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Ian H. Campbell, Hugh St. C. O'Neill

Institutions: Australian National University

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Evidence against a chondritic Earth

Ian H. Campbell¹ & Hugh St C. O'Neill¹

The $^{142}\text{Nd}/^{144}\text{Nd}$ ratio of the Earth is greater than the solar ratio as inferred from chondritic meteorites, which challenges a fundamental assumption of modern geochemistry—that the composition of the silicate Earth is ‘chondritic’, meaning that it has refractory element ratios identical to those found in chondrites. The popular explanation for this and other paradoxes of mantle geochemistry, a hidden layer deep in the mantle enriched in incompatible elements, is inconsistent with the heat flux carried by mantle plumes. Either the matter from which the Earth formed was not chondritic, or the Earth has lost matter by collisional erosion in the later stages of planet formation.

The paradigm that underpins much of modern geochemistry is that the integrated chemical composition of the whole Earth should be that of the Sun, except for depletion in volatile elements, according to their volatility under the conditions of the solar nebula. Similar solar-related compositions are found in ‘chondritic’ meteorites, which are fragments of small rocky bodies that escaped the usual course of planetary differentiation into a metallic core, silicate mantle and crust. The composition of a chondritic meteorite is therefore presumed to reflect its entire parent body. Although the solar composition can be determined from spectroscopic measurements of the solar photosphere, measurement is not possible or imprecise for many elements, is model-dependent and does not give information on the isotopic make-up of the elements¹. Instead, a more complete picture of the solar composition is inferred from chemical analyses of chondrites. The compositions of the chondrites vary, with at least 27 parent bodies sampled², reflecting local differences in the solar-nebula-like density or proportions of gas to solids, or different accretion processes. The various chondrite compositions are distinguished by enrichment or depletion of refractory elements, ratio of lithophile to siderophile elements (for example, Mg/Fe), oxidation state, oxygen isotopic compositions, and their patterns of depletion of the volatile elements. No examples with volatile-element enrichment are known, except for a slight enrichment in a few of the least volatile of these elements in the highly reduced enstatite chondrites. Yet all chondrites share one distinctive compositional feature: their refractory lithophile elements (RLEs) are present in the same ratio relative to each other and to the solar composition. The RLEs are defined by two properties: they are refractory, because they condense from a gas of solar composition at temperatures higher than the main constituents of rocky planets, the magnesium silicates and iron metal; and they are lithophile, because they do not enter metal or sulphide phases, either in chondrites or into the metallic cores formed during planetary differentiation. There are 28 RLEs that are stable or have long half-lives; they include Ca and Al among the major elements, the entire suite of rare earth elements (REEs), and the radiogenic heat-producing elements U and Th.

The constant RLE ratio rule is ever challenged on several fronts: by exceptions due to terrestrial weathering or *ad hoc* effects on parent bodies such as impact brecciation, incipient melting or aqueous alteration; by the scale of heterogeneity in chondrites relative to the small sample sizes available for analysis; by improvements in the precision of chemical analysis; and by the increasing numbers of chondritic meteorites available for analysis. It is therefore difficult to quantify the precision to which the rule holds, but variations from the solar ratios reflecting whole-body chemistry that are larger than a few per cent are exceptional. The

REE pattern in the RLE-rich CV chondrite Allende is perhaps the largest well-attested deviation³. New techniques of isotopic analysis are revealing small anomalies in the isotopic make-up of heavy elements in bulk samples of chondrites, ascribed to less than perfect homogenization of different nucleosynthetic components in the solar nebula, such as Ti (ref. 4), Ni (ref. 5), Ba (refs 6 and 7) and Mo (ref. 8). This evidence challenges the conceptual basis behind the constant RLE ratio rule, but as yet at no more than the few-per-cent level already accepted. For example, although the range in Lu/Hf and Sm/Nd in unequilibrated carbonaceous, ordinary, and enstatite chondrites is as much as 7.9% and 3.5% respectively, the average Lu/Hf and Sm/Nd values for these three main classes of chondrites agree within 1% and 0.3% respectively⁹.

