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Volatile accretion history of the terrestrial planets and dynamic implications

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Accretion left the terrestrial planets depleted in volatile components. Here I examine evidence for the hypothesis that the Moon and the Earth were essentially dry immediately after the formation of the Moon—by a giant impact on the proto-Earth—and only much later gained volatiles through accretion of wet material delivered from beyond the asteroid belt. This view is supported by U–Pb and I–Xe chronologies, which show that water delivery peaked ~100 million years after the isolation of the Solar System. Introduction of water into the terrestrial mantle triggered plate tectonics, which may have been crucial for the emergence of life. This mechanism may also have worked for the young Venus, but seems to have failed for Mars.

Earth, Mars and Venus are three planets with very different histories. Active plate tectonics, the presence of a liquid ocean, and teeming life characterize the Earth. Mars has a tenuous atmosphere, shows no incontrovertible evidence of plate tectonics, lacks an abundant hydrosphere, and has so far evaded all attempts to reveal the presence of life. Venus is a dead inferno of carbon dioxide with clouds of sulphuric acid, and its solid surface seems to have been violently resurfaced some 600–900 million years (Myr) ago. At a time when so many satellites and telescopes are probing the Universe in search of habitable planets, it is worth questioning what made three planets of our Solar System so different from each other that only one of them harbours life.

Figure 1 | Fractionation of Zn isotopes is incompatible with volatilization. The data[87] represent the δ^{66}Zn value, the relative deviation of the ^{66}Zn/^{64}Zn ratio in per mil with respect to a terrestrial standard, of each sample. Data for terrestrial samples are shown in pale grey; data for the different classes of carbonaceous chondrites are shown in dark blue (CI), green (CM), red (CV) and orange (CO). In the case of volatilization, preferential loss of the light ^{64}Zn isotope in the residue is expected to accompany the increase of the Mg/Zn ratio, as magnesium ($T_{50} = 1,336$ K) is much more refractory than zinc ($T_{50} = 726$ K). Because the opposite is observed, fractionation processes other than volatilization must be sought. T_{50}, at which 50% of the element is condensed[13].

When life is the topic, the presence of liquid water immediately becomes an issue. The origin of water and its fate have also been central concerns of the planetary sciences, because water changes the rheological properties of planetary mantles and seems to be a prerequisite for plate tectonics to operate. A commonly held view is that the terrestrial ocean results from the outgassing of the Earth's mantle[1]. Recent dynamic calculations, however, emphasize the hot temperatures next to the nascent Sun, and suggest that the planetary embryos from the inner Solar System remained essentially dry. It is only late in accretion history that perturbations of asteroid orbits in the inner Solar System by giant planets started to launch ice-rich material that delivered water to the planets in that part of the Solar System. A simplistic but efficient description of the debate on planetary water is that of 'dry' versus 'wet' accretion.

This Review will first show that the depletion of the volatile content of the Earth and other terrestrial planets is not due to loss by outgassing but to incomplete stepwise accretion of nebular material; this accretion was interrupted by energetic electromagnetic radiation that was emitted by the young Sun during its T Tauri phase and swept through the disk. The timing of volatile accretion, water in particular, with respect to the giant lunar impact, the formation of the terrestrial core, and its implications for the contrasting geodynamic regimes of the Earth, Mars, and Venus will be discussed.
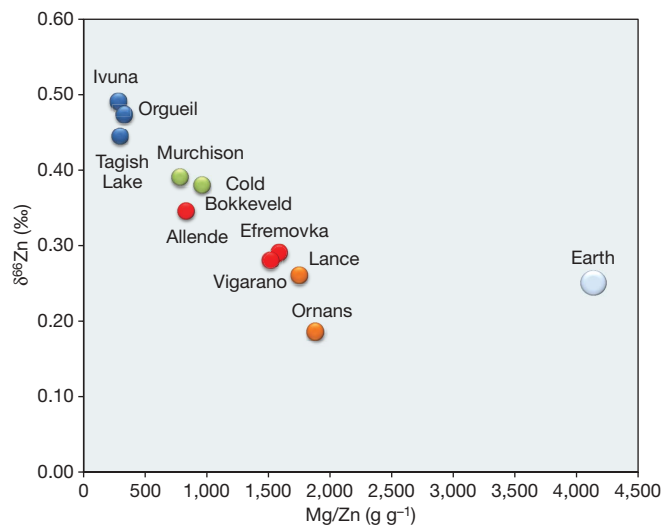
Water in the deep Earth

