

ISOTOPIC EVOLUTION OF THE MANTLE IV

THE ORIGIN OF MANTLE PLUMES AND THE COMMON COMPONENT IN PLUMES

Determining how the various geochemical reservoirs of the mantle have evolved is among the most vexing problems in geochemistry. The principal observation to be explained is that mantle plumes invariably have less depleted isotopic signatures than MORB, and the isotopic compositions of some indicate net enrichment in incompatible elements. As we saw in the previous lecture, mantle plumes were initially thought to consist of primitive mantle (e.g., Schilling, 1973). As we found, mixing between primitive and depleted mantle can explain the Sr and Nd isotopic compositions of some plumes, but virtually none of the Pb isotope data can be explained this way, nor are the trace element compositions of OIB consistent with plumes being composed of primitive mantle. Indeed, although 'primitive mantle' has proved to be a useful hypothetical concept, no mantle-derived basalts or xenoliths have appropriate compositions to be 'primitive mantle' or derived from it. It is possible, and indeed likely, that no part of the mantle retains its original, primitive, composition.

Hofmann and White (1982) suggested mantle plumes obtain their unique geochemical signature through deep recycling of oceanic crust (Figure 19.1). Partial melting at mid-ocean ridges creates oceanic crust that is less depleted in incompatible elements than the depleted upper mantle. The oceanic crust is apparently inevitably subducted as virtually none is preserved at the surface, so it clearly is recycled back into the mantle. The question is what becomes of it? Hofmann and White noted that once oceanic crust reaches depths of about 90 km it converts to eclogite as is more dense than peridotite. Because it is rich in Fe, and garnet-forming components, it remains denser than peridotite at all depths greater than 90 km (except, perhaps, just at the 660 discontinuity due to the negative Clapeyron slope). Thus it will sink to the base of the convecting region. If the mantle is chemically stratified, with a Fe-rich lower mantle, the oceanic crust would sink to a thermal boundary layer at the 660 discontinuity. If the entire mantle convects as a single unit, that is if it is not chemically stratified, ocean crust will sink to base of the mantle, becoming embedded in thermal boundary layer there (D'). Hofmann and White originally suggested radioactive heating would ultimately cause it to become buoyant. It now seems more likely that heat conducted into it from below, from either the lower mantle or the core, may be more important. In any case, upon sufficient heating, it rises, melting near the surface to create intraplate volcanos.

As we shall see in a subsequent lec-

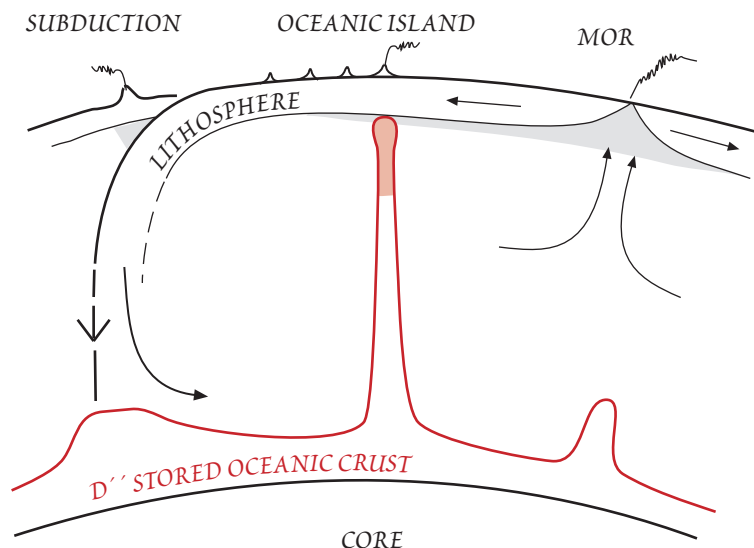


Figure 19.1. Cartoon illustrating the oceanic crustal recycling model of Hofmann and White (1982). Oceanic crust is transformed into eclogite and post-eclogite assemblages upon subduction. It separates from the less dense underlying lithosphere and sinks to the deep mantle where it accumulates. Eventually, it becomes sufficiently hot to form plumes that rise to the surface, producing oceanic island volcanism. After Hofmann and White (1982).

ture, sediment appears often, if not always, to be subducted along with the oceanic crust. This subducted sediment would also contribute to incompatible element enrichment of plumes. Varying amounts, types, and ages of subducted sediment may be responsible for some of the geochemical variety displayed by plumes. Since sediment is ultimately derived from the continents, recycling of oceanic crust, continental crust, mantle plumes, and oceanic island basalts may all be part of a grand geochemical cycle. Tectonic erosion of continental crust in subduction zones and delamination of continental crust may be alternative mechanisms for deep recycling of continental crust.

Because the major element chemistry of OIB is often similar to that of MORB, it seems unlikely plumes could be composed entirely of recycled oceanic crust. Presumably they consist primarily of peridotite, with perhaps at most a few tens of percent oceanic crust. However, because the oceanic crust has much higher incompatible element concentrations than peridotite, it provides most of the isotopic and incompatible element "flavor" of plumes.

Trace elements provide some evidence that some plumes contain a recycled sediment component. The Pb/Ce ratio is particularly useful indicator of the presence of sediment for several reasons. First, the Pb/Ce ratio is comparatively uniform in MORB and many OIB. Second, the Pb/Ce ratio is an order of magnitude higher in sediments than in the mantle (typically, Ce/Pb is greater than 0.3 in sediments and <0.04 in MORB). Third, sediments have two orders of magnitude higher concentrations of Pb (typically 20 ppm or more) than the mantle (less than 0.05 ppm), so that addition of even small amounts of sediment to mantle shifts the Pb/Ce ratio. Finally, the near constancy of Pb/Ce in most basalts suggests this ratio is not significantly changed in by magmatic processes such as partial melting and fractional crystallization. There is a strong correlation between isotope ratios and Pb/Ce in basalts from the Society Islands. As Figure 19.2 shows, the correlation is consistent with mixing between recycled sediment and mantle.

