Chondrite Models for the Composition of the Earth's Mantle and Core

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Chondrite models for the composition of the Earth's mantle and core

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The terrestrial planets of the inner Solar System are believed to be broadly chondritic in composition. Here I suggest that the lithophile element composition of the terrestrial mantle, as approximated by primitive lherzolites having high Al/Si ratios and low Mg/Si ratios, was established by nebular rather than indigenous processes. The implications of this model include: (i) the Mg/Si ratio of the upper mantle is an instrinsic property of the bulk Earth and does not reflect differentiation of a terrestrial magma ocean; (ii) the Moon probably did not form by a giant impact on to the Earth; (iii) refractory lithophile elements should be 2.5–3.0 chondrites in the bulk silicate Earth; and (iv) silicon is not a major constituent of the Earth's core.

1. Introduction

The means by which the bulk silicate compositions of planets are derived are often quite convoluted. In the absence of primitive, undifferentiated samples, complex reconstructions are required (Anders 1977; Jagoutz *et al.* 1979; Wänke 1981; Jones 1984; Palme & Nickel 1985; Taylor & McLennan 1985; Ringwood *et al.* 1987; Jones & Delano 1989). Of the planets within the inner Solar System, the Earth is the only one for which we may actually have such primitive samples. And even for the Earth there is substantial disagreement as to how primitive these samples actually are!

Despite these complexities, a general consensus has emerged that rocky planets should be generally chondritic. Refractory lithophile elements such as Ca, Al, lanthanides (REE), and actinides should be present in chondritic relative proportions. However, less refractory elements such as Si and Mg may be slightly depleted. Moderately volatile elements such as Na and K may be more strongly depleted. And FeO and siderophile element concentrations are presumably determined by the redox state of the planet at the time of core formation.

Even under the auspices of these general guidelines, higher levels of complexity are still possible. For example, continued accretion after core formation may actually determine the levels of siderophile elements in the mantle, as opposed to core–mantle chemical equilibrium. (In fact, Wänke (1981) has reasoned that this is indeed the case since Ni and Co in the Earth's mantle are at *ca.* 0.2 X chondrites and the highly siderophile elements such as Os, Ir and Au are at *ca.* 0.006 X chondrites. This suggests that core formation occurred in stages with moderately siderophile elements such as Co losing their siderophile tendencies earlier in the core-forming process than did highly siderophile elements such as Ir. In this model core formation for Ni and Co ceased after about 80% of the Earth had accreted, whereas core formation for Au and Ir continued for more than 99% of the accretion process.) Further, the

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ostensibly most primitive samples of the Earth's mantle differ significantly from known chondrite classes. Is this because the Earth is a different flavour of chondrite or because even the most primitive samples have been processed in some way? Here I will suggest that our samples of the Earth's upper mantle indeed represent a distinct type of chondritic composition (similar to a particular class of chondrites termed CV) that primarily reflects nebular, as opposed to terrrestrial, processes. This view is in contradistinction to what I shall refer to as the 'standard model', which postulates that the Earth has CI-chondrite ratios of Mg/Si, Al/Si, and Ca/Al. (CI chondrites are closest in composition to the Sun (Anders 1971), which accounts for most of the mass of the Solar System.) I will then discuss three common modifications to the standard CI model that have been used to make theory jibe with observation. Finally, I will explore some consequences of the 'CV-like' chondrite model.

2. A nebular origin for the composition of the Earth's mantle

The bulk composition of the silicate portion of a planet may be approximated by knowing the concentration of only five elements: Al, Ca, Fe, Mg, and Si (actually the oxides of these elements). However, the FeO content of the Earth cannot be compared directly to chondrites because some Fe has been sequestered to the core. This leaves just Al, Ca, Mg, and Si. Figure 1, after Jagoutz *et al.* (1979), summarizes the Mg/Si and Al/Si ratios of (i) ultramafic nodules from the mantle (xenoliths entrained in basalts and diatremes), (ii) several varieties of chondrites, and (iii) various estimates of the composition of the bulk silicate Earth (BSE).

Chondrite compositions range from the low Mg/Si and Al/Si ratios of the enstatite (E) chondrites through CI to the refractory-enriched CK and CV chondrites, which have high Mg/Si and Al/Si ratios (Newsom 1995). A plot of Mg/Si against Ca/Si would appear quite similar. Perhaps the most important aspect of this diagram is the observation that nominally refractory elements such as Mg, Al, and Si can be fractionated by nebular processes. Although it has been successfully argued for some time that CI chondrites are more representative of solar composition than other chondrite types (Anders 1971), different chondrite types have distinctly different compositions, each of which is presumably equally valid in terms of choosing a *planetary*, as opposed to a *solar*, composition. The very fact that the Earth is depleted in volatiles compared to the Sun implies that fractionations between solar and planetary compositions are possible.

