POKHILENKO N. P., PEARSON D. G., MERTZMAN S. A., SOBOLEV N. V., and FINGER L. W. (1997) Composition of the Siberian cratonic mantle: evidence from Udachnaya peridotite xenoliths. *Contrib. Mineral. Petrol.* **128,** 228–246.

BRUEKNER H. K. (1974) Mantle Rb/Sr and 87Sr/86Sr ratios from clinopyroxenes from Norwegian garnet peridotites and pyroxenites. *Earth Planet. Sci. Lett.* **24,** 26–32.

BURNHAM O. M., ROGERS N. W., PEARSON D. G., VAN CALSTEREN P. W., and HAWKESWORTH C. J. (1998) The petrogenesis of the Eastern Pyrenean peridotites: An integrated study of their whole-rock geochemistry and Re-Os isotope composition. *Geochim. Cosmochim. Acta* **62,** 2293–2310.

CAPOBIANCO C. J. and DRAKE M. J. (1990) Partitoning of ruthenium, rhodium, and palladium between spinel and silicate melt and implications for platinum group element fractionation trends. *Geochim. Cosmochim. Acta* **54,** 869–874.

CARLSON R.W. (1995) Isotopic inferences on the chemical structure of the mantle. *J. Geodynamics* **20,** 365–386.

CARLSON R. W. and IRVING A. J. (1994) Depletion and enrichment history of subcontinental lithospheric mantle: Os, Sr, Nd and Pb evidence for xenoliths from the Wyoming Craton. *Earth Planet. Sci. Lett.* **126,** 457–472.

CARSLON R. W., PEARSON D. G., BOYD F. R., SHIREY S. B., IRVINE G., MENZIES A. H., and GURNEY J. J. (in press) Regional age variation of the southern African mantle: significance for models of lithospheric mantle formation. *Proc. 7th Int. Kimberlite Conf. Cape Town.*

CHESLEY J. and RUDNICK R. L. (1996) Growth and modification of the Tanzanian lithospheric mantle: Preliminary Re-Os results. *J. Conf. Abst.* **1,** 105.

COHEN A. S., BURNHAM O. M., ROGERS N. W., and MARTYN K. (1996) Re-Os isotope systematics of peridotite xenoliths from Dreiser Weiher and Gees, Eifel, Germany. *J. Conf. Abstracts.* **1,** 116–117.

COHEN E. (1879) Uber einen Eklogit, welcher als Einschluss in den Diamantgruben von Jagersfontein, Orange Freistaat, Sudafrika vorkommt. *Neues Jahrbuch fur Seismologie,* 864–872.

Cohen R. S., O'Nions R. K., and Dawson J. B. (1984) Isotope geochemistry of xenoliths from East Africa: implications for development of mantle reservoirs and their interaction. *Earth Planet. Sci. Lett.* **68,** 209–220.

Creaser R. A., Papanastasio D. A., and Wasserburg G. J. (1991) Negative thermal ion mass spectrometry of osmium, rhenium and iridium. *Geochim. Cosmochim. Acta* **55,** 397–401.

Deng F. L. and McDougall J. D. (1992) Proterozoic depletion of the lithosphere recorded in mantle xenoliths from Inner Mongolia. *Nature* **360,** 333–336.

Finnerty A. A. and Boyd F. R. (1987) Thermobarometry for garnet peridotite xenoliths:a basis for upper mantle stratigraphy. In *Mantle Xenoliths* (ed. P. H. Nixon), pp. 381–402. Wiley.

Gunther M. and Jagoutz E. (1994) Isotopic disequilibria (Sm/Nd, Rb/Sr) between minerals of coarse grained, low temperature peridotites from Kimberely floors, southern Africa. *Proc. 5th International Kimberlite Conference,*.

Gunther M. and Jagoutz E. (1997) The meaning of Sm/Nd apparent ages from kimberlite-derived coarse grained low temperatures peridotites from Yakutia. *Russian Geol. Geophys.* **38,** 229–239.

Gurney J. J. (1989) Diamonds. In *Kimberlites and Related Rocks,* Vol. Spec. Pub. 14 (eds. J. Ross *et al.*), pp. 935–965. Geol. Soc. Australia.

Hamilton M. A., Pearson D. G., Stern R., and Boyd F. R. (1998) Constraints on MARID petrogenesis: SHRIMP II U-Pb zircon evidence for pre-eruption metasomatism at Kampfersdam. *Ext. Abs. 7th Int. Kimberlite Conf. Cape Town,* 296–298.