Although most geochemists long ago abandoned the notion that the Earth’s composition mimics any particular type of chondrite¹⁰, the idea that the Earth has solar ratios of RLEs has persisted, providing the fundamental reference frame against which trace element and radiogenic isotopic ratios are compared. This reference frame has usually, if confusingly, been termed ‘chondritic’ rather than ‘solar’ in the literature, because of the history of fine-tuning the presumed solar composition to the compositions of chondrites. Emphasis has been placed on the CI chondrites, which match the solar composition within uncertainty for many elements irrespective of their chemical properties, except for the most volatile elements; but CIs are rare, and useful analyses come from just three falls, Orgueil, Ivuna and Alais¹¹, and mostly from Orgueil¹. The implicit assumption is that the bulk chemical composition of rocky bodies is established at the earliest stages in the planet-building process, of which the chondrite parent bodies are relicts. In this view, the subsequent stages by which these small chondritic bodies collide and merge to form planetary embryos and ultimately Earth-sized planets, while resulting in extensive differentiation associated with melting, does not affect the integrated whole-planet compositions: these, it is assumed, remain ‘chondritic’.

Planetary accretion

The ‘chondritic’ hypothesis for the Earth’s composition is a survivor from times when the understanding of how terrestrial planets form was quite different. Current models can be traced back to Safronov, whose monograph on the subject was only translated into English in 1974 (ref. 12). Our present understanding is that planetary accretion proceeds through several stages of ever increasing average size. Initially, runaway growth is from kilometre-sized bodies (approximately the size of parent bodies of chondrite meteorites) to form planetesimal oligarchs about a thousand kilometres in diameter. This is the approximate size of the differentiated bodies that are thought to be parental to the achondrite meteorites, like Vesta (diameter 500 km). The achondrite parent bodies

¹Research School of Earth Science, Australian National University, Canberra, Australian Capital Territory 0200, Australia.

all show non-chondritic patterns of volatile loss, for example, in their Mn/Na ratios¹³. This post-nebular volatile loss can be dated using the Rb/Sr chronometer to several million years after the chondrite stage¹⁴. The last stages of planetary accretion see the assembly of these planetesimals into Moon-to-Mars-sized planetary embryos, which then merge through highly energetic collisions to form a few terrestrial planets. The giant impact that formed the Moon is the last of significance in the formation of the Earth. None of this was envisaged when the chondritic hypothesis was first advanced. Maintaining the hypothesis in its current form requires that the collisions between bodies during the several stages of accretion result in no net fractionation of RLEs, despite the bodies being already differentiated at the earliest stages, which does not seem probable.

Challenge to the chondrite paradigm

The challenge to this paradigm started with two landmark papers showing that the $^{142}\text{Nd}/^{144}\text{Nd}$ ratio of chondritic meteorites is 20 ± 5 parts per million less than rocks of terrestrial mantle origin^{15,16}. ^{142}Nd is the daughter of ^{146}Sm , with a half-life generally assumed to be 103 million years (Myr) but which could be as short as 68 Myr (ref. 17). Sm and Nd are two typical RLEs, and their isotopic relationships provide particularly powerful constraints on Earth differentiation models, because the short-lived $^{146}\text{Sm}/^{142}\text{Nd}$ system is complemented by the long-lived $^{147}\text{Sm}/^{143}\text{Nd}$ system (half-life 106 billion years, Gyr), which has long been used to constrain the sizes of Earth reservoirs. Although there is some nucleosynthetic variability in the isotopic composition of Nd among chondrites, this is unlikely to explain the difference in $^{142}\text{Nd}/^{144}\text{Nd}$ (ref. 18), which therefore requires the ratio of Sm to Nd to be about 6% above the average chondritic value^{15,16}; because of its isotopic significance, this value is known to within 0.3% (refs 9 and 19).