In addition, it is clear that there must be some nebular process that is capable of changing Mg/Si and Al/Si ratios in a well-defined way. The chondrite trend in figure 1 is not simple addition/subtraction of Si, because Mg/Si does not change as rapidly as Al/Si and the best fit line of the trend does not pass through the origin. Compositions lying along the trend are both enriched and deficient in silica relative to CI. Therefore, we may not only consider constructing planets from those chondrites we have sampled, but also from other, hypothetical compositions that we produced by the same nebular process (i.e. that lie along the nebular trend).

Compositions of representative mantle lhenzolites and harzburgites (BVSP 1981; Jagoutz *et al.* 1979; Nixon & Boyd 1973) are also plotted on figure 1. (Lherzolites are dominantly olivine but also contain both ortho- and clinopyroxene; harzburgites are similar but clinopyroxene is missing.) A line denoting olivine control has been drawn from the composition of an Fo_{90} olivine through those lherzolites closest to

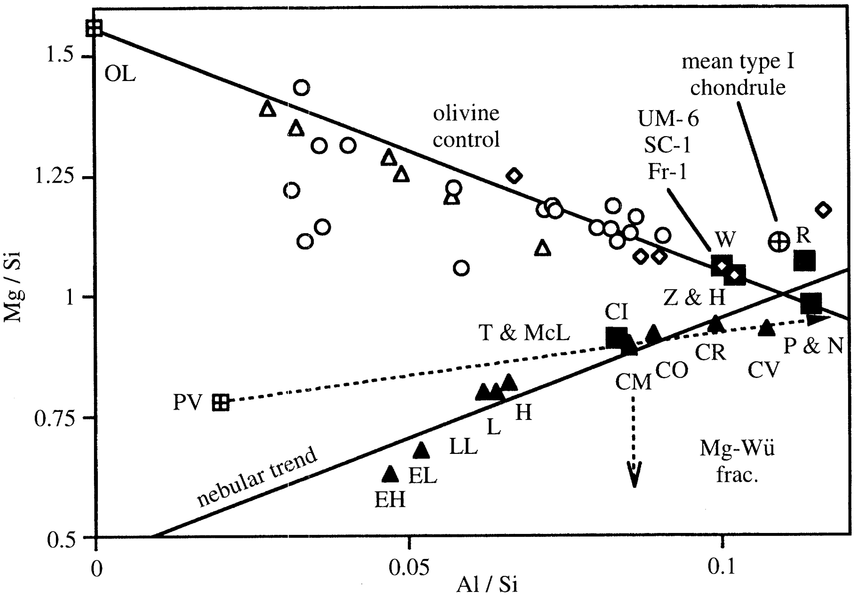

Figure 1. Mg/Si vs. Al/Si (wt.chondrites (▲), mantle xenoliths (△, ○, ◇), and various estimates (■) for the composition of the bulk silicate Earth (BSE). A line has been drawn through the most fertile (i.e. Al-rich) lherzolites and Fo_{90} olivine (OL). The composition of an experimental Mg-perovskite is given by PV. Vectors for the fractionation of a CI chondrite composition by Mg-perovskite and magnesiowüstite removal are also shown. The mean composition of Type I chondrules (Ferzberg, personal communication) and several estimates for the BSE fall near the intersection of the olivine (OL) control line and a least-squares regression of the chondrite data. Dashed lines from CI denote fractionation of MG-perovskite (PV) and magnesiowüstite (see text). BSE estimates: W, Wanke *et al.* (1984); R, Ringwood (1991); T & McL, Taylor & McLennan (1985); P & N, Palme & Nickel (1985); Z & H, Zindler & Hart (1986). Three fertile mantle lherzolites UM-6, SC-1 and Fr-1 fall near the BSE estimates of Wänke *et al.* (1984) and Zindler & Hart (1986).

the nebular trend. As basaltic components are extracted, the mantle becomes less and less 'fertile', and its composition, initially lherzolitic, becomes harzburgitic and finally approaches that of pure olivine (dunite). Thus, the nodules plotting furthest from olivine along the olivine control line are the most fertile and presumably are the best approximation of the composition of the upper mantle. Nodules that fall far from the olivine control line have presumably been subjected to other processes.

Near the intersection of the nebular trend and the olivine control line lie several postulated compositions for the BSE (Newsom 1995). With the exception of the Taylor & McLennan (1985) composition, all of these are richer in Mg than the major chondrite groups. However, several of these calculated BSE compositions plot close to CR and CV chondrites, and it is possible that the BSE represents just a more extreme example of the process that formed the CR and CV chondrites from a CI-like source.

(To a certain extent this is a circular logic. Most models for the BSE assume explicitly that the Earth should look much like a chondrite, and, thus, the fact that these model compositions fall on or near the nebular trend is far from accidental. A better statement of the situation is that these BSE estimates are strongly biased towards those spinel lherzolites that appear most fertile. These lherzolites themselves closely approach the nebular trend. Because most lherzolites have experienced some amount of depletion and are richer in olivine than the BSE, it is natural to give more weight to those lherzolites that are richest in Al_2O_3 and CaO and poorest in MgO.)