An alternative origin for mantle plumes was proposed by McKenzie and O'Nions (1983). They noted the common evidence for incompatible element enrichment in the subcontinental lithosphere (which we discuss in the next section) and suggested this material may occasionally become delaminated. Because it is cold, it would also sink to the deep mantle. As in the case of the Hofmann and White model, it would be stored in a thermal boundary layer, heated, and rise in the form of mantle plumes. However, as we shall see in the next section, recent studies have shown that the Os isotope composition of the subcontinental lithosphere is quite distinctive, and quite different from that of mantle plumes, as we shall see in the next section. This rather strongly suggests that "delaminated" subcontinental lithosphere does not contribute to mantle plumes. Because mantle plumes come in several geochemical varieties, it is possible that both mechanisms operate. Indeed, other as yet unknown processes may be involved as well.

Most oceanic islands show some variability in their isotopic compositions, defining elongated arrays on plots of isotope ratios. Such elongated arrays suggest mixing. This raises the rather obvious question of what is mixing with what. In a few cases, the Comores are a good example, the elongate arrays seems

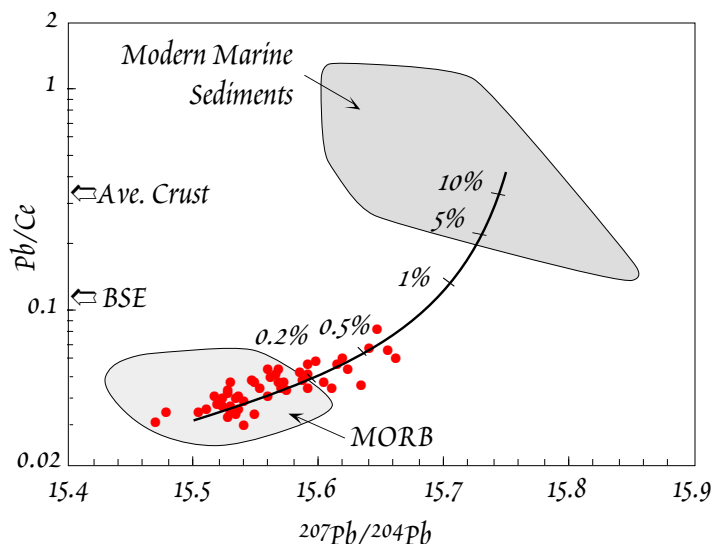


Figure 19.2. Pb/Ce and $^{207}\text{Pb}/^{204}\text{Pb}$ in basalts from the Society Islands studied by White and Duncan (1996). A calculated mixing line between depleted mantle and sediment passes through the data. Also shown are estimated Pb/Ce ratios of average continental crust and bulk silicate Earth (BSE).

to reflect mixing between different plume reservoirs. The Comores data defines a trend in isotopic space that appears to be the result of mixing between an EMI and a HIMU component. In other cases, such as the Galapagos, the plume is clearly mixing with the depleted upper mantle. However, in many cases, the cause of the isotopic variation is less clear.

Hart et al. (1992) plotted oceanic basalt isotope data in three dimensions, with axes of $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, and $^{206}\text{Pb}/^{204}\text{Pb}$ (Figure 19.3). Principal component analysis confirmed that 97.5% of the variance in the oceanic basalt isotope data could be accounted for by these ratios (leaving 2.5% to be accounted for by $^{207}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$, and $^{176}\text{Hf}/^{177}\text{Hf}$). They found that most of the data plotted within a tetrahedron defined by the hypothetical end members EM1, EM2, HIMU, and DMM. They also noticed that many arrays were elongated toward the base of this tetrahedron on the DMM-HIMU join. From this they concluded that in many, if not most cases, mantle plumes appear to mixing with a previously unidentified component, which they named "FOZO" (an acronym for Focal Zone), that has the approximate isotopic composition of $^{87}\text{Sr}/^{86}\text{Sr} = 0.7025$, $\epsilon_{\text{Nd}} = +9$, and $^{206}\text{Pb}/^{204}\text{Pb} = 19.5$. They suggested that FOZO is the isotopic composition of the lower mantle and that plumes rising from the core mantle boundary entrain and mix with this lower mantle material. It is unclear, however, whether such a composition for the lower mantle can be fitted to reasonable isotopic mass balances for the Earth. A rather similar idea was presented by Farley et al. (1992), who point out that this additional component, which they called "PHEM", seems to be associated with high $^3\text{He}/^4\text{He}$. White (1995) concurred with these ideas, but argued that the $^{87}\text{Sr}/^{86}\text{Sr}$ of FOZO is higher, and the ϵ_{Nd} lower, than estimated by Hart et al. (1992) and probably closer to the values chosen by Farley et al. (1992).

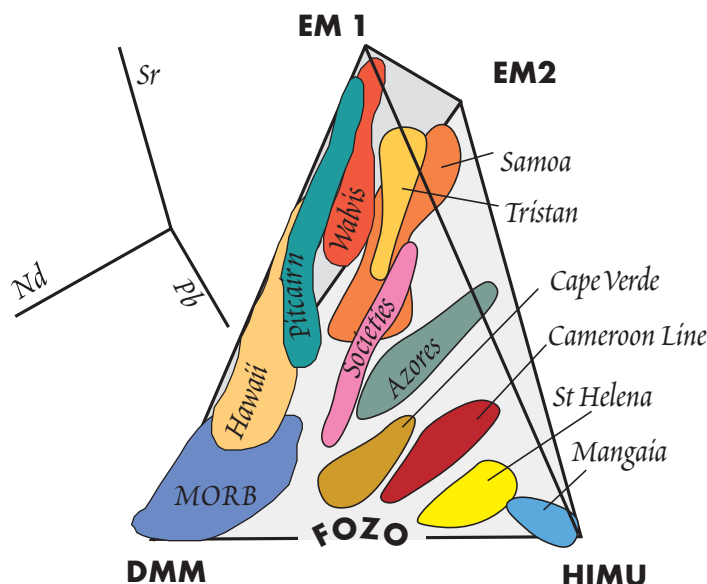


Figure 19.3. Three dimension plot of $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, and $^{206}\text{Pb}/^{204}\text{Pb}$. Most oceanic basalt data plot within a tetrahedron defined by the composition of EM1, EM2, HIMU, and DMM components. Oceanic islands and island chains tend to form elongate isotopic arrays, many of which seem to point toward a focal zone (FOZO) at the base of the tetrahedron. Adapted from Hart et al. (1992).

