

Determining the composition of the Earth

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A long-standing question in the planetary sciences asks what the Earth is made of. For historical reasons, volatile-depleted primitive materials similar to current chondritic meteorites were long considered to provide the 'building blocks' of the terrestrial planets. But material from the Earth, Mars, comets and various meteorites have Mg/Si and Al/Si ratios, oxygen-isotope ratios, osmium-isotope ratios and D/H, Ar/H₂O and Kr/Xe ratios such that no primitive material similar to the Earth's mantle is currently represented in our meteorite collections. The 'building blocks' of the Earth must instead be composed of unsampled 'Earth chondrite' or 'Earth achondrite'.

Most workers assume implicitly that the Earth is made of some sort of extant primitive material delivered to the Earth as meteorites and probably originating in the asteroid belt. Indeed, much has been learned from meteorites about the materials present and processes occurring in the accretion disk as the planets grew. However, confusion is caused by the convenient reference of terrestrial rock abundances to CI chondrites or just 'chondrites', leading to an unintended perception that the Earth must be made of such materials.

The formation of the Earth has been debated in terms of heterogeneous accretion versus homogeneous accretion, with the former holding sway for the last 25 years or so. Heterogeneous accretion, as most prominently championed by Wänke¹, envisioned the material accreting to the Earth changing in composition and oxidation state with time. Driven by the 'stair-step' distribution of siderophile (metal-seeking) elements in the terrestrial upper mantle (Fig. 1), Wänke¹ suggested that the first 80% to 90% of the Earth accreted from very reducing materials. All elements in Fig. 1 except the refractory lithophile elements such as Sc and the rare earth elements (REE) would be quantitatively extracted into the core, and the mantle would be devoid of Fe²⁺. The next 20% to 10% or so of material accreting to the Earth would be more oxidizing, and all but the highly siderophile elements (Ir, Os, Au and so on) would remain stranded in the mantle. The highly siderophile elements were again quantitatively extracted into the core. The last roughly 1% added (the 'late veneer'²) was so oxidizing that metallic Fe did not exist (note that CI chondrites³ and Tagish Lake⁴ are the only chondrites containing no metal³), and all siderophile elements delivered by the 'late veneer' were forced to remain in the mantle, where they were very efficiently homogenized at the hand-specimen (centimetre) scale on a global basis. The stair-step pattern of siderophile elements in Fig. 1 is thus explained. We note that the term 'late veneer' is unfortunate, as the last dregs of material accreted to Earth are well mixed into at least the upper mantle, rather than veneering the surface. The term is, however, entrenched in the literature.

The heterogeneous accretion hypothesis makes dynamical sense in that the 'feeding zone' of the Earth must have extended further out from the Sun as the growth of planets, particularly Jupiter, increased the relative velocities and hence the eccentricities of the accreting material. However, there is a general consensus⁵ that the Earth developed one or more magma oceans late in its accretion, effectively homogenizing any pre-existing material. Thus, there is unlikely to be any record of heterogeneous accretion remaining, with the possible exception of the 'late veneer'. The bulk geochemical properties of the Earth were probably established by magmatic processes in a high-pressure and high-temperature magma ocean environment (see large blue circles in Fig. 1).

The question of whether samples of the 'building blocks' of Earth

are still extant is addressed by examining specific elemental and isotopic properties of the Earth, Mars, comets and meteorites.

Major elements in the Earth and meteorites

It has long been known that the composition of the Earth's primitive upper mantle (PUM, the Earth's mantle immediately after core formation) is distinct from that of any kind of extant meteorite. Geochemical processes on differentiated planets tend to raise the Mg/Si ratio and lower the Al/Si ratio in mantle materials from which magma has been extracted, reflecting the compatible nature of Mg and the incompatible nature of Al. Thus, Mg/Si and Al/Si ratios in samples from both Earth and Mars correlate with a negative slope (Fig. 2). In contrast, primitive materials show a loose positive correlation of unknown meaning.