The similarity of the most fertile nodules (and of most model BSE compositions) to CV chondrites is good, especially in terms of Al/Si. And it is interesting to explore predictions of the concentrations of the lanthanide elements in the BSE, based on a CV model. Following Jagoutz *et al.* (1979), our goal will be to reproduce their estimate of REE in the BSE of *ca.* 2.7–3.0 X CI.

First, suppose the Earth were composed entirely of devolatilized CI chondrite material. What would we predict the REE content of the Earth to be? The exercise is essentially one of iterative removal processes that concentrate REE in the residue. CI chondrites contain about 30% volatiles. Removing them would cause REE to increase to *ca.* 1.4 X CI. The Earth has a core that is about 31% of its mass. Correcting for removal of this much material causes the REE to increase to 2.1 X CI. This value falls considerably short of the Jagoutz *et al.* estimate.

For a CV chondrite the calculation is the same except that nature has already removed most of the volatiles. But in this case we are starting with a sample that is already enriched in REE compared to devolatilized CI, so we must multiply the result of the CI calculation by that enrichment factor, 1.33 (Kallemeyn & Wasson 1981). The result is 2.75 X CI, a value nearly identical to that of the Jagoutz *et al.* (1979) model.

Herzberg & Zhang (1994) have presented similar arguments to those advanced here, but using different observations. Herzberg and colleagues have noted the similarity of common BSE models to the mean composition of chondrules, components of chondrites that have experienced high temperature processing in the early solar nebula. In an oversimplified view, chondrites are primarily composed of chondrules and matrix. Thus, in the model of Herzberg and colleagues, Earth-as-a-chondrite contains more chondrules and less matrix than the chondrites we currently sample and approaches the composition of the chondrules themselves (figure 1).

Summarizing, the standard CI model is inadequate to explain the best estimates of refractory lithophile major and trace element abundances in the Earth's upper mantle. While no particular chondrite group exactly matches the composition of the Earth, the CV chondrites come closest, especially in terms of their refractory element component. And although the assumption of a chondritic, 'CI-like' Earth has been taken as a starting point by several authors, modifications are typically necessary. In most of these cases, the common theme to this fine tuning has been that, because the Earth's mantle does not look exactly like a CI chondrite, other indigenous processes must have operated. In contrast, I believe that there is a legitimate basis for doubting that most of these additional processes actually occurred.

3. Fine tuning the standard model

Because of the special nature of CI chondrites, there has been a general reluctance on the part of geochemists to ascribe a Mg/Si ratio to the Earth that differs significantly from the CI value. The BSE composition of Taylor & McLennan (1985) best illustrates this point (figure 1). However, if we only consider planetary, as opposed to solar, compositions, there is ample evidence from the chondrite suite that the CI Mg/Si ratio is not sacrosanct (Ringwood 1989). Despite this, there have been determined efforts to bring the Earth in line with the CI Mg/Si value. Two of these models are discussed below. Also discussed is a somewhat analogous situation concerning the Earth's Ca/Al ratio (Palme & Nickel 1985).

(*a*) *Silicon in the Earth's core*

The models of Wänke (1981) and Wänke & Dreibus (1988) explain the divergence of the Earth's Mg/Si ratio from that of CI by postulating that some Si has been incorporated into the core. This view has been most recently championed by Allègre *et al.* (1995) and Poirier (1994). Under very reducing conditions Si can become siderophile (as in enstatite chondrites) and, therefore, such a model is chemically viable. In fact, in Wänke's heterogeneous accretion model, the earliest Earth looked much like an E-chondrite and there was no FeO in the Earth's mantle until the last *ca.* 10–20% of accretion.

Despite the fact that the amount of Si that Wänke places in the core is modest (*ca.* 12.5%), the redox conditions implied by this amount of metallic Si are quite reducing – probably at least as reducing as E-chondrites, which typically have less than 5 wt% Si as metal (Keil 1968). And the chemical consequences of such conditions are not totally attractive. In E-chondrites and achondrites, Ca, the REE, and the actinides all primarily reside in the sulphide phase (Furst *et al.* 1982; Murrell & Burnett 1982; Frazier & Boynton 1980; Lundberg & Crozaz 1988). This chalcophile behaviour for the lanthanides and actinides has also been observed in the laboratory at igneous temperatures (Jones & Boynton 1983; Murrell & Burnett 1986; Dickinson *et al.* 1990). Therefore, because the Earth appears to have retained its actinides and lanthanides in its silicate portion (recall the REE calculation performed above), it seems most likely that the extremely reducing conditions envisioned by Wänke (1981) did not pertain.