THE SUBCONTINENTAL LITHOSPHERE

Figure 19.4a shows Sr and Nd isotopic variations in continental basalts. The data span a much larger range than oceanic basalts. Some, but not all, of this variation reflects the effects of assimilation of continental crust on the isotopic signatures of the mantle-derived magmas. Assimilation effects can be avoided by considering only the data on peridotite xenoliths in continental basalts, the data for which is shown in Figure 19.4b. As may be seen, the range of values is reduced, but nevertheless much greater than that observed in oceanic basalts. One needs be cautious in directly comparing the heterogeneity observed in xenolith data to basalt data because the two represent different scales of sampling of the mantle. Basalts are created by melting of regions that have characteristic scales of tens of kilometers, and perhaps greater in some cases. The magma generation process undoubtedly averages out very small scale heterogeneities. Xenoliths, on the other hand, have characteristic dimensions of centimeters. Thus variations in isotope ratios in basalts reflect large scale heterogeneity in the mantle, while xenoliths reflect small scale heterogeneity. Despite this, it appears that the

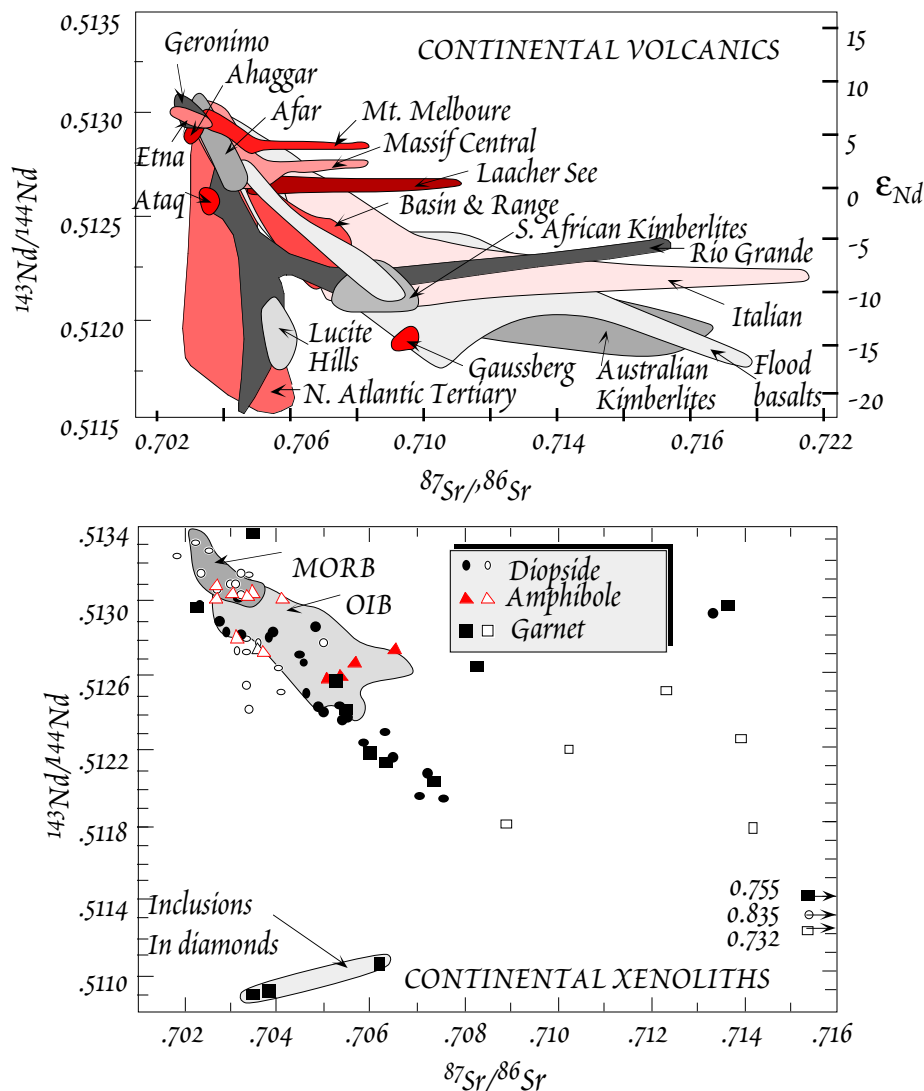


Figure 19.4. (a) top. Sr and Nd isotope ratios in continental basalts. (b) bottom. Sr and Nd isotope ratios in xenoliths in continental basalts. After Zindler and Hart (1986).

subcontinental lithosphere is more heterogeneous, even on relatively large scales, than is the suboceanic mantle.

It appears that the subcontinental lithosphere can be quite old, and, at least in some cases, has the same age as the crust it underlies. Studies of xenoliths and inclusions in diamond from South African kimberlites suggests the mantle is 3–3.5 Ga old in this region, ages similar to that of the South African craton. The greater isotopic heterogeneity of the subcontinental lithosphere probably reflects its long term stability, which allows variations in parent-daughter ratios to be expressed in variations in radiogenic isotope ratios. Convective mixing in the suboceanic mantle will tend to destroy heterogeneity in it.