Handler M. R., Bennet V. C., and Esat T. Z. (1997) The persistence of off-cratonic lithospheric mantle: Os isotopic systematics of variably metasomatised southest Australian xenoliths. *Earth Planet. Sci. Lett.* **151,** 61–75.

Hart S. R. and Kinloch E. D. (1990) Osmium isotope systematics in Witswatersrand and Bushveld ore deposits. *Econ. Geol.* **84,** 1651–1655.

Hassler D. R. and Shimizu N. (1998) Osmium isotopic evidence for ancient subcontinental lithospheric mantle beneath the Kerguelen Islands, southern Indian Ocean. *Science* **280,** 618–620.

Hauri E. H., Shimizu N., Dieu J. J., and Hart S. R. (1993) Evidence for hotspot-related carbonatite metasomatism in the oceanic upper mantle. *Nature* **365,** 221–227.

Hawkesworth C. J., Kempton P. D., Rogers N. W., Ellam R. M., and Calsteren P. W. V. (1990) Continental mantle lithosphere, and shallow level enrichment processes in the Earth's mantle. *Earth Planet. Sci. Lett.* **96,** 256–268.

Hawkesworth C. J., Rogers N. W., Calsteren P. W. C. V., and Menzies M. A. (1984) Mantle enrichment processes. *Nature* **311,** 331–335.

Herzberg C. T. (1993) Lithosphere peridotites of the Kaapvaal craton. *Earth Planet. Sci. Lett.* **120,** 13–29.

Hofmann A. W. (1997) Mantle geochemistry: the message from oceanic volcanism. *Nature* **385,** 219–229.

Hurley P. M., Fairburn H. W., and Pinson W. H. (1964) Rb-Sr relationships in serpentine from Mayaguez, Puerto Rico and dunite from St. Paul's rocks: a progress report. In *A Study of Serpentinite: The AMSOC Core Hole near Mayaguez, Peurto Rico,* Vol. 1118 (ed. C. A. Burke), pp. 149–151. Natl. Tes. Counc.

Ionov D. A., Dupuy C., O'Reilly S., Kopylova M. G., and Genshaft Y. S. (1993) Carbonated peridotite xenoliths from Spitsbergen: implications for trace element signature of mantle carbonate metasomatism. *Earth. Planet. Sci. Lett.* **119,** 283–297.

Ionov D. A. and Jagoutz E. (1989) Isotopic behaviour of strontium and neodymium in minerals of garnet- and spinel-containing peridotite xenoliths of the Vitim Plateau: first data from the USSR. *Trans. (Doklady) USSR Acad. Sci: Earth Sci. Sect.* **301,** 232–236.

Ireland T. R., Rudnick R. L., and Spetsius Z. (1994) Trace elements in diamond inclusions from eclogites reveal link to Archean granites. *Earth Planet. Sci. Lett.* **128,** 199–213.

Jacob D. and Jagoutz E. (1994) A diamond-graphite bearing eclogite xenolith from Roberts Victor (South Africa): Implications for petrogenesis from Pb-,Nd-, and Sr-isotopes. In *Kimberlites, related rocks and mantle xenoliths,* Vol. 1 (eds. H. O. A. Meyer and O. H. Leonardos), pp. 304–317. CPRM Spec. Publ.

Jacob D., Jagoutz E., Lowry D., Mattey D., and Kudrjavtseva G. (1994) Diamondiferous eclogites from Siberia: Remnants of Archean oceanic crust. *Geochim. Cosmochim. Acta* **58,** 5191–5207.

Jacob D., Jagoutz E., Lowry D., and Zinngrebe E. (1998a) Comments on "The origins of Yakutian eclogite Xenoliths" by G. A. Snyder, L. A. Taylor, G. Crozaz, A. N. Halliday, B. L. Beard, V. N. Sobolev and N. V. Sobolev. *J. Petrol.* **39,** 1527–1533.

Jacob D., Jagoutz E., and Sobolev N. V. (1998b) Neodymium and strontium isotopic measurements on single subcalcic garnet grains from Yakutian kimberlites. *Neues Jahrbuch fur Mineralogie* **172,** 357–379.