That is not to say that conditions in the early Earth were not reducing. Current estimates for the early stages of core formation suggest that the ambient oxygen fugacity was at least two orders of magnitude below the iron–wüstite buffer (IW-2; Jones & Drake 1986). However, these conditions are not so reducing that Si will enter the core in quantity and are about five orders of magnitude more oxidizing than E-chondrites (Larimer & Buseck 1974). Thus the early Earth was reduced, but probably not so reduced that significant Si entered the core. Note also that, by itself, removal of *ca.* 5% Si to the core will not increase the REE contents of the mantle much above the 2.1 X CI calculated in the previous section, assuming CI abundances as an initial constraint. Thus it seems most likely that the bulk Earth is enriched in Al and REE compared to CI chondrites. If the nebular trend of figure 1 has general application, then the Earth is probably enriched in Mg as well.

(*b*) *Perovskite fractionation and olivine flotation*

Another model for the Mg/Si ratio of the upper mantle is that of Agee & Walker (1988), who envisioned crystal sorting in a terrestrial magma ocean, and as this model is more complex, it is proportionally more difficult to evaluate. Also plotted in figure 1 are the compositions of olivine (OL) and magnesium perovskite (PV). It can be seen that, if the BSE possessed Mg/Si and Al/Si ratios identical to those of a CI chondrite, then removal of perovskite and subsequent addition of a small amount of olivine could produce an upper mantle composition having the chemical characteristics we presently observe. Of course, some other portion of the Earth, presumably the lower mantle, would have to be enriched in perovskite as a result.

Again, the motivation for the mode of Agee & Walker (1988) was that the bulk

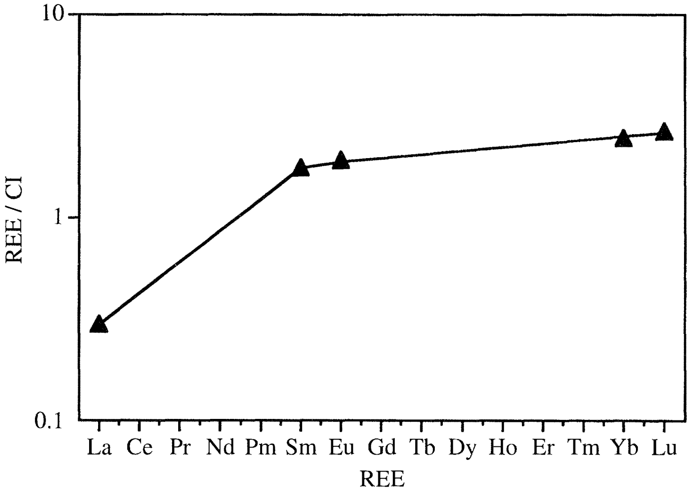

Figure 2. Rare earth elements (REE) in UM-6, a sample from the Basaltic Volcanism Study Project (BVSP 1981). Light REE are depleted as the result of basalt extraction. Heavy REE are 2.5–3.0 X CI, similar to the concentrations envisioned for the BSE (Wanke *et al.* 1984).

Earth should have Mg/Si in the CI ratio. But as we have seen above, this is not a necessary condition for chondrite formation (figure 1) and may not be a necessary condition for the formation of a planet. There is also the question of why the fractionation processes envisioned by Agee & Walker (1988) have resulted in an upper mantle composition that is so close to the nebular trend.

In principle, this model should be testable, using partition coefficients for trace elements of differing compatibilities in olivine and perovskite, to see if chondritic ratios are conserved in this process (McFarlane & Drake 1990). In practice, though, knowledge of the appropriate partition coefficients may still be an issue (Walker & Agee 1989).

However, the situation has changed somewhat since the work of Agee & Walker (1988). At that time it was believed that perovskite was the sole liquidus phase of the BSE composition at pressures greater than 250 kbar. Certainly, perovskite is an important phase at these pressures and subliquidus temperatures. However, the phase diagram for BSE compositions is somewhat more complicated than originally thought. Recent studies by Zhang & Herzberg (1994) on KLB-1 (a primitive spinel lherzolite) and by Agee *et al.* (1995) on the Allende meteorite indicate that magnesiowüstite is the liquidus phase at pressures sufficient to stabilize perovskite (*ca.* 600–700 km in the present Earth) and is followed by perovskite itself at slightly lower temperatures. Thus it does not seem possible for perovskite to fractionate alone. Magnesiowüstite contains significant MgO and, therefore, magnesiowüstite fractionation could significantly alter the Mg/Si ratio of the residual liquid, making the perovskite + magnesiowüstite fractionation trend difficult to precisely quantify. Thus whereas perovskite fractionation alone may result in liquids not far from the nebular trend (figure 1), the same may not be true of perovskite + magnesiowüstite fractionation.