Though many xenoliths have isotopic compositions indicating incompatible element enrichment, others xenoliths show parts of the subcontinental lithosphere can be extremely incompatible element depleted. ϵ_{Nd} values of +500 have been recorded in garnets in eclogites from the Roberts Victor mine kimberlite. These eclogites appear to be rafts of subducted oceanic crust stranded in the subcontinen-

tal lithosphere over 3 Ga ago, an interpretation supported by highly variable oxygen isotope ratios in the eclogites. They apparently suffered extreme LRE depletion around that time, perhaps by a small degree of melting or dehydration after subduction. Much of the subcontinental lithosphere may consist of mantle from which partial melts have been extracted to form the continental crust. Interesting, when the upper mantle undergoes melting both the melt and residual solid will have a density that is less than the original material. This residue is less dense because garnet, a very dense phase, is preferentially removed during melting. Thus both the crustal and mantle parts of the continental lithosphere have relatively low density, which may help to explain its stability.

If the subcontinental lithosphere is residual material from which melts have been extracted, why are xenoliths and basalts with "enriched" isotopic signatures so common? What process or processes could have produced this incompatible element enrichment of many parts of the subcontinental lithosphere? One possibility, first suggested by Brooks et al. (1976), is that partial melts from mantle plumes migrate upward into the lithosphere, where they freeze. The extent to which upwelling mantle can melt will depend on the depth to which it rises. Where continental lithosphere prevents plumes from rising above 200 km depth or so, the degree of melting is likely to be quite small, meaning the melts would be quite incompatible element enriched. These melts could then migrate upward into the lithosphere, reacting with it and enriching it in incompatible elements. Yet another possibility is that hydrous fluids released during dehydration of subducting oceanic lithosphere may migrate into the continental lithosphere and react with it

(Hawkesworth, 1990). Judging from studies of island arc magmas, such fluids appear to be particularly enriched in soluble incompatible elements, such as the alkalis and alkaline earths. These processes in which lithosphere reacts with melts or fluids is known as *mantle metasomatism**. Petrographic studies of some xenoliths clearly reveal features, such as the secondary growth of hydrous minerals such as phlogopite (Mg-rich mica) and richterite (an alkali-rich amphibole) indicative of such metasomatism.

Recent studies of Os isotope ratios in xenoliths from the subcontinental lithosphere have been particularly enlightening. Most xenoliths derived from below regions of old continental crust have low Os isotope ratios, which imply that low Re/Os ratios were established long

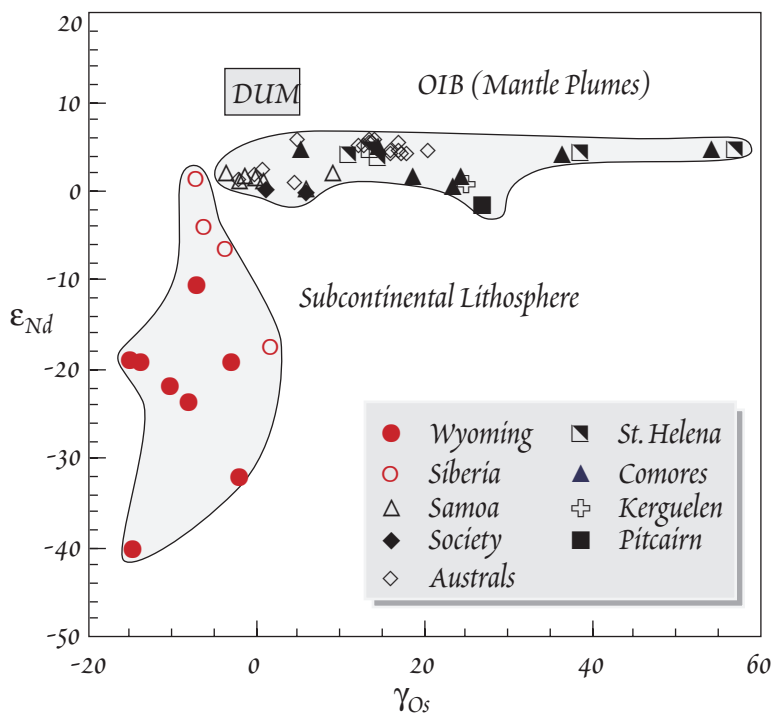


Figure 19.5. ϵ_{Nd} vs. γ_{Os} in xenoliths from the subcontinental lithosphere and oceanic island basalts. Despite low and variable ϵ_{Nd} , the subcontinental lithosphere appears to be characterized by systematically low γ_{Os} (γ_{Os} is the percent deviation of the $^{187}Os/^{188}Os$ ratio from the chondritic value).

* Metasomatism is defined in metamorphic petrology as a subsolidus process that results in a net change in the composition of the metamorphic rock. Usually this is accomplished by the flow of aqueous solutions through the rock. The term 'mantle metasomatism' is widely used to refer to reaction between rock and silicate liquid as well as between rock and aqueous solution.

ago. The low Re/Os ratios are consistent with the idea that this material undergone partial melting in the past, since Re is moderately incompatible, and would partition into the melt, while Os is highly compatible, and would remain in the solid. Despite their low $^{187}\text{Os}/^{188}\text{Os}$ ratios, many of these same xenoliths have quite low ϵ_{Nd} (Figure 19.5). The low ϵ_{Nd} suggests incompatible element enrichment, and hence would appear to be inconsistent with the high $^{187}\text{Os}/^{188}\text{Os}$ ratios (Figure 19.5). The explanation of this paradox appears to be that Os is was not affected by the metasomatism that enriched these regions in incompatible elements and decreased Sm/Nd ratios (e.g., Carlson and Irving, 1994). Apparently, neither Re nor Os are transported effectively by metasomatic fluids. If the fluids are aqueous, this is perhaps not surprising, since these elements have low solubilities under reducing conditions. If the fluids are silicate melts, it is unclear why they do not transport Re. The answer may have to do with dependence of the Re partition coefficient on composition and oxygen fugacity.