Several suggestions have been made to explain the elevated Mg/Si and Al/Si ratios in the Earth's PUM relative to undifferentiated meteorites. The most prominent of these include sequestering Si in

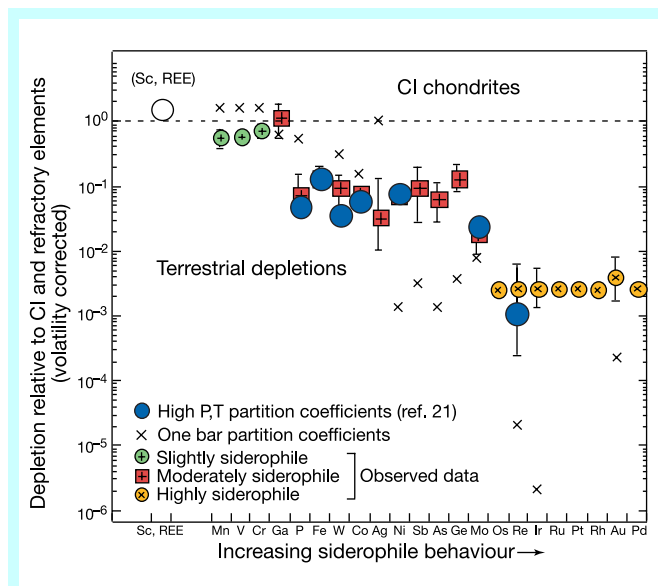


Figure 1 The abundances of elements in the Earth's primitive upper mantle after core formation show a stair-step pattern. This fingerprint contains clues to accretion and planetary differentiation. Comparison of the observed siderophile element depletions in Earth's upper mantle (green, red and yellow symbols; abundances normalized to CI carbonaceous chondrites and refractory elements), with those calculated using one bar partition coefficients (crosses) and high-pressure (P)/high-temperature (T) calculated partition coefficients (blue circles)²¹. Calculated depletions using the latter partition coefficients overlap the observed depletions, consistent with metal-silicate equilibrium and homogeneous accretion. REE, rare earth elements.

the core of the Earth, raising the Mg/Si and Al/Si ratios in the silicate mantle¹⁶, or appealing to the possibility that the lower mantle of the Earth has a different composition from the upper mantle, that is, that PUM is not representative of the bulk mantle⁷.

Although Si can be extracted into metallic cores under very reducing conditions, it is not extracted into metal at or near the iron-wüstite oxygen buffer and at the pressures and temperatures of the base of a magma ocean in sufficient abundance to account for the high Mg/Si ratio of PUM. Further, there is no compelling experimental evidence that Si is extracted into the core under present core–mantle boundary conditions. For example, at the base of a high pressure/temperature terrestrial magma ocean, the metal/silicate partition coefficient for Si (ref. 8) is approximately 10^{-3} to 10^{-2} . It is also inconsistent with the PUM abundances of first-transition-series elements such as V, Cr and Mn, because they would be depleted far below observed abundances if conditions were sufficiently reducing to allow Si to dissolve in the Earth's core⁹.

The question of whether the composition of the lower mantle is different from the upper mantle is more complicated. If the lower mantle, constituting 68% by volume of the mantle, has a different bulk composition from PUM, then arguments about the bulk composition of the silicate Earth based on PUM are flawed. Certainly distinct radiogenic isotopic reservoirs have evolved and been preserved over time, but these systems by their very utility are intensely sensitive to geochemical fractionation events associated with mantle melting (Rb/Sr, Sm/Nd), atmospheric outgassing (I/Xe) and core segregation (U/Pb), for example. The existence of these reservoirs does not imply the existence of distinct reservoirs with radically different major-element compositions.

Indeed, most geophysical measurements are at least consistent with the upper and lower mantle having broadly the same composition. Electrical conductivity measurements on magnesiowüstite¹⁰ indicate that the lower mantle must have the same molar Mg/(Mg + Fe) ratio as the upper mantle. Ito and Takahashi¹¹