Jagoutz E. (1988) Nd and Sr systematics in an eclogite xenolith from Tanzania: evidence for frozen mineral equilibria in the continental lithsphere. *Geochim. Cosmochim. Acta* **52,** 1285–1293.

Jagoutz E., Carlson R. W., and Lugmair G. W. (1980) Equilibrated Nd-, unequilibrated Sr isotopes in mantle xenoliths. *Nature* **296,** 708–710.

Jagoutz E., Dawson J. B., Hoernes S., Spettel B., and Wänke H. (1984) Anorthositic oceanic crust in the Archean Earth. *Lunar and Planetary Science Institute, Houston, Lunar Planet. Sci.* **XV,** 395–396.

Janse A. J. A. (1994) Is Clifford's Rule still valid ? Affirmative examples from around the world. In *Diamonds: characterisation, genesis and exploration,* Vol. 2 (eds. O. H. Leonardos and H. O. A. Meyer), pp. 215–235. CPRM.

Keleman P. B., Dick H. J. B., and Quick J. E. (1992) Formation of harzburgite by pervasive melt/rock reaction in the upper mantle. *Nature* **358,** 635–641.

Keleman P. B., Hart S. R., and Bernstein S. (in press) Silica enrichment in the continental upper mantle via melt/rock reaction. *Earth Planet. Sci. Lett.*

Kramers J. D. (1979) Lead, Uranium, strontium, potassium and rubidium in inclusion-bearing diamonds and mantle derived xenoliths from southern Africa. *Earth Planet. Sci. Lett.* **42,** 58–70.

Lanphere M. (1968) Sr-Rb-K and Sr isotopic ratios in ultramafic rocks, S.E. Alaska. *Earth Planet. Sci. Lett.* **9,** 247–256.

Lorand J. P. (1990) Are spinel lherzolite xenoliths representative of the abundance of sulphur in the upper mantle? *Geochim. Cosmochim. Acta.* **54,** 1487.

Luck J. M. and Allègre C. J. (1983) ^{187}Re-^{187}Os systematics in meteorites and cosmochemical consequences. *Nature* **302,** 130–132.

Maaloe S. and Aoki K. (1977) The major element composition of the upper mantle estimated from the composition of lherzolites. *Contrib. Mineral. Petrol.* **63,** 161–173.

MacGregor I. D. and Manton W. I. (1986) Robert Victor Eclogites: ancient oceanic crust. *J. Geophys. Res.* **91,** 14063–14079.

Martin C. E. (1991) Osmium isotopic characteristics of mantle-derived rocks. *Geochim. Cosmochim. Acta* **55,** 1421–1434.

Martin C. E., Esser B. K., and Turekian K. K. (1991) Re-Os isotopic constraints on the formation of mantle and crustal reservoirs. *Aust. J. Earth Sci.* **38,** 569–576.

McCulloch M. T. (1989) Sm-Nd systematics in eclogite and garnet peridotite nodules from kimberlites: Implications for the early differentiation of the earth. In *Kimberlites II,* Vol. 14 (ed. N. Ross), pp. 864–876. Geol. Soc. Australia.

Meisel T., Walker R. J., and Morgan J. W. (1996) The osmium isotopic composition of the Earth's primitive upper mantle. *Nature* **383,** 517–520.

Menzies A. H., Shirey S. B., Carlson R. W., and Gurney J. J. (1998) Re-Os isotope systematics of diamond bearing eclogites and peridotites from Newlands kimberlite. *Ext. Abstract 7th Int. Kimberlite Conf. Cape Town.* pp. 579–581.

Menzies M. A. (1989) Cratonic, Circumcratonic and Oceanic Mantle Domains Beneath the Western United States. *J. Geophys. Res.* **94,** 7899–7915.

Menzies M. A. (1990a) Archaean, proterozoic and phanerozoic lithospheres. In *Continental Mantle* (ed. M. A. Menzies), pp. 67–86. Clarendon Press.

Menzies M. A. (1990b) *Continental Mantle.* Clarendon Press.

Menzies M. A. (1990c) Petrology and geochemistry of the continental mantle: an historical perspective. In *Continental Mantle* (ed. M. A. Menzies), pp. 31–54. Clarendon Press.

Menzies M. A. and Chazot G. (1995) Fluid processes in diamond to spinel facies shallow mantle. *J. Geodynamcis.* **20,** 387–415.