Just as whole BSE melts in the deep mantle (above 230 kbar) show almost cotectic behaviour with manesiowüstite and perovskite, slightly lower pressure melts (180–230 kbar) show similar behaviour but with garnet and magnesiowüstite (Zhang & Herzberg 1994). Therefore, it is difficult for very high-pressure upper-mantle BSE liquids to evolve by monomineralic control, unless the mineral is magnesiowüstite. In turn, this cotectic behaviour will tend to move residual melt compositions away from the nebular trend. Thus I conclude that if multiphase, magma-ocean fractionations have affected the upper mantle, they were sufficiently minor that the proximity of primitive lherzolites to the nebular trend has not been seriously compromised.

(c) *The* Ca/Al *ratio of the Earth's upper mantle*

Palme & Nickel (1985) have pointed out that most spinel lherzolites have superchondritic Ca/Al ratios. This can be true even for those lherzolites that have chondritic ratios of Yb/Sc. And, unlike the Mg/Si ratio, the Ca/Al ratio of chondrites is rather constant. Consequently, Palme & Nickel concluded that the upper mantle must have undergone some modification since accretion. Palme & Nickel's solution to this problem was philosophically similar to that of Agee & Walker: either add a Ca-rich phase (diopside) to the upper mantle or deplete the upper mantle in an Al-rich phase (garnet). Addition of diopside is less easy than garnet fractionation, since diopsidic pyroxene is not known to be a near-liquidus phase at upper mantle (P,T) conditions, whereas garnet may be (Zhang & Herzberg 1994). However, even garnet fractionation may have difficulties, since some elements, such as Yb and the heavy REE, may be quite sensitive to garnet factionation. In the garnet-addition model that Palme & Nickel (1985) used to correct the Ca/Al ratio back to chondritic, the Yb/Sc ratio was substantially modified. (However, as discussed by Palme & Nickel, it is difficult to know whether the Yb and Sc partition coefficients used in their model were necessarily the appropriate ones.)

I suggest that recent work on melt inclusions in spinel lherzolites (Draper *et al.* 1994) and on the minimum melt compositions of these lherzolites (Baker *et al.* 1995) invites an alternative explanation. Low degree partial melts (*ca.* 2–5%) of anhydrous spinel lherzolites at modest pressure (*ca.* 10 kbar) are not tholeiitic but, rather, are very rich in silica and alumina. In the experiments of Baker *et al.* (1995), SiO and Al_2O_3 sum to about 80 wt% (table 1). Consequently, with the other components only summing to 20%, these liquids are depleted in FeO and MgO and enriched in silica and alumina. Therefore, very low degree partial melts of spinel lherzolites will have rather low Ca/Al ratios. I suggest that the modestly elevated Ca/Al ratios of fertile spinel lherzolites (as well as the depletions of highly incompatible elements) primarily reflect the removal of low degree partial melts and that Al behaves more incompatibly than Sc or Yb.

If correct, this view has consequences for how fertile lherzolites are interpreted. Rather than being a random arrangement of basaltic and hartzburgitic components, mixed *via* mantle convective processes, at least some fertile lherzolites may instead be residues of low degrees of partial melting.

(d) *Summary*

The picture that emerges is that it may be profitable to consider those fertile lherzolites that meet creiteria as candidates for nearly unmodified samples of the bulk silicate Earth. These criteria are: (i) Mg/Si and Al/Si ratios that fall near the nebular trend; (ii) chondritic Ca/Al ratios; (iii) refractory lithophile element abundances at 2.5–3.0 X CI; and (iv) noble siderophile elements at about 0.007 X CI (Jagoutz *et al.* 1979). Do any samples in our collection meet these criteria?

Table 1. *Composition of the bulk silicate Earth and selected comparative compositions*

wt%	Fe-depleted Allende (CV3) (Jarosewich 1990)	bulk silicate Earth (Wänke *et al.* 1984)	UM-6 (BVSP 1981)	low degree partial melt of spinel lherzolite (Baker *et al.* 1995)
SiO_2	48.0	46.0	46.1	57.3
TiO_2	0.21	0.22	0.14	0.59
Al_2O_3	4.6	4.2	4.1	19.3
FeO	≡ 7.7	7.6	7.8	4.2
MgO	34.5	36.8	37.7	5.4
CaO	3.7	3.5	3.4	6.7
Na_2O	0.63	0.39	0.35	5.7
Mg/Si	0.93	1.04	1.06	0.12
Al/Si	0.11	0.10	0.10	0.38
Ca/Al	1.09	1.14	1.14	0.47
ppm				
Co	—	105	101	—
Ni	—	2108	1980	—
Sc	—	17	16 (2.7 X CI)	—
Yb	—	0.49	0.4 (2.5 X CI)	—
Lu	—	0.074	0.064 (2.6 X CI)	—
Hf	—	0.28	0.12 (1.15 X CI)	—
ppb				
Re	—	0.24	0.18	—
Os	—	3.1	3.0	—
Ir	—	2.8	3.2 (0.0068 X CI)	—
Au	—	0.52	0.64	—