Regardless of why it arises, these unusual Os-Nd isotope systematics provide the continental lithosphere with a distinctive isotopic signature, and geochemists a means of identifying continental lithosphere. In an earlier section, we discussed the hypothesis of McKenzie and O'Nions that subcontinental lithosphere can delaminate and sink to the bottom of the mantle where it is incorporated into mantle plumes. The distinctive isotope signatures of mantle plumes on the one hand and subcontinental lithosphere on the other (Figure 19.5) is inconsistent with this hypothesis.

Continental flood basalts provide another interesting example. These are huge outpourings of basaltic lava that apparently occurred within relatively short time intervals, a few million years and possibly less in some cases. The great oceanic plateaus, such as Ontong-Java and Kerguelen are the marine equivalents. A number of continental flood basalts can be clearly associated with mantle plumes. For example, the Deccan Traps erupted 65 million years ago when India lay directly over the Reunion mantle plume, and the Parana in Brazil and Etendeka in Namibia were erupted 130 million years ago over the Tristan da Cunha mantle plume when Africa and South America were rifting. These observations have given rise to the idea that continental flood basalts are produced when new mantle plumes arrive at the surface. Fluid dynamic experiments and simulations show that new plumes will have large bulbous heads. When the heads arrive in the upper mantle, they melt, producing a pulse of volcanism. Others, however, have argued on geochemical grounds that continental flood basalts are produced by melting of the continental lithosphere. Because mantle plumes and continental lithosphere have such different Os and Nd isotope signatures, Os-Nd systematics provide a means of discriminating between these possibilities. Because of the difficulties in determining Os isotope ratios in basalts, only one such study has been carried out thus far. In it, Ellam et al. (1992) found that the Karroo flood basalts, erupted in South Africa 190 million years ago, have Os and Nd isotope compositions that lie on mixing lines connecting mantle plume compositions and continental lithosphere compositions (Figure 19.6). Thus at least in this case, then both a mantle plume and continental lithosphere appear to have contributed to the magmas. The data also demonstrate the assimilation of continental crust cannot explain the low ϵ_{Nd} observed in these basalts.

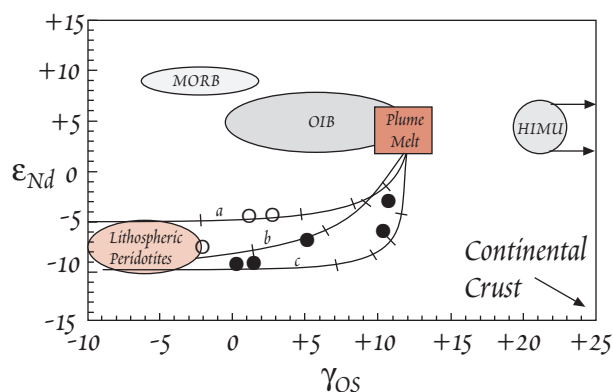


Figure 19.6. ϵ_{Nd} of picritic basalts from the Karroo flood basalts plotted against γ_{Os} . The fall between the fields. Three lines, illustrating 3 mixing models (different concentrations of Os and Nd in the end-members), connect the fields of xenoliths from the subcontinental lithosphere and oceanic island basalts (i.e., mantle plumes). The data fall close to these lines, suggesting they are mixtures of melts of lithosphere and a mantle plume. After Ellam et al. (1992).

ISOTOPIC EVOLUTION OF THE CRUST & MANTLE THROUGH TIME

An important and as yet largely unanswered question is how the mantle chemistry has changed through time; in other words, how did the chemical variations we observe today originate? We know the MORB source has been depleted in incompatible elements through extraction of partial melts. Presumably, this depletion is related to growth of the continental crust. Since the MORB source, or the *depleted mantle* as it is called, constitutes a major part of the mantle, let's consider evolution of this reservoir first. We can start by asking how the crust has grown with time, i.e. what is the rate of crustal growth; the mechanism of crustal growth is even less well understood. As Figure 19.7 indicates, there are a variety of possible answers to this question. These can be broken into three types: (1) more or less linear growth through time, such as the curve marked O'N (= O'Nions), (2) less than linear growth, e.g., curve V & J (=Verzier and Jansen) and H & R (Hurley and Rand), and (3) early rapid growth followed by later slow growth or no growth, e.g., curve AM (=Armstrong). The present consensus is that continental growth has been either linear or more rapid in the early part of Earth's history; late continental growth models do not appear to be consistent with the presently available data. One of the most provocative models is that of the late R. L. Armstrong. He argued the crust reached its present size by about 4.0 Ga. Since then, new additions to crust have been balanced by losses through erosion and subduction to the mantle. A more extreme model is that of Fyfe (curve F), in which the recycling rate is greater than the crust creation rate in the latter part of Earth history.

Let's consider the effect these different continental growth models might have on the isotopic evolution of the mantle. The reason we want to consider isotope ratios is that, due to the time-integrating effect, present day mantle isotope ratios are path-dependent, element concentrations or ratios are, in general, path-independent. To understand this, consider 3 simple models of mantle evolution. In case 1, partial melting at 4.0 Ga increases the Sm/Nd of the mantle by 20%. Case 2, several melting events over time increase Sm/Nd by 20%. In case 3, partial melting 100 Ma ago increases Sm/Nd by 20%. All three cases result in identical present day mantle Sm/Nd ratios 20% lower than chondrites. But the three different models lead to very different Nd isotope ratios. $^{143}\text{Nd}/^{144}\text{Nd}$ is highest in case 1, intermediate in case 2 and only slightly different from chondritic in case 3. Thus isotopic composition of the depleted mantle is a strong function of the rate and timing of crustal growth.