The Earth contains water in different forms: a liquid ocean at the surface, various forms of ground water and, in the mantle, dense hydrous mineral phases and water dissolved in nominally anhydrous minerals such as olivine. Evidence for how much water the solid Earth contains is robust. In the absence of a gaseous phase, that is, at depths in excess of about 90 km, water behaves as an incompatible element with properties remarkably similar to those of cerium[2]: the H_2O/Ce ratio is about 200 in the source of both mid-ocean ridge basalts and ocean island basalts, which are widely taken as melts from upper- and lower-mantle material, respectively. Given this strong constraint and reasonable assumptions on the degrees of melting prevailing during the formation of these melts, the amount of water held by the mantle is approximately equivalent to an oceanic mass, which translates into 150–350 p.p.m. H_2O in the mantle and a bulk terrestrial water concentration of 300–550 p.p.m. (refs 3, 4). The water content of the Archaean mantle is open to interpretation[4],

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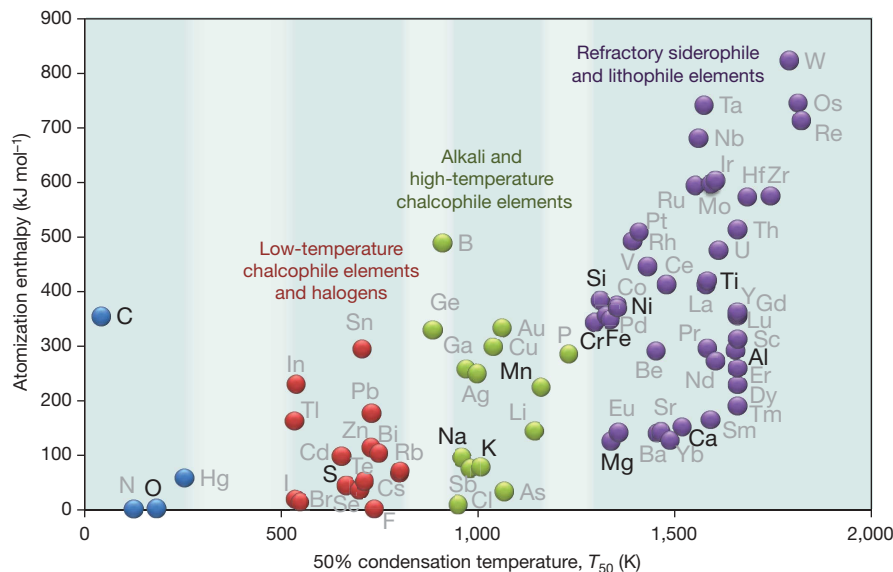
Figure 2 | Stepwise accretion of the elements on cooling of the solar nebula, shown as atomization enthalpy versus T_{50}. The two axes represent two different volatility scales, an intrinsic scale given by the atomization enthalpy[29], which is essentially equivalent to the mean bonding energy per atom in solids, and a scale dependent on the nebular chemistry, T_{50} (see Fig. 1 legend). Black letters, major elements; grey letters, minor and trace elements. The platinum group elements, plus Al, Ti, Zr and W, and most rare-earth elements and actinides, which condense first above 1,600 K, are preferentially found in refractory inclusions. The group of mildly refractory lithophile elements, which comprise the major elements Si, Mg, Fe and Ca, accrete down to 1,300 K as metal, olivine and pyroxenes, and make up the bulk of the planetary mantle and core. These refractory elements are separated from the high-T chalcophile elements (As, Ga, Ge, Cu, Ag), chlorine, and the alkali elements (Li, Na, K, Rb and Cs), which condense between 1,150 and 850 K. From 750 to 530 K, the low-T chalcophile elements (Pb, Bi, Sn, Zn, Cd, S, Te) precipitate, followed by the truly volatile elements (N, C, H) and Hg. Each group appears to be separated from its neighbours by a temperature gap (highlighted in white).