showed that the isochemical transformation of $(\text{Mg,Fe})_2\text{SiO}_4$ (spinel) with the upper-mantle molar Mg/(Mg + Fe) ratio of 0.9 to $(\text{Mg,Fe})\text{SiO}_3$ (Mg-perovskite) and $(\text{Mg,Fe})\text{O}$ (magnesiowüstite) is sharp to less than 6 km and perhaps as sharp as 1.5 km at 660 km depth, in agreement with seismic evidence for a sharp boundary. Thermal expansivity measurements¹² show that a change in chemistry (higher Fe-content) at 660 km could be compensated by an increase in temperature across the 660-km boundary, precluding evaluation of model compositions of the lower mantle using density comparisons. However, melting curves for Fe, FeO and FeS are consistent with a core–mantle boundary temperature below 3,500 K, implying that there is not a thermal boundary layer at 660 km and that the upper and lower mantle compositions are the same. Seismic tomography shows mixing of material from the upper mantle into the lower mantle and a return flow of lower mantle material into the upper mantle, as does fluid dynamical modelling¹³. Indeed, if the lower mantle was Fe-rich and had a higher density than the upper mantle, the lower and upper mantle would have to convect separately. Thus there is no compelling evidence that the bulk composition of the lower mantle is different from the upper mantle, with the possible exception of the very deep mantle¹⁴.

It is important to note that there is no such thing as a unique 'chondritic' or 'average Solar System' composition (Fig. 2). Primitive, undifferentiated meteorites, all of which presumably sample material currently present in the Main Belt of asteroids and are residues of the formation of the inner Solar System, have distinct Mg/Si versus Al/Si ratios in spite of their residence between about 2 and 4 AU. Clearly spatially associated reservoirs in the accretion disk were produced with modestly distinct bulk compositions. Estimates of the Earth's PUM are also distinct from any known type of meteorite. A reasonable conclusion is that the Earth accreted primarily from material with major-element compositions that were distinct from extant primitive meteorite types.

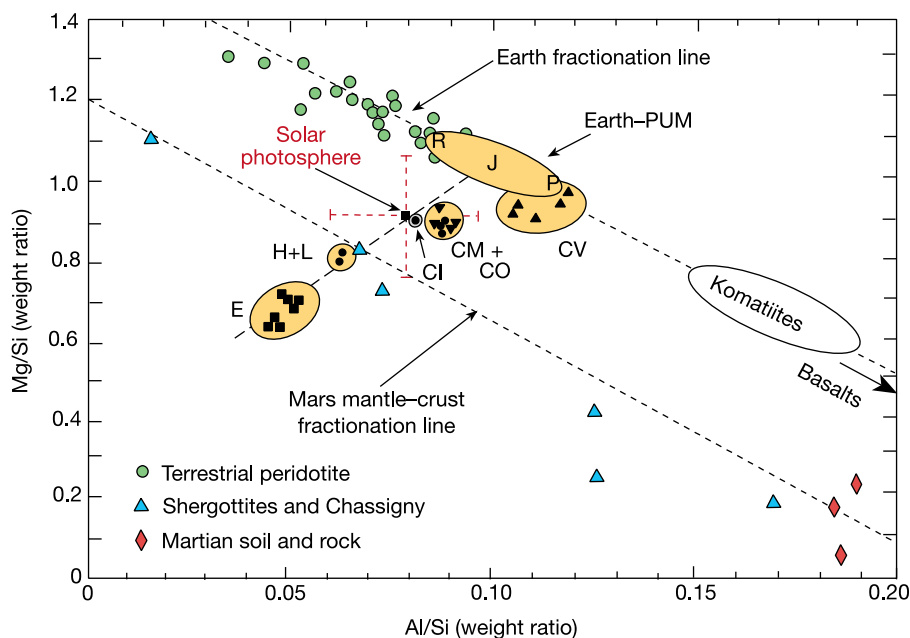


Figure 2 The major-element composition of primitive material in the inner Solar System is not of uniform composition, but defines an unexplained trend. Mg/Si versus Al/Si ratios in chondritic, terrestrial and martian materials^{35–37}. Abbreviations are as follows: enstatite (E), ordinary (H, L) and carbonaceous (CI, CM, CO and CV) chondrites. Dots are terrestrial peridotites, komatiites and basalts that fall off the diagram to the

right. The letters R, J, and P refer to estimates of the bulk silicate Earth composition (refs 38, 35 and 39, respectively). The martian fractionation line is defined by Chassigny, shergottites and martian soils and rocks from the Viking and Pathfinder mission³⁷. PUM, primitive upper mantle of the Earth.