4. A hopeful example

(*a*) *A fertile spinel lherzolite*

One interesting sample which meets many of the criteria that we have set is UM-6, from the mantle xenolith suite of the Basaltic Volcanism Study Project (BVSP 1981). A comparison of several major and trace element characteristics between UM-6 and the model mantle of Wänke *et al.* (1984) is given in table 1. The agreement is quite good for major elements and, unlike most of the xenoliths studied by Palme & Nickel (1985), the Ca/Al ratio is within 5% of chondritic. Compatible refractory lithophile trace elements such as Sc and Yb exist at 2.5–2.7×CI in UM-6. Cobalt and Ni are about 0.2×CI (figure 3); and both compatible and incompatible noble siderophiles in UM-6 exist at about 0.006 X CI (figure 3). And, indeed, these are very close to the criteria envisioned by Wänke *et al.* for the BSE (table 1). Conceivably, these

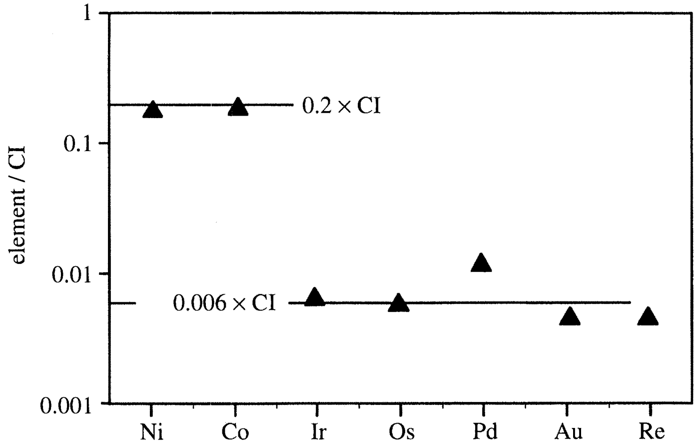

Figure 3. Siderophile elements in UM-6. Nickel and Co exist at about 0.2×CI and the highly siderophile elements Ir, Os, Re, Pd and Au are about 0.006×CI. In both cases, these are the recommended values for the BSE given by Wänke *et al.* (1984).

characteristics of UM-6 could have been arrived at by chance, either through mantle mixing or by metasomatic processes in the subcontinental lithosphere, although the probability of such a felicitous conspiracy seems low. The geochemical behaviours of Al, Sc, Ni, heavy REE, Re, and Ir are sufficiently different that chance mixing of these elements in the proper proportions seems unlikely.

Still, UM-6 is not perfect. It has experienced depletion events that have removed highly incompatible trace elements such as La and Hf (figure 2; table 1). Perhaps as a consequence, the Ca/Al ratio is also slightly elevated. Still, the fact that such a rock can be found at all is quite remarkable. But even so, it would be of interest to know something about the timing of the events that have affected UM-6. (Presently, all that is known about the isotopic characterisitcs of UM-6 is that its ^{187}Os/^{186}Os ratio is within 1% of average carbonaceous chondrites (i.e. γ(Os) = −1; R. J. Walker, unpublished data), in agreement with the bulk Re and Os data cited above. But these data do indicate that UM-6 has spent much of its lifetime in a reservoir with chondritic Re/Os.) If these events are ancient, then they may tell us something about the hypothetical terrestrial magma ocean (Tonks & Melosh 1990). If they are recent, then UM-6 may have survived the Earth's magma ocean stage relatively unscathed.

(*b*) *Geochronology of fertile lherzolites*

There are very few isotopic analyses of fertile lherzolites. However, Nd isotopic analyses have been performed on two of the Jagoutz *et al.* (1979) xenoliths, SC-1 and KH-1 (Jagoutz *et al.* 1980). Like UM-6 these spinel lherzolites are from the southwestern USA (SC–San Carlos, AZ; KH–Kilbourne Hole, NM). They are also the most fertile lherzolites studied by Jagoutz *et al.*

Both SC-1 and KH-1 have, within error, identical CHUR model ages (CHondritic Uniform Reservoir; DePaolo & Wasserburg 1976) of 820 Ma (although the error in the age of KH-1 is large). Because these two lherzolites have experienced different degrees of depletion of incompatible elements, they have different Sm/Nd ratios and therefore define a two-point whole rock isochron. Because they both have the same model age, their model initial ^{143}Nd/^{144}Nd ratio has an ϵ(Nd) of zero (Jagoutz *et al.*

1980; the notation refers to the deviation of the Nd isotopic composition from that of chondrites, in parts per 10^4 (DePaolo & Wasserburg 1976).)