but seems to have been lower than that of the modern mantle. As it is particularly difficult to ascertain whether the measured water contents of lavas reflect their contents at the time of eruption, the Ce contents of melt inclusions in olivine from the 2.7-Gyr-old komatiites from Belingwe, Zimbabwe[5], and Alexo, Canada[6], can be used as a proxy; they show that if the H_2O/Ce ratio has not significantly evolved since that time, the mantle at 2.7 Gyr ago contained ~150 p.p.m. H_2O for 50% melting and ~60 p.p.m. for 20% melting.

It has been suggested that much of the mantle's water may accumulate in the transition zone in waddsleyite[7,8] and, therefore, that the water content of the mantle may not be homogeneous. This is true only if water is held back in the transition zone on subduction and not dragged down with its carrier minerals. Fractionation across the phase-change boundary requires that when wet material is transported in and out of the transition zone, the advective flux is compensated for by diffusion of hydrogen: at the temperatures prevailing in the sinking plates (600–1,200 °C), the diffusion coefficients of hydrogen in the major minerals are very small[9] and the wet boundary layer appearing across the reaction zone very thin. Accumulation of water in waddsleyite is therefore of little significance to the overall budget of water in the mantle.

Volatile depletion in the terrestrial planets

Planets formed by accretion of solid material condensed from the solar nebula. The strong electromagnetic winds emitted by the early Sun swept away the nebular gas and condensation stopped well before the debris disk was cleared, a process that lasted less than a few Myr after the isolation of the Solar System[10]. Most of the material that eventually formed the Earth accreted well within the 'snow line', which is the virtual line beyond which water freezes out[11,12]. A widely used scale of volatility is the temperature T_{50} at which 50% of the nebular inventory has been accreted to the solid phase. Let us consider two elements with widely different values of T_{50}, namely, the refractory element uranium ($T_{50} = 1,610$ K), and the more volatile element potassium ($T_{50} = 1,006$ K)[13]. The K/U ratio is a measure of the relative depletion of planetary volatile elements with respect to

refractory elements. Carbonaceous chondrites and the solar photosphere provide a coherent estimate of the initial K/U ratio of 60,000 (ref. 14). The terrestrial value of ~10,000 (refs 15, 16) indicates that the Earth lacks 85% of the nebular K inventory, while the deficit for the Moon (K/U ≈ 3,000) is 95%. Martian meteorites that have been witnessed falling and therefore evaded long periods of terrestrial weathering show K/U ratios <20,000 (ref. 17). Depletion of 92–98% is also inferred for Zn, Ag, As, Sb, Sn, Pb and, most importantly, S (refs 18, 19). Planets that lack such large fractions of moderately volatile elements cannot have been endowed with large amounts of water.

As shown by isotopic abundances of different elements, the volatile deficit in planetary material is not due to volatilization but to incomplete accretion[20]. Loss of volatile elements due to impact or volatilization during accretion, whether it reflects planetary escape velocities or the molecular stampede of hydrogen escape known as hydrodynamic entrainment[21], is expected to be mass-dependent, and the light isotopes should preferentially be enriched in the vapour phase. The homogenous stable isotope composition of K in planetary samples is inconsistent with preferential evaporation of the light isotopes from initially condensed (CI chondrite) material. Even more conspicuously, the Earth is depleted in the heavy isotopes of Zn by about 0.1‰ per atomic mass unit with respect to CI chondrites, as are the CV and CO chondrites, which are enriched in refractory elements (Fig. 1). This is exactly the opposite of what is expected from preferential loss of the light ^{64}Zn during volatilization. These observations contrast with evidence from lunar soils, which on volatilization by impacts become remarkably enriched in the heavy ^{66}Zn and ^{68}Zn isotopes by 3–4‰ per atomic mass unit[22]. The processes leading to reversed mass fractionation are currently not well understood, and may involve kinetic effects[23] or electromagnetic sorting (Hall effect) of the ionized fraction of the nebular gas[24]. Incomplete accretion is also inferred from the terrestrial abundances of alkali elements, which have comparable volatilities and chemical properties over a broad range of atomic mass M. The depletions of K ($M = 39$, $T_{50} = 1,006$ K), Rb ($M = 85$, $T_{50} = 800$ K)[25] and Cs ($M = 133$,