Oxygen isotopes in the Earth

A cursory examination of the oxygen isotopic composition of meteorites indicates that only the enstatite meteorites (chondrites and achondrites) share a common oxygen reservoir with Earth, ruling out all other individual meteorite types as the ‘building blocks’ of the Earth (Fig. 3). Although the Earth could, in principle, be a mixture of existing meteorite types falling on both sides of the Earth–Moon–enstatite meteorite line, this possibility is unlikely. Clayton and Mayeda¹⁵ point out that the bulk oxygen compositions of the Earth, the Moon and Mars are very similar to ordinary chondrites (Fig. 3). They are sufficiently distinct from carbonaceous chondrites that no more than a few per cent of carbonaceous-chondrite-like material contributed to the formation of the Earth and terrestrial planets. Further, the existence of Mars at 1.5 AU with a different oxygen-isotopic composition from the Earth indicates that distinct oxygen reservoirs are preserved over relatively small annuli of heliocentric distance.

The existence of enstatite chondrites points to at least one primitive material with appropriate oxygen-isotopic composition. There is no reason why materials with different characteristics should not have the same oxygen-isotopic composition. Indeed, if the Earth’s Moon was formed in a giant impact and the Moon is derived largely from the impactor^{16,17}, then at least two large bodies, the proto-Earth and the impactor, had identical oxygen-isotopic composition¹⁸, and are within error of the oxygen-isotopic ratio in enstatite chondrites and achondrites.

Initial ¹⁸⁷Os/¹⁸⁸Os ratio in PUM of the Earth

The chondritic relative abundances of highly siderophile elements (HSE) in Earth’s PUM (Fig. 1) are proposed to be the result of late addition of chondritic material to the mantle after core formation had ceased (the ‘late veneer’). Rhenium and osmium are two HSEs that are linked by beta decay, $^{187}\text{Re} = ^{187}\text{Os} + \beta$. Thus Os isotopes can be used as a constraint on Earth’s bulk composition. The Earth’s PUM has a significantly higher ¹⁸⁷Os/¹⁸⁸Os ratio than carbonaceous chondrites, effectively ruling them out as the source of the ‘late veneer’ (Fig. 4). The PUM ¹⁸⁷Os/¹⁸⁸Os ratio overlaps anhydrous ordinary chondrites and is distinctly higher than anhydrous enstatite chondrites. The identification of anhydrous meteorites with the

‘late veneer’ is important in the context of the possible identification of material that delivered water to Earth with the material that delivered the siderophile element ‘late veneer’ (see below).

D/H ratios in the Earth, Mars, meteorites and comets

The origin of Earth’s water can also be investigated by examining deuterium/hydrogen (D/H) ratios in various planetary materials (Fig. 5). The D/H ratio of Vienna standard mean ocean water (VSMOW) on Earth is 150×10^{-6} , similar to the average for carbonaceous chondrites (150×10^{-6}). The corresponding average for Mars (there is considerable spread and there is no extant water ocean) is about 300×10^{-6} , similar to the value for comets: 300×10^{-6} (Fig. 5). These observations suggest local and distinct sources for most of the water in Earth and Mars.

It is possible that the D/H ratio on Mars has been raised from its original value by differential loss of H, as is suggested by the elevated D/H ratio in the martian atmosphere (Fig. 5). However, Mars has been outgassed less than the Earth because its smaller mass would lead to more rapid loss of heat. Thus, the lower martian mineral and rock D/H ratios are most probably representative of the solid undegassed planet (Fig. 5). An alternative interpretation¹⁹ notes that the lack of exchange between the martian lithosphere and hydrosphere allows for the possibility that the D/H ratio of the unsampled martian interior could be very different from rocks, minerals and atmosphere. Sampled rocks, minerals and atmosphere could reflect addition of unrecycled cometary material.