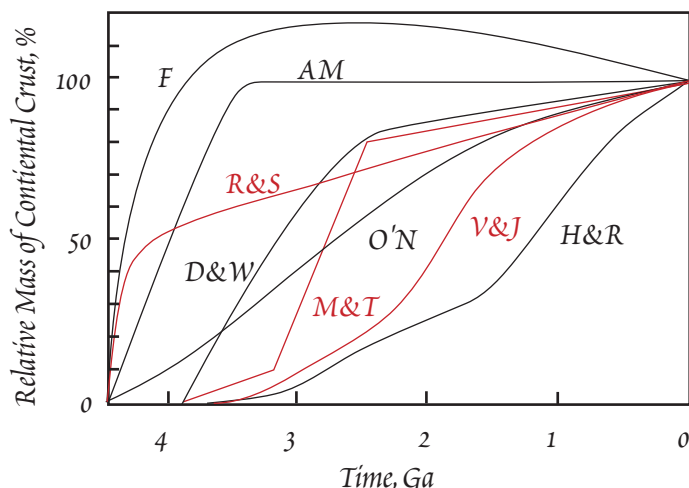


Figure 19.7. Models of the rates of crustal growth. AM: Armstrong (1981), R&S: Rymer and Schubert (1984), F: Fyfe (1978), D & W: DePaolo and Wasserburg (1979), M & T: McLennan and Taylor (1982), O'N: O'Nions and Hamilton (1981), V & S: Veizer and Jansen (1979), H & R: Hurley and Rand (1969).

While isotope ratios in modern basalts and xenoliths provide some indication of the evolutionary aspect of mantle geochemistry, additional information can be obtained by examining how isotopic compositions of mantle-derived magmas have changed through time. To illustrate this, consider three other scenarios for evolution of the crust-mantle evolution. In the first scenario, the continental crust is created in one pulse at 4.5 Ga. The mantle Sm/Nd ratio increases at this time and remains fixed thereafter. In this case, ϵ_{Nd} in the depleted mantle should increase linearly through time (curve A in Figure 19.8; radiogenic growth is in general non-linear, but in this case, the half-life of ^{147}Sm is so long that the $e^{\lambda t}$ approximates $1 + \lambda t$ very well, and the growth is effectively linear). In the second scenario, the crust grows continu-

ously through time. The Sm/Nd ratio in the mantle therefore increases with time. In this case ϵ_{Nd} follows a concave upward path (curve B in Figure 19.8). In the third case, crust is created at 4.5 Ga, but after that there is a net return of crust to the mantle, so that the Sm/Nd ratio in the mantle decreases with time. In this case, ϵ_{Nd} follows a concave downward path (curve C in Figure 19.8).

There are some limitations to isotopic studies of ancient mantle-derived rocks. The first is the scarcity of appropriate samples. The second is that we often do not know the tectonic environment in which the magmas were erupted or implaced. A third is that such samples are preserved only in the continental crust, where there is the danger of assimilation. Finally, the weathering and metamorphism can affect the isotopic compositions. For the latter reason, Nd and Hf isotope systems are most useful in such studies because they are relatively robust with respect to these effects.

Now let's consider how Nd and Hf isotope ratios actually have grown in the mantle. Figure 19.9 shows initial ϵ_{Nd} values as a function of time for rocks containing a large mantle component at the time of formation. There are several features of the data that are somewhat surprising. First, even the oldest known rocks appear to have been derived from a mantle that had experienced LRE depletion at significantly earlier (a few hundred million years) times. Second, if we view those rocks with maximum ϵ_{Nd} at any given time as reflecting the composition of the mantle and others as having experienced crustal contamination, then the mantle does not seem to have become increasingly LRE depleted with time. The data are more consistent with a one-time depletion event near 4.55 Ga and approximately closed system (or at least constant Sm/Nd) evolution since then (Model A in Fig. 19.8).

The discovery that 3.8 Ga rocks had ϵ_{Nd} between +2 and +4 was particularly surprising. The depletion of the source of these rocks suggests the existence of a complimentary enriched reservoir such as the continental crust, which must have formed several hundred million years earlier (because time is required before high Sm/Nd ratios are manifest by high ϵ_{Nd}). However, there was, and is, precious little evidence for significant amounts of crust several hundred Ma older than 3.8 Ga. The zircons in quartzite from the Jack Hills and Mt. Narryer and a very small volume from the Great Slave Province are the only bits of continental crust as older or older than 4.0 Ga that have been identified to date. If significant continental crust was created before 4.0 Ga, it has since been largely destroyed.

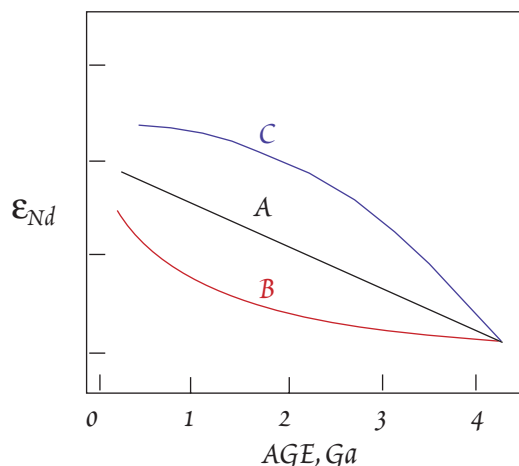


Figure 19.8. Evolution of ϵ_{Nd} in the mantle for three scenarios of crustal growth. A: all crust is created at 4.5 Ga, B: continuous crust creation through time, C: crust creation at 4.5 Ga followed by net return of crust to the mantle.