$T_{50} = 800 \, \text{K})^{26}$ are of comparable magnitude, which also argues against loss by volatilization in a gravity field.

A robust consequence is that the Earth, like the other terrestrial planets, is depleted in volatile elements, not because these were lost by impact or vaporization, but because they did not accrete along with the more refractory elements in the first place.

The stepwise accretion of planetary material

In order to explain the volatile deficit, the idea being pursued here is that the nebular gas was blown off by the energetic radiation of the young Sun before temperature decreased enough for volatile elements to condense on the terrestrial planets. Thermodynamic calculations[27,28] successfully predict the mineralogy and composition of planetary objects. Most elements condense within a narrow temperature interval. As a consequence, accretion takes place as a stepwise process and bulk accretion goes through plateaus when shifting from one group of elements to another with decreasing temperature.

The narrow temperature range of condensation of most elements is a common feature of thermodynamics calculations[13,27,28] and reflects relatively simple properties of solid–gas equilibria. The temperature range ΔT over which elements condense is approximately $RT_{50}^2/\Delta H_{at}^i$, where R is the gas constant and ΔH_{at}^i is the atomization enthalpy[29]. Energy of mineral formation from solid elements and energy of melting can be safely neglected with respect to the enormous energies involved in vaporization. For most elements, ΔT corresponds to a few tens of degrees, except for the alkali elements, Eu and Yb (150–200 K).

Intrinsic volatility is not the sole control of planetary abundances. Figure 2 is a plot of atomization enthalpy versus T_{50}. The highly refractory elements—that is, the platinum group elements, Al, Ti, Zr, W, and most rare-earth elements and actinides, which are all particularly abundant in chondrite refractory inclusions—condense above 1,600 K. They are followed by the dominant group of refractory lithophile elements (Si, P, and the alkali-earth and transition elements typical of chondrules), which condense down to 1,300 K. These refractory elements are separated from a group comprising the high-T chalcophile elements (As, Ga, Ge, Cu and Ag), chlorine, and the alkali elements (Li, Na, K, Rb and Cs), which accrete between 1,150 and 850 K. At lower temperatures (750 to 530 K), the group of low-T
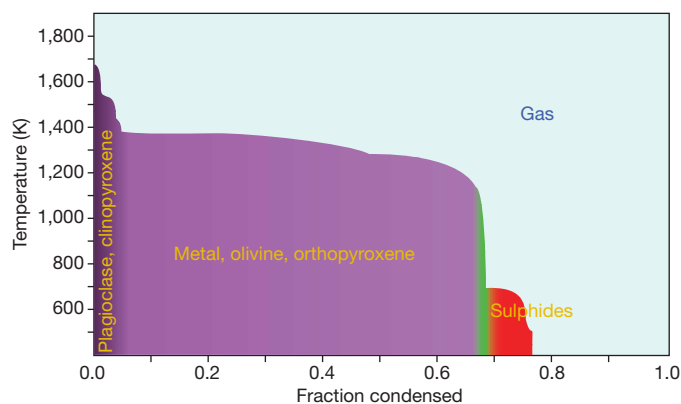
chalcophile elements (Pb, Bi, Sn, Zn, Cd, S and Te) and the rest of the halogens leave the vapour phase. A last group consists of the three most volatile elements (N, C and H) and Hg. Each group appears to be separated from its neighbouring groups by a temperature gap. The stepwise accretion of the planetary material is well illustrated in refs 30 and 31, which show that, at 1,200 K, 50–60% of the nebular inventory is still in the gas phase (Fig. 3). This reflects the combination of the elements into stoichiometric solid phases such as oxides, olivine, pyroxenes, feldspars and metal[13], and, to a lesser extent, the intrinsic volatility of the elements themselves.