Indigenous or exogenous sources of the Earth’s water

The origin of the Earth’s water is intimately associated with the nature of the ‘building blocks’ of Earth. Two schools of thought bracket the possibilities. One view holds that temperatures were too high at 1 AU for hydrous phases to exist in the accretion disk, so that the Earth accreted ‘dry’. Water, and probably organics, were most probably delivered from exogenous sources (such as comets or meteorites) after the Earth had formed. An alternative view holds that the Earth accreted ‘wet’, with anhydrous and hydrous silicate phases among the material accreted to the growing planet. In this view, Earth’s water has an indigenous origin. We note that one version of the magma-ocean hypothesis^{20–23} requires the Earth’s magma ocean to be hydrous (~3 to 4 wt% H₂O).

Delivery of water while metal is present would lead to H being extracted to the core through metal–silicate equilibrium²⁴. The

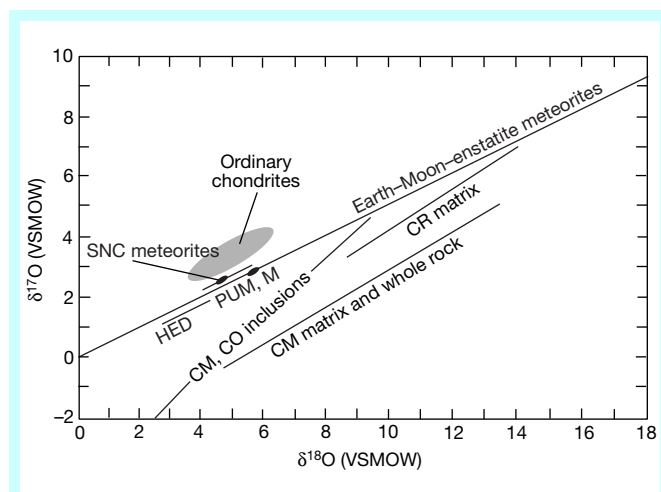


Figure 3 Simplified oxygen-isotope plot of inner Solar System material, after refs 15 and 40–42. The PUM and M (the bulk Moon) are in the small black ellipse on the Earth–Moon–enstatite meteorites line. SNC (shergottite, nakhlite, chassignite) meteorites are believed to be martian (bulk Mars denoted by black ellipse). The Solar System is divided into discrete oxygen reservoirs, and relationships between Solar System objects can be established by use of this technique. CM, CO and CR are carbonaceous chondrites. HED (howardite, eucrite, diogenite) meteorites are believed to be samples of asteroid Vesta. VSMOW, Vienna standard mean ocean water.

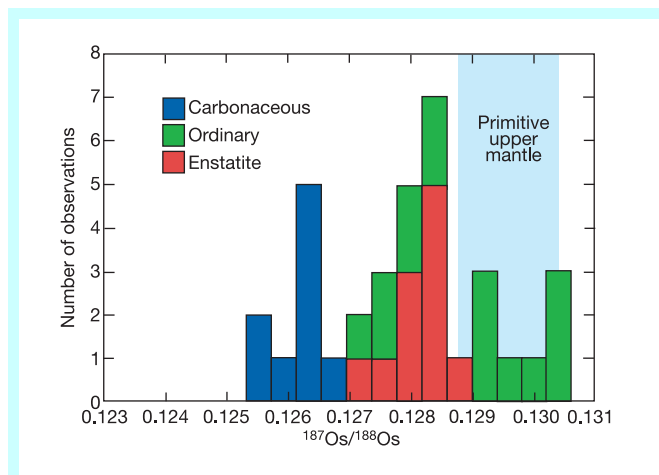


Figure 4 ¹⁸⁷Os/¹⁸⁸Os ratios in carbonaceous, ordinary and enstatite chondrites, and in the Earth’s primitive upper mantle. The ratios are distinct and are diagnostic of the nature of the Earth’s ‘late veneer’⁴³. Mars is not plotted because the uncertainty in its initial ¹⁸⁷Os/¹⁸⁸Os ratio is larger than the range of the x axis.

efficiency of this process is not well characterized, but work until now suggests that Earth must have had large additions of water during accretion so that there was enough left in the mantle to make the oceans. Given such water additions, there are a number of possible ways in which the Earth received its water:

(1) Earth could have accreted 'dry' with all water being added late in accretion from carbonaceous chondrites, or 'wet' with some addition of water from carbonaceous chondrites (exogenous). In this case, the amount of carbonaceous chondrite material added would scale directly with the mass of water in the Earth. However, as discussed below, neither scenario is consistent with the observation that the HSE 'late veneer' and the Earth's Kr/Xe ratio are not carbonaceous chondritic.