There are two possible interpretations¹⁵. The simplest is that the Earth is not chondritic after all, and the measured $^{142}\text{Nd}/^{144}\text{Nd}$ ratio of terrestrial samples is that of the bulk silicate Earth (BSE). Many geochemists have opted for an alternative scenario, in which the Earth's mantle underwent an early fractionation event into an early-enriched reservoir with low Sm/Nd and an early-depleted reservoir (EDR) with high Sm/Nd^{15,16,20–22}. Boyet and Carlson (refs 15 and 16) suggest that the low-Sm/Nd reservoir was an incompatible-element-enriched basaltic crust that sank to the core–mantle boundary, becoming isolated in the seismically anomalous region at the base of the mantle called D'' , an irregular 200–250-km-thick layer overlying the core. The seismic properties of D'' make it unlikely to be a simple thermal boundary layer and it is interpreted to be a stable layer with a density greater than that of the overlying mantle^{23,24}. Furthermore, because the half-life of ^{146}Sm is no more than 103 Myr, the early fractionation event must have occurred well within the first 10 Myr of Solar System formation to prevent the average $\epsilon^{143}\text{Nd}$ value of the complementary EDR rising above about 10, the observed average value of the mid-ocean-ridge basalt (MORB)^{25,26}.

The $^{142}\text{Nd}/^{144}\text{Nd}$ ratios of lunar samples, however, are indistinguishable from terrestrial values^{27–29}, so the Moon and the Earth developed their $^{142}\text{Nd}/^{144}\text{Nd}$ enrichment before the Moon's formation³⁰. If the Moon formed by a giant impact, the collision would have melted and homogenized the Earth's mantle³¹, which would have destroyed any hypothetical early-enriched reservoir³⁰. Furthermore, the effect of extraction of the continental crust from the mantle on the Sm–Nd mass balance can be modelled, assuming that the BSE has a composition similar to the EDR, without a hidden reservoir³⁰.

The heat carried by mantle plumes provides an equally compelling argument against a hidden early-enriched reservoir³². Most hidden-reservoir advocates^{15,16,33,34} equate it with D'' . If D'' is the hidden early-enriched reservoir, then under the chondritic assumption, a mass balance requires it to contain over 40% of the Earth's heat-producing elements (U, Th and K), which produce 9 terawatts (TW) of heat¹⁵. Regardless of whether D'' is a stable layer or forms a double-diffusive convecting layer³⁵, the heat it liberates can only be transmitted through the overlying mantle in plumes. The amount of heat transferred by mantle plumes can be estimated from the dynamic topography they

generate on the sea floor. Early estimates^{36,37} placed the heat flow carried by plumes at 3.5 TW, which has been revised³⁸ to 7 TW or 15% of the Earth's total heat flow³⁹ of 47 ± 2 TW, to take into account the mantle's subadiabatic thermal gradient. However, models of mantle heat transfer, which takes into account both the heat required to warm subducted lithosphere and the additional heat required to lift compositionally dense plumes, suggest a higher figure^{38,40–42} of 7–14 TW. From this must be subtracted the heat transferred from the core to the mantle, which⁴¹ must be at least 3–4 TW, the minimum amount of heat required to sustain the geodynamo, but is more likely to lie between 5–7 TW and 12–14 TW (ref. 38). As a consequence, if heat transfer from the core to the mantle is greater than the low estimate of 5 TW or if the heat carried by mantle plumes is less than the high estimate of 14 TW, 40% of the Earth's heat-producing elements cannot be hidden in the D'' layer.

A sudden drop in the maximum MgO content of plume-related komatiites and picrites 2.5 Gyr ago from 30–35 wt% to 18–23 wt%, which implies a temperature drop of 200 to 250 °C, has also been used to argue that D'' did not form until the end of the Archaean eon³⁵. The simplest explanation for the observed drop in MgO is that D'' formed as a stable layer about 2.5 Gyr ago, which insulated the mantle from the core. The predicted drop in plume temperatures, depending on assumptions such as whether D'' is a stable layer or formed a double-diffusive convecting layer, lies within the range 33% to 50%, which is consistent with the observed MgO drop³⁵. If D'' formed after the first 10 Myr of the Earth's evolution it cannot be responsible for the Earth's $^{142}\text{Nd}/^{144}\text{Nd}$ anomaly.