The energetic electromagnetic radiation of the young Sun swept away the nebular gas and stopped accretion while the nebular temperature in the neighbourhood of the terrestrial planets was still in the temperature range of alkali element condensation (800–1,000 K)[30,32,33] (Fig. 4). This is the main cause of volatile element depletion in the inner Solar System. In contrast, in material accreted at the snow line and beyond, water and other volatile elements were plentiful. The 'late veneer' hypothesis[34], which holds that small amounts of chondritic material from the asteroidal belt or beyond were added to the Earth at an unspecified late stage, was devised to account for the present-day excess of highly siderophile elements, such as the platinum group elements, in the terrestrial mantle. The depletion of the most volatile elements discussed above places an upper limit on the proportion of low-temperature CI-like material of the order of 2–5%, which is still somewhat higher than the 0.3% proportion of carbonaceous chondrite-type (with ~10% water) material that is deemed[4] necessary to account for terrestrial water.

Making planets and adding water

One model[35] of planetary growth and development may be summarized into three stages: (1) the settling of dust onto the equatorial disk of the planetary nebula and formation of kilometre-sized planetesimals, (2) the runaway growth of planetesimals into Mars-sized planetary embryos, and (3) collision of planetary embryos to form the planets with more or less their modern masses. How fast the nebular gas was
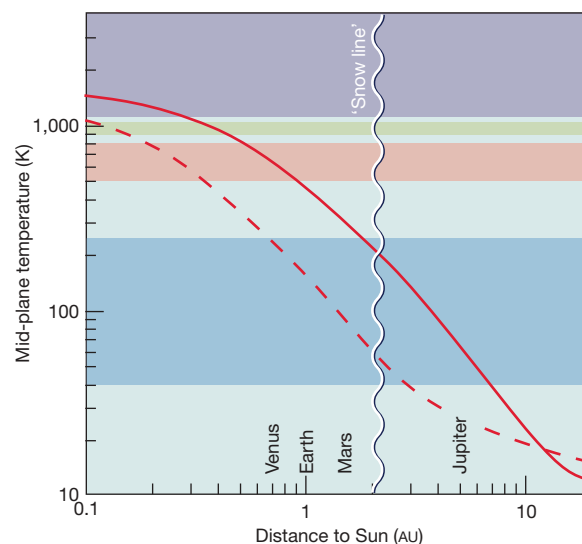
Figure 3 | Stepwise accretion of the elements upon cooling of the solar nebula, shown as fraction condensed versus temperature. Plotted is the fraction of the original condensable matter remaining in the solar nebula at a given temperature (redrawn with changes from ref. 30). The kinks in the accretion rate correspond to the temperature gaps in Fig. 2. After formation of the most abundant refractory phases (plagioclase and clinopyroxene), the bulk of the metallic core and the mantle silicates (olivine and orthopyroxene) is quickly removed from the nebular gas (purple). Alkali elements and high-T chalcophile elements precipitate next (green), but do not constitute a large fraction of the planetary material. Low-T chalcophile elements, sulphur and halogens come after (red), followed by volatile elements. Most elements accrete over a few tens of degrees, but over 150–250 K for the alkali elements, and Eu and Yb. A planet with a substantial deficit of K or Zn with respect to chondrites therefore cannot have accreted much, if any, water.