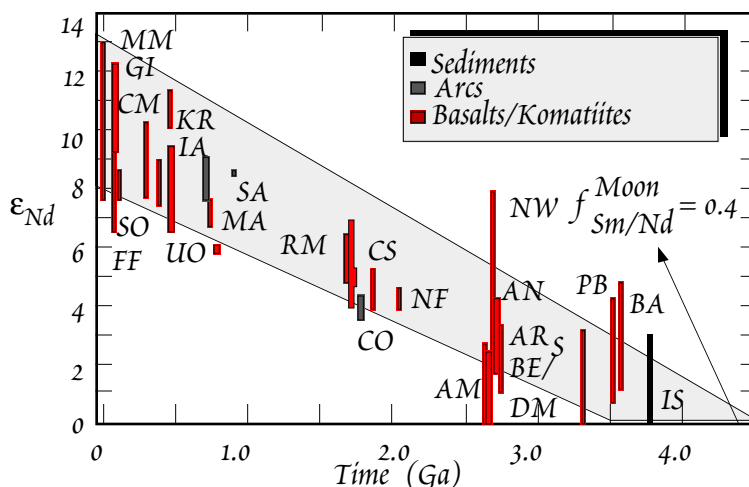


Figure 19.9. ϵ_{Nd} in rock suites for which there is little evidence of involvement of much older crust in their genesis (after Smith and Ludden, 1989).

Lecture 19

Spring 1998

Recent Hf isotope studies of some of the oldest rocks, the Isua gneisses from Greenland (3.8 Ga), suggests that the high positive initial ϵ_{Nd} may have been disturbed by subsequent metamorphism. ϵ_{Nd} and ϵ_{Hf} are generally well correlated with ϵ_{Hf} values being about twice those of ϵ_{Nd} . Thus, the samples with ϵ_{Nd} of +4 should have ϵ_{Hf} of about +8. Vervoort et al. (1996) found that ϵ_{Hf} are only around +4. Thus while the Hf isotope ratios confirm that mantle depletion occurred early, it does not appear to have been as severe as suggested by some of the Nd isotope data.

There is also some Pb isotope evidence for very early mantle differentiation. Figure 19.10 shows initial Pb isotope ratios from sulfide ores associated with submarine volcanic rocks that erupted in the Abitibi Belt of Canada around 2.7 Ga ago. The data plot virtually along the 2.7 Ga Geochron (the Geochron as it was 2.7 Ga ago). The most straightforward interpretation of this data is that it reflects heterogeneity in the mantle that dates from the time the Earth formed, or shortly thereafter.

If the crust has grown through time, we would have expected the upper mantle to have become correspondingly increasingly depleted, and to have followed an ϵ_{Nd} evolution along a concave upward curve. This does not seem to be the case. This point is illustrated in Figure 19.11 from DePaolo (1983). Though there is considerably more data available now than when that paper was written, and DePaolo's curved evolution lines may no longer be appropriate, his main point remains valid: ϵ_{Nd} and ϵ_{Hf} do not follow concave upward evolution paths. There are two alternative explanations. In the first scenario, the crustal mass has remained relatively constant since very early in Earth's history. Although new portions of crust have been added, they have been balanced by an equal amount of crust eroded and recycled into the mantle. Alternatively, crustal mass may have grown, but the growth has resulted not in increased depletion of the upper mantle, but in a growth in the mass of the depleted mantle at the expense of primitive mantle. DePaolo (1983) argued for the first alternative (originally Armstrong's hypothesis) in his paper. Patchett and Chauvel wrote a short criticism of this paper pointing out the second alternative explained the observations equally well. Figure 19.12 is a

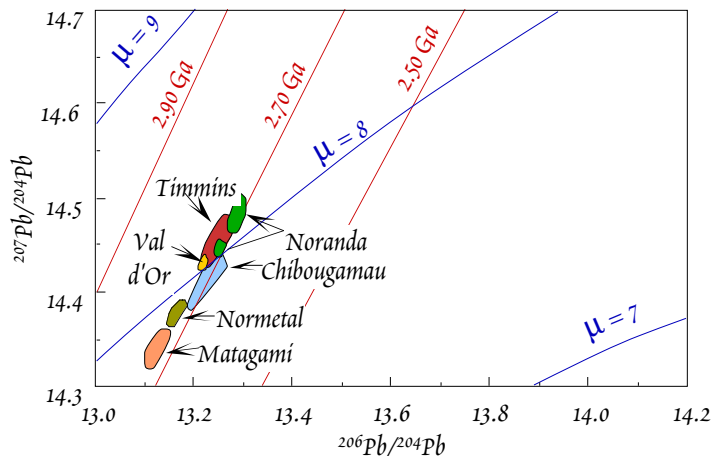


Figure 19.10. $^{207}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ plot showing Pb isotopic fields volcanic massive sulfide deposits from the Abitibi greenstone belt. Also shown in this diagram are single-stage Pb growth curves corresponding to μ values of 7, 8, and 9 and isochrons at 2.5, 2.7, and 2.9 Ga assuming an age for the Earth of 4.52 Ga. From Vervoort, et al. (1994).

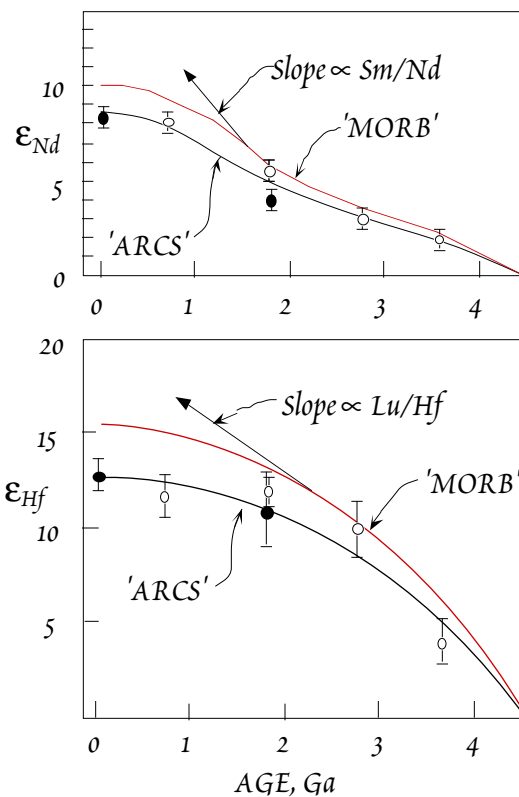


Figure 19.5. Initial ϵ_{Nd} and ϵ_{Hf} in mantle-derived rocks as a function of time (after DePaolo, 1983).