If the composition of the EDR is that of the BSE²⁰, or if it formed within 10 Myr of the Solar System^{25,26} and is unaffected by subsequent events, then the $\epsilon^{143}\text{Nd}$ value for the EDR today^{30,43} is 7.0 ± 2.0 . These values are remarkably similar to the prevalent mantle (PREMA) value of 7 ± 1 in ocean island basalts (OIBs)^{44,45}. A component with this Nd characteristic can be recognized in four flood basalts⁴³—the Baffin Island–West Greenland province, the Antarctic Karoo, the Siberian Traps and the Deccan Traps—and in two oceanic plateaus—the Kerguelen and Ontong Java plateaus³⁵. The EDR component plots within 150 Myr of the 4.5-Gyr geochron on a $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram, which suggests that it developed early in the Earth's history⁴³. It also has enriched $^3\text{He}/^4\text{He}$, showing that the source region to these plumes is less degassed than the MORB source^{30,43}.

Torsvik *et al.* suggest that most plume-related basalts that erupted over the last 320 Myr were above one of two large low-shear-wave-velocity provinces, which form part of D'' and make up about 2% of the mantle's mass⁴⁶. However, this primitive component in plumes may be much more extensive^{35,45}. The isotopic trend in a number of ocean island suites, produced by melting plume tails, converges towards a common point called FOZO⁴⁴. A remarkably similar component was identified in the two oceanic plateaus that are free from contamination by continental crust, the Ontong Java and the Caribbean plateaus^{35,43}. Basalts from these plateaus are characterized by flat REE patterns and in this respect they are dissimilar to OIBs and MORBs but are isotopically similar to the EDR recognized in flood basalts⁴³. Archaean basalts associated with komatiites, whose Nb/U ratios indicate that they are free of crustal contamination^{47–50}, commonly have flat REE patterns^{48–50}, and basalts from Kambalda in Western Australia have an $\epsilon^{143}\text{Nd}$ value of 3 (ref. 47), which lies on the EDR growth curve for Nd at 2.7 Gyr ago. Jackson and Carlson⁴³ interpret the EDR component to originate from the boundary layer source of plumes, whereas Campbell and Griffith³⁵ suggest that it is lower mantle that was entrained into plumes during their ascent. The first interpretation allows the early-enriched reservoir to be a minor component in plumes, whereas the second requires it to be a dominant component in the lower mantle. Because this difference is critical to the debate on whether the Earth has chondritic RLE ratios, we now summarize the basis for the second interpretation^{35,51}.

Plumes must originate from a thermal boundary layer; in the Earth, only the core–mantle boundary has the properties required to sustain the temperature drop implied by plume activity on geological timescales⁵². A

new plume has a large head, which is followed by a smaller tail (Fig. 1). As the head rises through the mantle it heats the adjacent mantle, lowering its density so that it is swept into the plume head by its recirculating motion. The plume head is therefore a mixture of material from the hot boundary-layer source of the plume (dark material in Fig. 1) and cooler entrained material (light material in Fig. 1). This entrained material, which makes up a large fraction of the head, comes from the lower half of the lower mantle^{51,52}. When a plume head reaches the top of the mantle it melts to produce a continental flood basalt or an oceanic plateau^{52,53}. The first material to reach the top of the mantle and undergo decompressional melting is the hot mantle that originated from the boundary layer above the core (Fig. 1), which melts to produce picrites or komatiites. Later, when the head flattens against the overlying lithosphere, the cooler entrained material from the lower mantle, which is calculated to be three times as thick as the hot material from the boundary layer⁵⁴, enters the melting zone. Production of high-temperature picrites or komatiites should therefore be followed by lower-temperature basalts formed by melting a mixture of boundary layer and entrained lower-mantle with the latter becoming increasingly important with time as the plume head continues to rise and flatten. It is this primitive entrained lower-mantle component that has been identified in the Ontong Java and Caribbean plateaus^{35,43,51} and in several flood basalt provinces⁴³.

Lower-mantle material is also entrained along the side of rising plume tails by viscous drag (Fig. 1). As a consequence, when plume tails melt to produce a chain of ocean islands, which progressively increase in age away from the current position of the plume, the basalts that make up the islands may contain a component from the lower mantle. The existence of FOZO as a component in plume tail basalts is therefore consistent with the interpretation⁴⁵ that it was entrained from the lower mantle during ascent of a plume tail (Fig. 1). Its presence in all or most plume tails provides further support that FOZO is a major component in the lower mantle.