Figure 4 | The thermal structure of the planetary solar nebula: temperature at mid-plane of the nebular disk. Data are taken from ref. 88. Two models of temperature distribution are shown for two different values of the viscous dissipation parameter, α (viscosity × sound velocity at mid-plane × mean elevation above mid-plane) for a rate of solar accretion of 1% per Myr: $\alpha = 10^{-3}$ (solid line) and $\alpha = 10^{-1}$ (dashed line). The position of the wiggly 'snow line', which separates two domains, ice-free inwards and frosty outwards, nearly coincides with that of the asteroid belt[12]. Colour coded areas correspond to the four groups of elements identified by their T_{50} values in Fig. 2. The depletion of volatiles in the inner Solar System is caused by the strong electromagnetic winds emitted by the young Sun, which swept away the nebular gas before accretion was complete.

blown off by energetic solar radiation is unclear: the delay is constrained by the short lifetime (<3 Myr) of the debris disk[10] and by dynamical models, which require a reduction of planetary eccentricity by dynamic friction between planets, asteroids and planetary embryos[36]. It is likely, however, that the planets may have accreted to a substantial fraction of their final mass before the disk was blown off.

Water delivery by comets[37] with a D/H ratio of 3×10^{-4} (refs 38, 39) seems incompatible with the terrestrial D/H ratio of the terrestrial ocean (1.5×10^{-4})[40]. Carbonaceous chondrites represent an alternative source of terrestrial water[1,41]. Orbits of planetary embryos across the Solar System during accretion have been computed[42] and these authors concluded that the bulk of the water at present on Earth was carried by only a few of these objects, originally formed in the outer asteroid belt and accreted to the Earth during the waning stages of its formation. As long as the nebular gas was present and was absorbing electromagnetic radiation, the inner Solar System was too hot to allow for significant water condensation along with metal and silicates: only during the late stages of accretion had temperature declined enough for water delivery to be efficient. Dynamical models[43] suggest that early accretion of asteroid and planetary embryos was local, and therefore that the accreted material was largely dry up to the snow line and ice-rich beyond. It is also found that radial mixing and inward migration of wet high-eccentricity objects from the outer Solar System increased dramatically in the later phases of accretion. Water absorption in the hot inner Solar System has been proposed[44] but, as two-dimensional liquid films cannot form below the critical temperature of water, this process is unlikely to be significant.

The mechanism of water accretion depends on the relative timing of three important events—the segregation of the terrestrial core, the giant lunar impact, and the arrival of the late veneer (Fig. 5). The identical ^{182}W excesses found in the silicate fractions of the Earth and the Moon require that the giant impact took place at the earliest 60 Myr after the formation of calcium-aluminium-rich inclusions[45] unless the Hf/W ratios of the two planetary bodies also are similar, in which case this time can be reduced to ~30 Myr (refs 46, 47). A

lunar impact with a wet Earth, that is, after substantial amounts of late veneer had been accreted, is difficult to reconcile with the remarkable depletion of volatiles in the lunar mantle[30,48] with respect to the terrestrial mantle. The contrasting abundances of the stable (unradiogenic) Ne isotopes 20 and 22 (ref. 49) and of the stable Xe isotopes 124, 128 and 130 (ref. 50) between the terrestrial mantle, represented by basalts and CO_2 wells, and the terrestrial atmosphere also require that a substantial fraction of the volatiles was accreted after the last large-scale melting of the Earth. The invariant proportions of the stable Ar isotopes 36 and 38 in all terrestrial solids and gases[51,52] indicates that isotope fractionation of Ne and Xe was not caused by hydrodynamic escape. Although the case has been made recently that the lunar mantle may locally hold traces of water[53], the depletion of the Moon in volatile elements, regardless of their atomic weights and therefore of gravitational loss, remains unexplained. However, the occasional closeness of planetary bodies with very different degrees of hydration and, because of lateral transfer, the highly variable water contents of impactors are strong features of dynamic simulations[43].