Menzies M. A. and Halliday A. N. (1988) Lithospheric Mantle Domains beneath the Archean and Proterozoic crust of Scotland. *J. Petrol.* **Special Lithosphere Issue,** 275–302.

Menzies M. A. and Murthy V. R. (1980a) Mantle metasomatism as a precursor to the genesis of alkaline magmas- Isotopic evidence. *Amer. J. Sci.* **280A,** 622–638.

Menzies M. A. and Murthy V. R. (1980b) Nd and Sr isotope geochemistry of hydrous mantle nodules and their host alkali basalts; implications for lacal heterogeneities in metasomatically veined mantle. *Earth Planet. Sci. Lett.* **46,** 323–334.

Morgan J. W. (1986) Ultramafic xenoliths: Clues to earth's late accretionary history. *J. Geophys. Res.* **91,** 12375–12387.

Nagler T. F., Kramers J. D., Kamber B. S., Frei R., and Prendergast M. D. A. (1997) Growth of subcontinental lithospheric mantle beneath Zimbabwe started at, or before 3.8 Ga: Re-Os study on chromites. *Geology* **25**(983–986).

Neal C. R., Taylor L. A., Davidson J. P., Holden P., Halliday A. N., Nixon P. H., Paces J. B., Clayton R. N., and Mayeda T. (1990) Eclogites with oceanic crustal and mantle signatures from the Bellsbank kimberlite, South Africa, part 2: Sr, Nd and O isotope geochemistry. *Earth Planet. Sci. Lett.* **99,** 362–379.

Nixon P. H. (1987) *Mantle Xenoliths.* Wiley.

Nixon P. H. and Boyd F. R. (1973) Petrogenesis of the granular and sheared ultrabasic nodule suite in kimberlite. In *Lesotho Kimberlites* (ed. P. H. Nixon), pp. 48–56. Cape and Transvaal.

Nixon P. H., Calsteren P. V., Boyd F. R., and Hawkesworth C. J. (1987) Harzburgites with garnets of diamond facies from Southern Africa. In *Mantle Xenoliths* (ed. P. H. Nixon), pp. 523–533. Wiley.

Nixon P. H., Von Norring O., and Rouke J. M. (1963) Kimberlites and associated inclusions: a mineralogical and geochemical study. *Amer. Mineral.* **48,** 1060–1132.

Pearson D. G., Boyd F. R., Hoal K. E. O., Hoal B. G., Nixon P. H., and Rogers N. W. (1994) A Re-Os isotopic and petrological study of Namibian peridotites: contrasting petrogenesis and composition of on- and off-craton lithospheric mantle. *Mineral. Mag.* **58A,** 703–704.

Pearson D. G., Carlson R. W., Boyd F. R., Shirey S. B., and Nixon P. H. (1998a) Lithospheric mantle growth around cratons: A Re-Os isotope study of peridotite xenoliths from East Griqualand. *Ext. Absts. 7th Int. Kimb. Conf. Cape Town.*

Pearson D. G., Carlson R. W., Shirey S. B., Boyd F. R., and Nixon P. H. (1995a) The stabilisation of Archaean lithospheric mantle: A Re-Os isotope study of peridotite xenoliths from the Kaapvaal craton. *Earth Planet. Sci. Lett.* **134,** 341–357.

Pearson D. G., Davies G. R., and Nixon P. H. (1993) Geochemical constraints on the petrogenesis of diamond facies pyroxenites from the Beni Bousera peridotite massif, north Morocco. *J. Petrol.* **34,** 125–172.

Pearson D. G., Davies R. M., Shirey S. B., Carlson R. W., and Griffin W. L. (1998b) The age and origin of eastern Australian diamonds: Re-Os isotope evidence from sulfide inclusions in two diamonds from Wellington, New South Wales. *Ext. Absts. 7th Int. Kimb. Conf. Cape Town.*

Pearson D. G., Meyer H. O. A., Boyd F. R., Shirey S. B., and Carlson R. W. (1995b) Re-Os isotope evidence for Late Archaean stabilisation of a thick lithospheric mantle keel beneath the Kirkland Lake area, Superior Province, Canada. Further evidence for long-term crust-mantle coupling. *Extended Abstracts, 6th International Kimberlite Conference, Novosibirsk.,* 427–429.

Pearson D. G., Rogers N. W., Irving A. J., Smith C. B., and Hawkesworth C. J. (1996) Re-Os isotope constraints on the sources of kimberlites and lamproites. *Jour. Conf. Abst.* **1,** 453.