Late delivery of water from carbonaceous chondritic material must be consistent with the siderophile element 'late veneer' (see Fig. 1). Let us make conservative assumptions designed to maximize the possibility that late-delivered asteroidal material is the source both of the Earth's water and the 'late veneer'. The mass of the Earth is 5×10^{27} g and the mass of the Earth's mantle is 4.11×10^{27} g. The minimum mass of water in the Earth is the current water content of the Earth's oceans, about 1.4×10^{24} g. We note, however, water masses up to 50 times this amount have been postulated²⁵. The abundance level of siderophile elements which characterize the 'late veneer' is $0.003 \times \text{CI}$ (Fig. 1), where CI is the abundance of siderophile elements in CI carbonaceous chondrites. It has been suggested that the abundance level might be as high as $0.007 \times \text{CI}$ (ref. 26), but this factor-of-two uncertainty is insignificant for the arguments that follow. The mass of material necessary to generate the siderophile element 'late veneer' is about 10^{25} g if the 'late veneer' is mixed throughout the entire mantle of the Earth, and about 0.3×10^{25} g if the 'late veneer' is mixed only into the upper mantle.

Using these numbers, assuming carbonaceous chondritic material containing 10 wt% water, and assuming that the fraction of water retained by Earth is 1, the mass of material accreted to yield the minimum mass of water in the Earth is 1.4×10^{25} g. This value is not distinguishable from the mass of material needed to generate the 'late veneer' in the whole mantle, 10^{25} g, but appears to be a factor of five too high if the 'late veneer' is only mixed into the upper mantle (0.3×10^{25} g)²⁶. Moreover, addition of such a water-rich 'late veneer' would require carbonaceous chondritic material, but the Os-isotopic compositions of carbonaceous chondrites are inconsistent with that of the Earth's PUM.

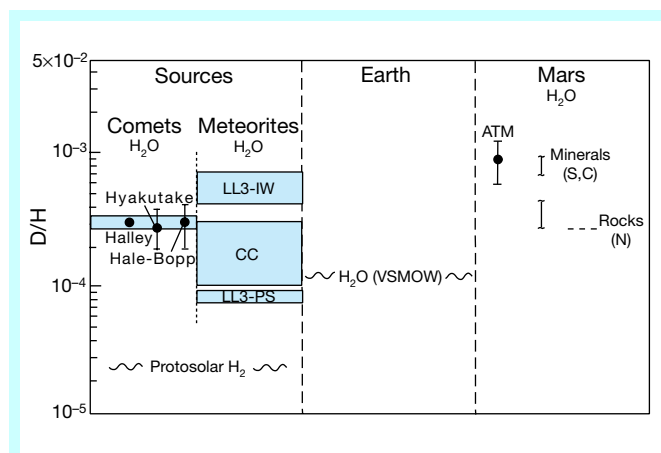


Figure 5 The D/H ratios in H₂O in three comets, meteorites, Earth, protosolar H₂, and Mars^{19,28,29,44–46}. CC, carbonaceous chondrites; LL3-IW, interstellar water in Semarkona; LL3-PS, protostellar water in Semarkona. D/H, deuterium/hydrogen ratio. ATM, atmosphere.

Recall, further, that we have made the most conservative assumptions. C-type asteroids are concentrated in the outer part of the Main Belt. CI, CM and CR carbonaceous chondrites contain 3,600–11,800 p.p.m. H (ref. 27), corresponding to about 3–9 wt% H₂O if all the H is in H₂O. It is unclear how much of the H measured is bound up in organic material rather than H₂O. Thus, the average H₂O-content of these carbonaceous chondrites may be much less than the maximum value of about 9 wt% H₂O. CO carbonaceous chondrites contain trivial amounts of H. Other asteroid types, such as S-types, are concentrated in the inner part of the belt and are anhydrous. If the average water content of the accreting material is lower than 10 wt%, as it must have been because other lower water-content or anhydrous material must also have been accreted, then the mass of material required to generate the minimum mass of water in the Earth would increase inversely with the average water content of accreting material. If the fraction of water retained is less than 1, as seems probable, the mass required also increases by inverse relation. If the 'late veneer' is restricted to the upper mantle, only, then the mass required to deliver the minimum mass of the Earth's water is three times higher than that required to deliver the 'late veneer'. If the mass of the Earth's water exceeds the minimum (one Earth ocean mass) used here, as seems inevitable, the mass of material required to deliver that water would exceed the mass required by the 'late veneer' by a precisely proportionate amount.