FOZO⁴⁵, EDR¹⁵, SCHEM³⁰ (super-chondritic Earth model), and NCPM⁴³ (non-chondritic primitive mantle) are therefore all the same: the primordial component of the BSE. The evidence from oceanic plateaus, flood basalts and OIBs is that this is a major component in the lower

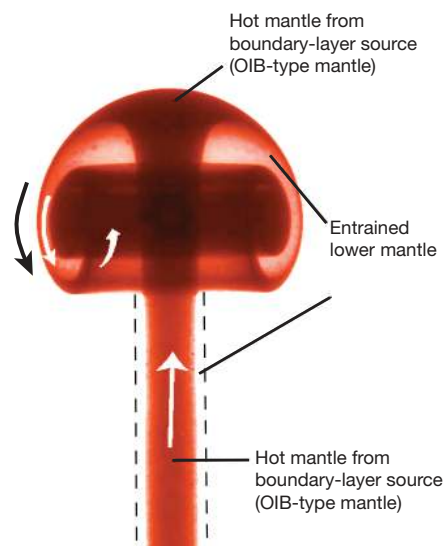


Figure 1 | Laboratory model of a mantle plume. The dark-coloured fluid is from the hot boundary-layer source of the plume, whereas the light material is cooler overlying fluid that was entrained into the rising plume. In the case of the mantle the dark-coloured material is from the thermal boundary layer above the core, whereas the light material is entrained lower mantle (after ref. 54). The entrained material makes up a large fraction of the plume head⁵⁴ and comes mainly from near the bottom of the lower mantle but above the boundary-layer source of the plume. The critical parameter in the present context is the thickness of the upper entrained layer (light material near the top of the plume head), which is about three times the thickness of layer at the top of the head (dark material) that originates from the boundary-layer source of the plume⁵⁴.

mantle. The high $^3\text{He}/^4\text{He}$ ratios recognized in the EDR component are consistent with this interpretation³⁰. The displacement of most oceanic plateaus and flood basalts, with $\epsilon^{143}\text{Nd}$ between 5 and 9, slightly to the right of the geochron on a plot of $^{207}\text{Pb}/^{204}\text{Pb}$ against $^{206}\text{Pb}/^{204}\text{Pb}$, shows that the lower mantle, as sampled by Phanerozoic plumes, includes some recycled oceanic crust⁴³. Basalts from Malaita Island, part of the Ontong Java Plateau, have an average Nb/U of 42, which is between that of the average for both the OIB- and MORB-type mantles (47) and the BSE value of 34, indicating that some continental crust has also been extracted from the lower mantle⁵¹.

The picture of mantle convection that is emerging is one in which the upper mantle differentiates into harzburgite and basalt at mid-ocean ridges, which are subducted to the thermal boundary layer above the core and returned to the upper mantle in plumes, mixed in varying proportions, with perhaps a small sedimentary component. It appears that the bulk of the lower mantle is largely bypassed by this process, so that it is less degassed, has had less subducted basalt mixed into it, and less continental crust extracted from it, compared to OIB- and MORB-source mantles.

Volatile elements

Although the comparison of Earth's composition with chondrites has focused on the RLEs, the differences in the abundances of the moderately volatile elements between the Earth and chondrites provide another line of evidence that chemical fractionations, which occurred in the latter stages of accretion, moved the final compositions of terrestrial planets away from the compositions encompassed by chondritic meteorites^{13,14}. The moderately volatile elements are those calculated to condense from the solar nebula after magnesian silicates and Fe metal, but at temperatures above the ice-forming elements (H, C, N and the noble gases). Many moderately volatile elements are also siderophile and were depleted in the BSE by partitioning into the core, making their bulk Earth abundances inaccessible, but among the lithophile elements are the alkali metals, the halogens and boron. For the other potentially siderophile elements like Zn and In, their BSE abundances provide useful constraints on minimum Earth abundances. The pattern of depletion of the moderately siderophile elements is unlike that found in any chondrite group (Fig. 2). In the chondrites, depletion correlates with calculated condensation temperatures, but in the Earth, elements that are very highly incompatible during partial melting, namely the heavy halogens and Cs, are much more depleted than the nearly compatible Zn and In. This is highlighted by Zn/Cl ratios, which are an order of magnitude greater in the BSE than in any chondrite group (Fig. 2). The dependence of volatility on incompatibility suggests volatilization from early-formed crusts during the latter stages of accretion¹³. In the case of the halogens, their volatilities are enhanced by relatively oxidizing conditions that prevailed after dispersion of the H-rich solar nebula. Post-nebular oxidizing conditions are reflected in the ubiquitous fractionation of Na from Mn in small-differentiated planetary bodies¹³, although this particular fractionation is not seen in the nearly chondritic Na/Mn ratios of the BSE, perhaps because some Mn has also been partitioned into the core. Attempts to define simple volatile-element depletion trends in the BSE have invariably omitted key elements from consideration, like the heavy halogens.