Pearson D. G., Shirey S. B., Bulanova G. P., Carlson R. W., and Milledge H. J. (1998c) Single-crystal rhenium-osmium isotopic dating of sulfide inclusions within a zoned Siberian diamond. *Geochim. Cosmochim. Acta* **62.**

Pearson D. G., Shirey S. B., Carlson R. W., Boyd F. R., Pokhilenko N. P., and Shimizu N. (1995c) Re-Os, Sm-Nd & Rb-Sr isotope evidence for thick Archaean lithospheric mantle beneath the Siberia craton modified by multi-stage metasomatism. *Geochim. Cosmochim. Acta* **59,** 959–977.

Pearson D. G., Shirey S. B., Carlson R. W., and Taylor L. R. (1992) Os isotope constraints on the origin of eclogite xenoliths. *Eos, Trans. Amer. Geophys. Union* **73**(No. 14), 376.

Pearson D. G., Shirey S. B., Harris J. W., and Carlson R. W. (1998d) Sulfide inclusions in diamonds from the Koffiefontein kimberlite, S. Africa: Constraints on diamond ages and mantle Re-Os systematics. *Earth Planet. Sci. Lett.* **160,** 311–266.

Pearson D. G., Snyder G. A., Shirey S. B., Taylor L. A., CARLSON R. W., and SOBOLEV N. V. (1995d) Archaean Re-Os age for Siberian eclogites and constraints on Archaean tectonics. *Nature* **374,** 711–713.

REISBERG L. and LORAND J. P. (1995) Longevity of subcontinental mantle lithosphere from osmium isotope systematics in orogenic peridotite massifs. *Nature* **376,** 159–162.

RICHARDSON S. H., ERLANK A. J., and HART S. R. (1985) Kimberlite-borne garnet peridotite xenoliths from old enriched subcontinental lithosphere. *Earth Planet. Sci. Lett.* **75,** 116–128.

RICHARDSON S. H., GURNEY J. J., ERLANK A. J., and HARRIS J. W. (1984) Origin of diamonds in old enriched mantle. *Nature* **310,** 198–202.

RICHARDSON S. H., HARRIS J. W., and GURNEY J. J. (1993) Three generations of diamonds from old continental mantle. *Nature* **366,** 256–258.

ROE G. D. (1964) Rubidium-strontium analyses of ultramafic rocks and the origin of peridotites. Ph.D. thesis, Massachusetts Institute of technology.

RUDNICK R. L., MCDONOUGH W. F., and CHAPPELL B. W. (1993) Carbonatite metasomatism in the northen Tanzanian mantle: petrographic and geochemical characteristics. *Earth Planet. Sci. Lett.* **114,** 463–475.

RUDNICK R. L., MCDONOUGH W. F., and ORPIN A. (1994) Northern Tanzanian peridotite xenoliths: a comparison with Kaapvaal peridotites and inferences on metasomatic interactions. In *Proc. 5th Int. Kimb. Conf.,* Vol. 1 (eds. H. O. A. MEYER and O. H. LEONARDOS), pp. 336–353. CRPM.

SCHULZE D. J. (1989) Constraints on the abundance of eclogite in the upper mantle. *J. Geophys. Res.* **94,** 4205–4212.

SHIMIZU N., POKHILENKO N. P., BOYD F. R., and PEARSON D. G. (1997) Geochemical characteristics of mantle xenoliths from the Udachnaya kimberlite pipe. *Russian J. Geology Geophys.* **38,** 194–205.

SHIREY S. B. (1991) The Rb-Sr, Sm-Nd and Re-Os isotopic systems: A summary and comparison of their applications to the cosmochronology and geochronology of igneous rocks. In *Application of radiogenic isotope systems to problems in geology,* Vol. **19** (eds. L. HEAMAN and J. LUDDEN), pp. 109–166. Mineralogical Association of Canada.

SHIREY S. B., CARLSON R. W., GURNEY J. J., and HERDEN L. V. (1998) Re-Os systematics of eclogites from Roberts Victor: Implications for diamond growth and Archean tectonic processes. *Ext. Abstract 7th Int. Kimberlite Conf. Cape Town.* pp. 808–810.