Because these xenoliths arrived at the surface several hundred kilometres apart, it is unlikely that they are cogenetic, and therefore there must be some other explanation for their simple relationship. Mantle mixing of two components could have serendipitously produced samples lying on a mixing line that could be misinterpreted as an isochron, but it is unlikely that such a mixing line would have a chondritic initial ^{143}Nd/^{144}Nd. Therefore, it is possible that the 820 Ma 'age' is real and represents a regional event that affected nearly pristine BSE materials in the subcontinental lithosphere at the time (Jagoutz *et al.* 1980). Clearly, more analyses of fertile lherzolites are necessary to evaluate this suggestion. But if this were to be the case, not only did undifferentiated samples of the BSE remain until late Proterozoic times, but there may be regions of the subcontinental lithosphere where they were/are fairly common. Such a discovery would have important implications for the accretion and early differentiation of the Earth.

5. Fertile lherzolites and their implications for the early Earth

The thesis that has been developed here is that nearly undifferentiated samples of the bulk silicate Earth have been preserved in subcontinental lithospheres over geologic time. The main evidence for this is that samples can be found which meet the main criteria we expect, on the basis of geochemistry and cosmochemistry. And although these samples have been affected by magma extractions, these events appear to have been relatively recent and were not imposed early in Earth's history. What are the consequences of this thesis?

(*a*) *What if fertile lherzolites are not representative of the BSE?*

Before we perform this exercise, it is of interest to ask if there would be any implications if the thesis were wrong. The immediate conclusion that we should draw is that we have no good constraint on the composition of the bulk silicate Earth. Since the seminal work of Jagoutz *et al.* (1979), great weight has been given to fertile spinel lherzolites in addressing the BSE composition. Implicit in this procedure is the thesis I have expounded. If the procedure is wrong, then we could be far from the mark in our assessment of the composition of the BSE. This observation should not be taken as a supportive argument in favour of the thesis (unless, of course, an independent method for estimating the BSE composition arrives at the same conclusion), but it should be disquieting. For example, if the spinel lherzolites that we sample today are the products of complex mixing processes associated with upper mantle convection, then samples having high Al contents are not necessarily indicative of the composition of the Earth. They are simply mixtures of high-Al components (e.g. eclogites) and low-Al components (e.g. dunites), and unless it could be shown that the bulk system can be approximated by this two-component mixture, we would be up a creek. Thus, if fertile spinel lherzolites are red herrings, we should be actively about the business of finding replacements for them.

(*b*) *Light element in the core*

Geophysical data indicate that the outer liquid core is several percent less dense than pure Fe at the same temperature and pressure (Birch 1964). It is therefore believed that about 10±2 wt% of a lighter element(s) exists in the outer core (Poirier

1994), lowering the core's density and perhaps lowering the core's melting point as well. Poirier (1994) has recently given a review of possible light elements in the core and has correctly emphasized the difficulties associated with uniquely assigning the role to any particular element. It may well be that the outer core is a complex alloy whose composition is not well represented as a simple binary system. Unless, as mentioned by Jeanloz (1990), the light element in the core actually comes from the wholesale dissolution of the lower mantle, redox considerations imply that Si should play only a minor role (see the earlier discussion on Si in the core).

Returning to the comparison between the Earth and CV chondrites, it is of interest to ask whether the core-seeking non-metals in CVs would be sufficient to provide the requisite amount of light elements. The answer is that, taking the model literally, CV chondrites come fairly close. The typical CV has abut 2.2 wt% S and 0.56 wt% C (Newsom 1995). Correcting for the increase in concentration as they are concentrated into a core results in a total non-metal concentration of 8.9 wt%, well within the range permitted by the geophysical data. But this literal interpretation should only be accepted with caution. The Earth is more depleted in volatile lithophile elements than CV chondrites (e.g. Na; table 1) and may possibly be more depleted in volatile siderophile elements as well. Even so, it is possible that some combination of S and C will do the job without recourse to Si (Wänke 1981) or O (Ringwood 1977).

(*c*) *A terrestrial magma ocean*

A model that is currently in vogue is that of the terrestrial magma ocean (Newesom & Jones 1990; and references therein), and it is difficult to envision how pristine samples of the BSE could have survived such an event. Although Tonks & Melosh (1990) have pointed out that, because of the extreme turbulence of a terrestrial magma ocean, fractionation by crystal settling should be minimal, eventually there must come a point in the crystallization sequence when the system 'locks up' and no longer convects turbulently. And at some point it is hard to understand how one distinguishes, for example, between 90% equilibrium crystallization from 10% partial melting. Since this latter type of behaviour is thought to be the main mechanism for the production of basalt, how would conditions in the Hadean have had to differ so as to keep basalt and crystal from separating? This was one of Ringwood's arguments against a magma ocean (Ringwood 1990). In my view it is a valid one, and one that needs to be answered.