For elements that are both volatile and siderophile, the complexities of the volatile-element depletion in the Earth, as indicated by the full pattern (Fig. 2), prevents us from assigning how much of an element's loss is due to volatility and how much is due to partitioning into the core. This is particularly vexing for Pb. Was the extent of Pb depletion by volatility in the material that formed the Earth like that of Zn and In, or was it like Cl and the other heavy halogens, or was it somewhere in between? On the $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram, it is well established that both the mantle and crust of the Earth plot well to the right of the 4.57-Gyr geochron, which, neglecting the 'hidden reservoir' explanations, is usually taken to imply loss of Pb relative to parental U sometime later, at about 4.45 Gyr ago⁵⁵. Because feasible hypotheses can be constructed to argue for Pb loss by both mechanisms at several stages

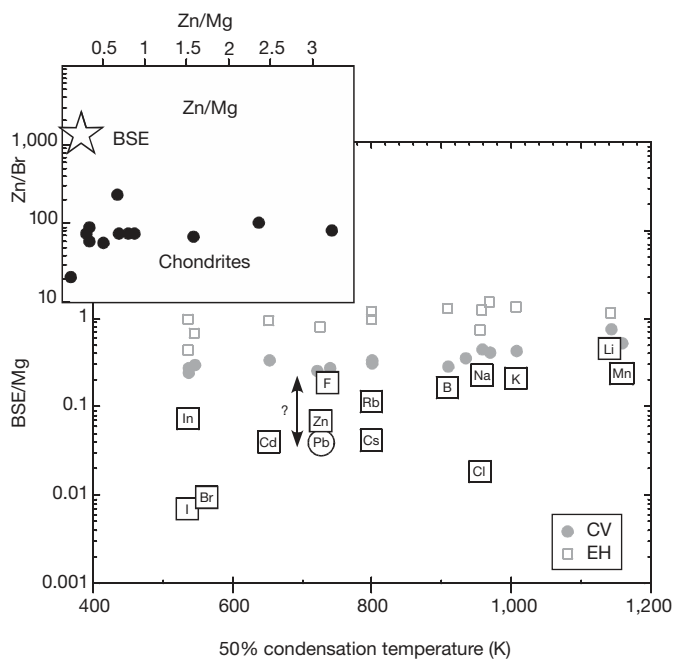


Figure 2 | The pattern of volatile element depletion in the BSE for lithophile elements compared to CV carbonaceous chondrites and EH enstatite chondrites. CV carbonaceous chondrites are the most volatile-depleted of the chondrites and EH enstatite chondrites are a class of chondrites sometimes considered to have affinities to the Earth because of their stable isotope ratios. Elements are normalized to CI abundances and Mg. The calculated 50% condensation temperatures of elements for the solar nebula are from ref. 10. Some elements in the BSE may have been additionally depleted by core formation (for example, Zn, In and Pb), in which case their depletions due to volatility alone will be overestimated. The chondrites form smooth depletion trends with calculated condensation temperatures, but the BSE is not only more depleted in moderately volatile elements than any known chondrite, but the pattern of depletion is qualitatively different, probably owing to post-nebula volatile loss under more oxidizing conditions¹³. This is shown, for example, by the BSE Zn/Br ratios (inset), which are about an order of magnitude greater than that found in any class of unmetamorphosed chondrites (black circles). The lack of any clear volatility trend in the BSE means that it is not at present possible to constrain how much Pb, if any, was partitioned into the Earth's core, making the interpretation of Pb isotopic systematics in terms of Earth accretion and core formation uncertain. Meteorite abundances are from ref. 66, and BSE abundances from ref. 13, which was derived under the 'chondritic assumption'. A non-chondritic BSE would have lower abundances of B, K, Rb, Cs, Cl, Br and I but not Mn, Na, F, Zn or In (ref. 12), increasing the discrepancy with the chondritic trends.

of the planet-building process, the significance of this age information remains ambiguous.