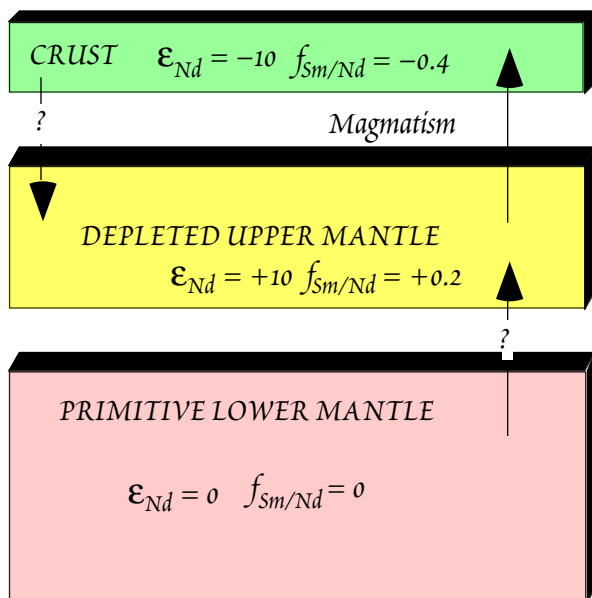


Figure 19.12. Box model illustrating how the isotopic composition of the depleted mantle could be buffered either by transfer of material from the crust or from primitive lower mantle.

subducted sediment.

Another phase of recycling, recycling of oceanic crust, may also be important in creating mantle heterogeneity. The oceanic crust is clearly recycled to the mantle. If the mantle cannot reassimilate this material and homogenize itself down to a scale less than the scale of melting in the mantle, then this process of creating and recycling oceanic crust will certainly create heterogeneity in the mantle.

Evolution of the Mantle Through Time: the Th/U ratio

We saw that initial ϵ_{Nd} ratios of mantle-derived rocks did not provide clear evidence of an increasing Sm/Nd ratio in the mantle through time such as we would expect if the mantle had become increasingly depleted. Allègre et al. (1986), however, have provided evidence that the Th/U ratio of the mantle has decreased with time. Figure 19.13 shows $^{208}Pb^*/^{206}Pb^*$ ratios and time-integrated Th/U ratios in komatiites* and

"box model" illustrating these choices. Both have similarities to the open system evolution models advocated by Galer and O'Nions (1985) and White (1993).

The apparent buffered evolution of the depleted mantle has thus been used to argue in favor of mantle evolution scenarios in which recycling of continental crustal material to the mantle, through subduction of sediment, plays an important role. More or less independently, this idea was proposed on the basis of isotopic variations observed in oceanic basalts (White and Hofmann, 1982). In particular, deviations from the linear correlation between Nd and Sr isotopes in oceanic basalts (called the "mantle array") can be modeled as mixing between depleted mantle and recycled

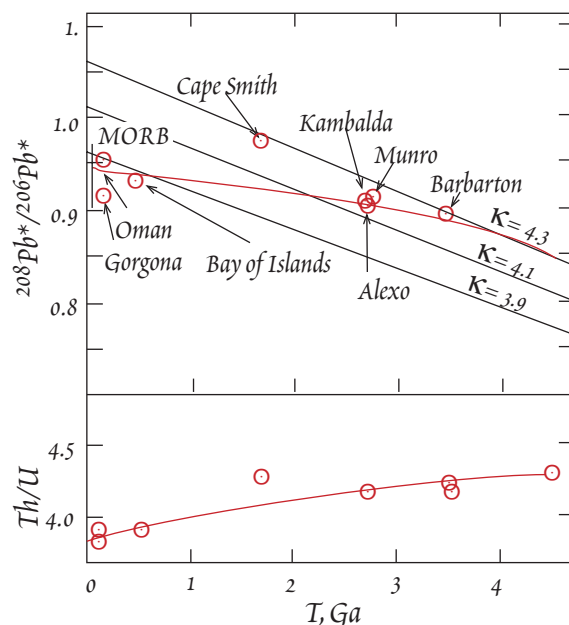


Figure 19.13 $^{208}Pb^*/^{206}Pb^*$ ratios and time-integrated Th/U ratios in komatiites and MORB and ophiolitic basalts as a function of age. The upper diagram also shows evolution of the $^{208}Pb^*/^{206}Pb^*$ ratio in closed systems with various values of κ . From Allègre et al. (1986).

* Komatiites are ultramafic lavas which occur mainly in the Archean and early Proterozoic. One early Tertiary occurrence, Gorgona Island on the coast of Columbia, is known. They are undoubtedly the result of comparatively high degrees of melting (~ 40%). Such a large degree of melting would leave a residua consisting almost exclusively of olivine. Because the incompatible element distribution coefficients of olivine are all very low, there should be essentially no fractionation of incompatible

basalts of various ages. The data suggest Th/U in the mantle has indeed decreased with time. Of particular importance is their result suggesting a bulk Earth Th/U ratio of 4.2. An increase of bulk Earth Th/U from the value of 3.9 assumed by Galer and O'Nions (1985) to 4.2 results in a substantially longer residence time of Pb in the steady-state upper mantle model of Galer and O'Nions. Allègre et al. also found that the time-integrated Th/U ratio appears to be closely correlated with initial ϵ_{Nd} in komatiites. They also found that the Th/U ratio in the komatiites (as determined by the $^{208}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ correlation) was correlated with Sm/Nd.

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