Stated differently, there is equivalence between the mass of the 'late veneer' and the mass of water only if the hydrous material averages 10 wt% water, the fraction of water retention is one, the mass of water in the Earth corresponds to one Earth ocean (the minimum mass), the 'late veneer' is mixed throughout the mantle, and currently unsampled hydrous material with PUM isotopic ratios was accreted.

(2) Earth could have accreted 'wet' with some exogenous addition of water from comets. Indigenous Earth water could have had D/H ratios representative of the inner Solar System, that is, low values because of relatively higher nebular temperatures, perhaps like protosolar hydrogen ($2\text{--}3 \times 10^{-5}$)²⁸, in which case a cometary contribution of up to 50% is possible. Alternatively, indigenous Earth water could have had D/H ratios representative of a protostellar water component identified in meteorites ($\sim 9 \times 10^{-5}$)²⁹, in which case there could be as little as a 10–15% cometary contribution¹⁹.

Delivery of water from comets can be evaluated in the light of other cometary geochemical data. For instance, for an assumed Ar/H₂O ratio of 1.2×10^{-7} in the bulk Earth, comets like Hale–Bopp with an approximately solar ratio of Ar/H₂O (ref. 30) would bring in 2×10^4 more Ar than is presently in the Earth's atmosphere³¹, if 50% of Earth's water, the maximum amount permitted by D/H ratios, was derived from comets. If this measurement of comet Hale–Bopp is applicable to all comets (note that an Ar/O ratio of less than 0.1 times the solar ratio has recently been reported for comet LINEAR³²) that collided with Earth over Solar System history, then there has been minimal delivery of water in the form of comets subsequent to core formation. Both Ar/H₂O and D/H data suggest either that (1) the 'late veneer' was non-cometary water-bearing material or that (2) Earth accreted 'wet'.

(3) Earth could have accreted 'wet', that is, from hydrous and anhydrous materials, with no significant addition of water from exogenous sources. In this case, hydrous phases would have a mean D/H ratio yielding VSMOW in liquid water. Oxygen, D/H and Os isotopic ratios all point to this scenario being most likely, as these ratios rule out extant meteoritic materials as sources of the Earth's water. If the Ar/H₂O ratio measured in comet Hale–Bopp is correct and representative of all comets colliding with Earth (again, see ref. 32), then cometary water may also be ruled out. The most probable source of water is a hydrous inner Solar System reservoir at approximately 1 AU, but we cannot formally rule out a single wet planetary embryo from the asteroid belt or a large comet with the

appropriate elemental and isotopic characteristics³³. Such an asteroid or comet would have to be unlike any sampled materials, however.

Kr/Xe ratios

⁸⁴Kr/¹³⁰Xe ratios in the Earth's atmosphere, average Solar System material, CI carbonaceous chondrites, and enstatite chondrites³⁴, are given in Table 1. It is immediately clear that Earth's noble gases are distinct from both types of primitive meteorites. These differences may have arisen from some secondary process. Regardless, it seems unlikely that Earth's Kr/Xe ratio is derived from carbonaceous chondrites.

What the Earth is not made of

Selected features of the Earth, Mars, primitive meteorites, and comets imply mutually inconsistent requirements for the Earth to be composed of extant materials. For example:

(1) The major-element composition of the PUM of the Earth seems to be part of a progression of closely related compositions (Fig. 2). There is a continuum of planetary materials increasing in Mg/Si and Al/Si ratios in the order: enstatite, ordinary, bulk Mars, carbonaceous chondrites, PUM.