(*d*) *Giant impact origin of the Moon*

One of the main reasons for the popularity of the terrestrial magma ocean is the giant impact hypothesis for the origin of the Moon. In this highly popular model, a Mars-sized impactor collided with the Earth, ejecting plumes of material that later coalesced in Earth orbit, forming the Moon (Benz *et al.* 1986; Melosh & Sonett 1986). The thermal consequences to the Earth of such an impact are tremendous. Any material that is not melted during such an event is vaporized (Melosh 1990). Thus a magma ocean is a necessary consequence of the giant impact hypothesis, and if we are skeptical about magma oceans we should be skeptical of giant impacts as well.

(*e*) *Accretion and early thermal history of the Earth*

The implications of finding only modestly modified samples of BSE with young chondritic model ages are quite profound. Most current models for the accretion of the Earth favour hot accretion (Newsom & Jones 1990; and references therein). The combination of core formation, which is highly exothermic, and the infall of large planetesimals, hundreds to thousands of kilometres in dimension, could raise the temperature of the Earth substantially above the silicate solidus (Wetheril 1990). If samples of the BSE survived the time of early bombardment relatively unscathed, then perhaps a new paradigm of accretion is required.

6. Is the model testable?

I have argued that it is possible to find hand-specimen-sized samples that approximate the bulk silicate composition of the Earth. This, in turn, argues for a moderately quiescent formation of the Earth. But both these conclusions are model-dependent, and an important aspect of any scientific model is that it be testable. This is a case where testing is difficult, if not impossible. Of course, the finding of an ancient (*ca.* 4.5 Ga) rock with the requisite characteristics would be strong evidence in favour of the model, but this is unlikely in the extreme. Many of the mantle xenoliths show that isotopic equilibration in their source region was maintained until shortly before their emplacement at the surface (Jagoutz *et al.* 1980) and, thus, their origin cannot be dated.

I suggest, however, that there are ways of evaluating the plausibility, if not the veracity, of the model. First, more work needs to be done to expand the database on fertile lherzolites. Most mantle xenoliths are depleted and so finding fertile xenoliths is rare. How rare are such xenoliths and are there any correlations between their occurrence and other considerations such as tectonic setting or the composition of the host magma in which they are entrained? Of clear importance is that this work be carried out in a consortium-type mode, with petrography; major-, minor-, and trace-element geochemistry; and isotopic work all carried out on aliquots of the same samples. Individual, piecemeal efforts will not accomplish the task at hand.

I suggest that it would also be very important if fertile lherzolites could be found that had concordant Nd and Os chondritic-reservoir model ages. Unlike the other chronometer systems at our disposal, we can be reasonably confident that the bulk Earth has chondritic parent/daughter ratios of ^{147}Sm–^{143}Nd, ^{176}Lu–^{176}Hf, and ^{187}Re–^{187}Os. However, Sm–Nd and Lu–Hf often yield partially redundant information, since in both cases the parent is usually more compatible than the daughter. Therefore, because Re is less compatible than its daughter Os, a concordance of Nd and Os model ages would give some confidence that this date had true age significance. Currently such concordance is lacking (Walker *et al.* 1989); there is almost no correlation between Nd and Os isotopes in mantle xenoliths. But it is also true that most of the samples studied using Os isotopes have not been particularly fertile.

7. Summary and conclusions

This has been an advocacy of a particular point of view for the composition of the Earth. The correctness of this viewpoint has repercussions in that any model of the Earth's composition will have important implications for how we think about the Earth and its origins. And I hope that useful wheat will emerge from the process of evaluating these models, even if some of their predictions turn out to be chaff.

For example, if the Moon formed by giant impact, then there are clear consequences of that model for the Earth. And it is easier to study the Earth than it is the Moon (at least we have more data). We should endeavour to identify and study those samples that will best constrain theories of the accretion and early differentiation of the Earth and Moon.

In addition, I know of no compelling reason why solar and planetary compositions must be the same. Certainly, there is the issue of mass to be considered. Presumably the bigger the body, the higher the probability that its composition will approach that of the bulk Solar System. Because most of the mass of the Solar System resides in the Sun, we commonly equate the bulk compositions of the two. Therefore, it is probably easier for a small asteroid to deviate from solar composition than for the Earth. But there is also compelling evidence that there are gross differences between planets: (i) the outer planets are much more enriched in volatiles than the terrestrial planets; (ii) there are systematic, radial gradients in the mineralogies of the asteroid belt (Bell *et al.* 1989), suggesting that this region could once have been a chemical boundary layer between the inner and outer Solar System; and (iii) even the planets of the inner Solar System can have very different proportions of metal to silicate (BVSP 1981). In short, while known chondrite classes serve as useful guides to condensation and accretion in the early Solar System, the processes they indicate may not be completely representative of other regions in the solar nebula.

Finally, I believe that there is utility in taking at face value those primitive mantle lherzolites that lie near the nebular trend. If they meet the criteria of primitive, undifferentiated samples, then they have an important story to tell.

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