Likewise, the interpretation of other early-Earth geochronometers is also affected if the Earth has a non-chondritic composition. For example, short-lived ¹⁸²Hf (half-life 9 Myr) decays to ¹⁸²W, providing a chronometer with which to constrain the duration of core formation, because W is a moderately siderophile element that partitioned incompletely into the core. Evaluating the time significance of this chronometer for the Earth depends on knowing the W/Hf ratio in the BSE⁵⁶. The W content of the BSE has been estimated by noting that W/Th (or W/Ba) ratios remain constant in igneous processes, hence $W/Hf = (W/Th) \times (Th/Hf)$. Because Hf and Th (or Ba) are both RLEs, it is then assumed that their ratio is the same as in chondrites. But the non-chondritic Earth model of ref. 13 predicts that Th/Hf would be only around 70% of the chondritic ratio; for a simple two-stage model of core formation, this would increase the calculated time from about 30 to about 35 Myr.

Alternative hypotheses

There are two classes of explanation for the Earth not being chondritic. Most simply, the compositions of chondrites may not reflect that of the

Solar System precisely enough to deduce detailed element ratios for RLE. It needs to be remembered, however, that the average Sm/Nd ratio of the three main classes of chondrites agrees to within 0.3%.

Alternatively, the Earth could have been assembled from initially chondritic material that was then modified during the subsequent stages of the planet-building process by collisional erosion^{13,57,58}. Current estimates of the Earth's Fe/Mg ratio are consistent with about 10% of its silicate part having been lost by this mechanism relative to its Fe-rich metallic core. The meteorite record attests to the differentiation of small rocky bodies into metal and silicate being inevitably associated with partial melting and hence also the formation of an incompatible-element-enriched crust. If material from these crusts were preferentially lost during the collisions, it would deplete the Earth systematically in incompatible elements according to their incompatibility (Fig. 3). One weakness of the hypothesis is that it implies the loss of incompatible-element-enriched material to space that no class of meteorite has sampled. However, no meteorites sample the moderately volatile elements missing from all chondrites (apart from the CIs) and from the achondrites and terrestrial planets. Did the gravitation field of the Sun or Jupiter capture this missing material?

The pattern of depletion caused by preferential collisional erosion is geochemical rather than cosmochemical, and its effect on the composition of the Earth's mantle is essentially the same as that which subsequently occurred throughout the Earth's history by crust formation. Detecting the effects of collisional erosion therefore depends on observations that can sum all the reservoirs in the BSE to see whether they add up to chondritic ratios of RLEs. The Sm/Nd ratio provides the most compelling evidence, but once the idea of a non-chondritic Earth is allowed, the resolution of other so-called geochemical paradoxes becomes achievable.

Geochemists are fascinated by the many paradoxes of the Earth's mantle, which are summarized in Table 1. All of these paradoxes are predicated on geochemistry's most fundamental paradigm; that the Earth was produced by the accretion of meteorites with the same ratios of RLEs as in chondrites. Most of these paradoxes disappear if this assumption is relaxed, but one existing paradox becomes worse: the low value of the Earth's Urey ratio. The Urey ratio is the Earth's radiogenic heat production divided by its surface heat flux, which—under the assumption of BSE U, Th and K concentrations given by the chondritic hypothesis—is about 0.5. The difference must be accounted for by secular cooling. Collisional erosion lowers the heat-producing element content of the BSE by up to