(2) Oxygen isotopes require that the Earth be made of either enstatite meteorites or a mixture of meteorites falling above and below the Earth–Moon–enstatite meteorite mass fractionation line (Fig. 3). The similarity of the bulk oxygen-isotopic composition of the Earth and chondritic meteorites precludes more than a few per cent of carbonaceous chondritic material accreting to the Earth (Fig. 3). Further, the existence of Mars at 1.5 AU with a different oxygen-isotopic composition from the Earth points to distinct oxygen reservoirs being preserved over relatively small annuli of heliocentric distance.

(3) The Os-isotopic composition of the PUM of the Earth, believed to be that of a late addition called the 'late veneer', is inconsistent with water-bearing carbonaceous chondrites, but is consistent with anhydrous ordinary chondrites (Fig. 4).

(4) Measurements of D/H ratios in Earth and carbonaceous chondrites differ from Mars and comets by about a factor of two (Fig. 5). These observations are best explained by an indigenous and distinct source of most of the water on Earth.

(5) Measurements of ⁸⁴Kr/¹³⁰Xe ratios in Earth's atmosphere are different from extant carbonaceous and ordinary chondritic meteorites.

(6) A source of water further from the Sun than 1 AU requires water-bearing carbonaceous chondrites to deliver water. Mass balance considerations, however, indicate that even the minimum water budget of the Earth being delivered in this manner would lead to excesses of highly siderophile elements in the PUM relative to observation, if the 'late veneer' is mixed only into the upper mantle. Comets can deliver no more than 50 wt% of the Earth's minimum water budget.

What the Earth is made of

The logical conclusion of the previous discussion of major element, O and Os isotope, noble gas and D/H data is that the Earth accreted at least in part from hydrous materials that are not represented in

our meteorite collections—they are no longer extant in the inner Solar System. Free water in the Earth is derived from such material accreted after core formation effectively ceased. A cometary contribution of less than 50 wt% of the Earth's minimum water budget cannot be presently excluded.

In this case, the similarity of the ¹⁸⁷Os/¹⁸⁸Os ratio in PUM with ordinary chondrites and oxygen isotopic composition of PUM with the enstatite meteorites is *prima facie* evidence for the existence of Earth-building materials sharing some properties in common with various extant meteorites, although no extant meteorites share all of the properties of Earth material. All such material is either contained in the Earth and Moon or was ejected from the inner Solar System, consistent with the fate of material during the giant impact that is believed to have formed the Moon. Earth-forming material contained both metal and silicate, at least some portion of which was hydrous.

Although comets and known meteorite types are not suitable candidates for exogenous sources for most of Earth's water, we note that many potential exogenous, water-bearing materials have not yet been characterized or recognized. Studies of Kuiper-belt objects, trans-neptunian objects, interplanetary dust particles (IDPs), interstellar ice, and rare meteorites may all offer new insights into this problem. Only if we postulate the existence of hydrous material with ordinary chondritic Os isotopes, a material not currently sampled on Earth, can the 'late veneer' be reconciled with the Earth's water budget.

A unique bulk composition for Earth implies that compositionally distinct reservoirs were maintained in the main asteroid belt and in planetesimals at Earth's and Mars' semi-major axes. The distinct oxygen-isotope signatures of Earth and Mars reinforce that conclusion. The implication is that there was not widespread mixing of the bulk of the material in the inner Solar System during accretion and that planetary objects forming in the inner Solar System received the overwhelming majority of their masses from narrow annuli around the Sun. □

Table 1 Ratios of ⁸⁴Kr/¹³⁰Xe in various Solar System objects³⁴

Object	⁸⁴ Kr/ ¹³⁰ Xe ratio
Solar System	0.7 × 10 ⁻²
CI carbonaceous chondrites	5.1 × 10 ⁻²
Enstatite chondrites	(5–23)
Earth's atmosphere	12. × 10 ⁻²

We note that extant meteorites have ⁸⁴Kr/¹³⁰Xe ratios that are very different from Earth's atmosphere.

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Acknowledgements

Supported by NASA and NSF. We thank D. Lauretta for comments. A review by T. Owen brought noble gas ratios in Solar System bodies to our attention. Discussions with H. McSween, D. Kring, R. Boehler, D. Mao, L. Stixrude, A. Morbidelli, J. Lunine, F. Robert and T. Swindle have been helpful.

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