SHIREY S. B. and WALKER R. J. (1998) The Re-Os isotope system in cosmochemistry and high-temperature geochemistry. *Ann. Rev. Earth Planet. Sci.*

SMOLIAR M. I., WALKER R. J., and MORGAN J. W. (1996) Re-Os ages of Group IIA, IIIA, IVA and IVB iron meteorites. *Science* **271,** 1099–1102.

SNOW J. E. and REISBERG L. (1995) Erratum of "Os isotopic systematics of the MORB mantle; results from altered abyssal peridotites". *Earth Planet. Sci. Lett.* **136,** 723–733.

SNYDER G. A., JERDE E. A., TAYLOR L. A., HALLIDAY A. N., SOBOLEV V. N., and SOBOLEV N. V. (1993) Nd and Sr isotopes from diamondiferous eclogites, Udachnaya kimberlite pipe, Yakutia, Siberia: Evidence of differentiation in the early Earth? *Earth. Planet. Sci. Lett.* **118,** 91–100.

SOBOLEV N. V. (1977) *Deep-Seated Inclusions in Kimberlites and the Problem of the Composition of the Upper Mantle.* Amer. Geophys. Union, Washington, 279 pp.

STOLZ A. J. and DAVIES G. R. (1988) Chemical and isotopic evidence from spinel lherzolite xenoliths for episodic metasomatism of the upper mantle beneath southeast Australia. *J. Petrol. Special Lithosphere Issue,* 303–330.

STOSCH H.-G. and SECK S. A. (1980) Geochemistry and mineralogy of two spinel peridotite suites from Dreiser Weiher, West Germany. *Geochim. Cosmochim. Acta* **44,** 457–470.

STUEBER A. M. and MURTHY V. R. (1966) Sr isotope and alkali element abundances in ultramafic rocks. *Geochim. Cosmocim. Acta* **33,** 543–553.

SWEENEY R.J., THOMPSON, A.B., and ULMER, P. (1993) Phase relations of a natural marid composition and implications for MARID genesis, lithospheric melting and mantle metasomatism. *Contrib. Mineral. Petrol.* **115,** 225–241.

TAYLOR L. A., SNYDER G. A., CROZAZ G., SOBOLEV V. N., YEFIMOVA E., and SOBOLEV N. V. (1996) Eclogitic inclusions in diamonds: Evidence of complex mantle processes over time. *Earth Planet. Sci. Lett.* **142,** 535–551.

THALHAMMER O. A. R., PROCHASKA W., and MUEHLHAUS H. W. (1990) Solid inclusions in chrome-spinels and platinum group element concentrations from the Hochgroessen and Kraubath ultramafic massifs (Austria). *Contrib. Mineral. Petrol.* **105**(1), 66–80.

VOLKENING J., WALCZYK T., and HEUMANN K. G. (1991) Osmium isotope ratio determinations by negative thermal ionization mass spectrometry. *International Journal of Mass Spectrometry and Ion Processes* **105,** 147–159.

WALKER R. J., CARLSON R. W., SHIREY S. B., and BOYD F. R. (1989a) Os, Sr, Nd, and Pb isotope systematics of southern African peridotite xenoliths: Implications for the chemical evolution of subcontinental mantle. *Geochim. Cosmochim. Acta* **53,** 1583–1595.

WALKER R. J., SHIREY S. B., HANSON G. N., RAJAMANI V., and HORAN M. F. (1989b) Re-Os, Rb-Sr and O isotopic systematics in of the Kolar schist belt, Karnataka, India. *Geochim. Cosmochim. Acta* **53,** 3005–3013.

WALKER R. J., SHIREY S. B., and STECHER O. (1988) Comparative Re-Os, Sm-Nd and Rb-Sr isotope and trace element systematics for Archean komatiite flows from Munro Township, Abitibi Belt, Ontario. *Earth Planet. Sci. Lett.* **87,** 1–12.

ZHURAVLEV A. Z., LAZ'KO Y. Y., and PONOMARENKO A. I. (1991) Radiogenic isotopes and REE in garnet peridotite xenoliths from the Mir kimberlite pipe, Yakutia. *Geokhimiya* **7,** 982–994.

ZINDLER A. and HART S. R. (1986) Chemical Geodynamics. *Ann. Rev. Earth Planet. Sci.* **14,** 493–571.

ZINDLER A. and JAGOUTZ E. (1988) Mantle cryptology. *Geochim. Cosmochim. Acta* **52,** 319–333.