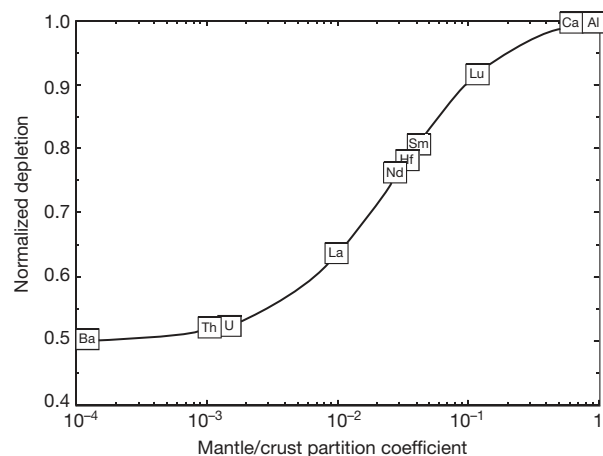


Figure 3 | Depletion of some RLEs in the BSE by preferential collisional erosion of early-formed basaltic crust during accretion of planetesimals and planetary embryos. The figure is based on the model of ref. 13, assuming three constraints: (1) loss of silicate (crusts plus mantles) relative to metallic cores is 10%; (2) the most incompatible RLEs (here represented by Ba) are depleted to 50% of their chondritic abundance; and (3) Sm/Nd is 6% above the chondritic ratio. The partition coefficients during crust formation are from ref. 67 for the production of oceanic crust.

Table 1 | The geochemical paradoxes of the mantle

Paradox	Chondritic solution	Non-chondritic solution
The $^{142}\text{Nd}/^{144}\text{Nd}$ ratio of chondritic meteorites is 20 ± 5 parts per million less than that of rocks of terrestrial mantle origin.	A low-Sm/Nd hidden reservoir became isolated from the convecting mantle within 10 Myr of the Earth's formation ^{15,61} .	The Sm/Nd ratio of the primitive Earth was about 6% above the chondritic value ¹³ .
Earth's oldest rocks show evidence of being derived from a mantle with positive ϵ_{Nd} and ϵ_{Hf} before the formation of the first preserved continental crust.	Extensive continental crust formed before the first preserved continental crust and was recycled through the mantle ⁶² or there is a hidden basaltic low-Sm/Nd reservoir ¹⁵ .	The Sm/Nd ratio of the primitive Earth was about 6% above the chondritic value ¹³ .
The Ar concentration in the mantle is about half the value predicted from the chondritic model ⁶³ .	Only half of the mantle is degassed ⁶³ .	The collisional erosion hypothesis ¹³ predicts a K content of the mantle appreciably below that expected from the chondritic model. Alternatively, the Earth is not chondritic ¹⁶ .
Nb/Ta and Nb/La values of both continental crust and depleted mantle lie below (Nb/Ta) and above (Nb/La) the primitive mantle values of 17.5 for Nb/Ta and 0.9 for Nb/La.	Hidden reservoir enriched in Nb, Ta and Nb with super-chondritic Nb/Ta and sub-chondritic Nb/La ⁶⁴ .	The Nb/Ta and La/Nb values of the primitive mantle lie between those of the depleted mantle (15.5 and 1.2) and the continental crust (12.5 and 2.2).
^4He production in oceans is less than that predicted from observed heat flow and about half that predicted from chondritic Earth model.	^4He stored in lower mantle that is separated by a boundary layer that transmits heat but not ^4He (ref. 65).	Collisional erosion model predicts the Th–U content of the BSE to be about half the chondritic value ¹³ .

half¹³, which halves the already low Urey ratio, implying unlikely cooling rates extrapolated over geological time. Perhaps the Earth is currently in a phase of abnormally fast ocean crust formation and subduction⁵⁹.

It is apparent that the only reliable way of determining the composition of the Earth is by sampling the Earth itself. As argued in this study, the heads of mantle plumes entrain primitive lower mantle. By studying basalts produced by melting this material, especially Archaean basalts associated with komatiites, provided they are not affected by crustal contamination, we are sampling basalts derived from the Earth's earliest and most primitive mantle. It may also be possible to obtain the integrated BSE composition of two of the RLEs most susceptible to collisional erosion—Th and U—from the geoneutrino flux⁶⁰. It would then be possible to see whether the ratios of these elements with other RLEs, such as Ca and Al, were indeed within the range found in chondritic meteorites or that predicted by collisional erosion.

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