Because Pb is volatile, with a T_{50} value (~725 K; ref. 13) similar to that of Zn, the arrival of the late veneer can be dated by Pb–Pb chronology. Old feldspars and galenas indicate Pb–Pb ages of the Earth younger by 50–160 Myr relative to the age of the Solar System[54,55] (Fig. 6). The delayed ingrowth of radiogenic Pb therefore is best explained by impacts of asteroids with very low, chondrite-like μ (^{238}U/^{204}Pb) ratios[56] onto a volatile-depleted, high-μ proto-Earth. The μ value of the lunar mantle attested to by Pb isotope systematics of Apollo samples is 200–600 times the ratio of the modern terrestrial mantle and 1000–10,000 times that of CI chondrites[57]. Simple mass balance using the μ values suggests that well over 99% of terrestrial Pb was added by the late veneer. The young Pb–Pb age of the Earth therefore appears to be the mean age of the arrival of the late veneer material and does not represent a date in the history of primordial terrestrial Pb. Some U/Pb fractionation due to volatilization or to incomplete mergers ('hit-and-run' collisions) during the encounter of these asteroids with the Earth may account for the young Pb–Pb ages. Likewise, the apparent I–Xe and Pu–Xe 'ages of the Earth', which are bracketed between 50 and 110 Myr (refs 58–60), date the arrival on Earth of I and Xe, two highly volatile elements, and are
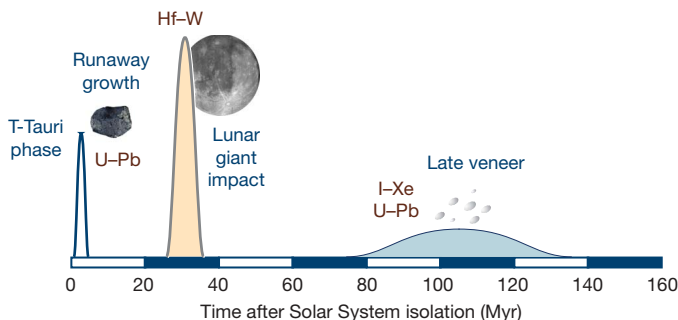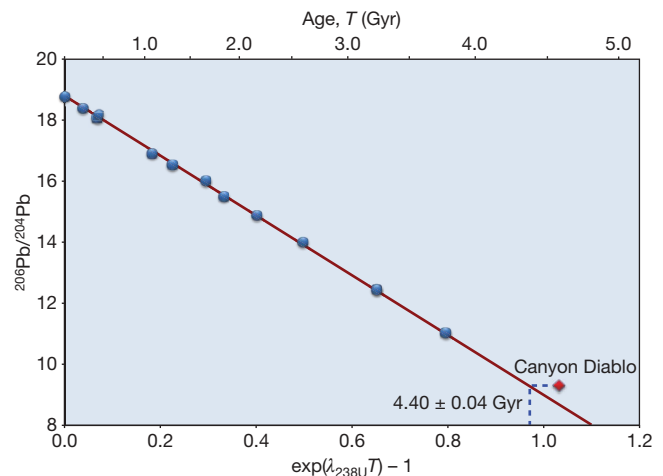

Figure 5 | A tentative chronology of the Earth's accretion. Chronometers shown in brown. Accretion of planetary material was interrupted by energetic electromagnetic radiation (T Tauri phase) sweeping across the disk within a few Myr of the isolation of the solar nebula. Runaway growth of planetesimals produces Mars-sized planetary embryos, which, collision after collision, form the planets with their modern masses. The last of these 'giant' collisions left material orbiting the Earth that later reassembled to form the Moon. The ^{182}Hf–^{182}W chronometer dates metal–silicate separation. The identical abundance of radiogenic ^{182}W between the Earth and the Moon indicates that either the Moon formed after all the short-lived ^{182}Hf had disappeared (>60 Myr) or, rather, the Moon-forming impact and terrestrial core segregation took place simultaneously 30 Myr after isolation of the solar nebula. Addition of a late veneer of chondritic material coming from beyond 2.5 AU provides a strong explanation for the modern abundances of siderophile and volatile elements in the terrestrial mantle. This material also contained water and other volatile elements, which account for the origin of the terrestrial ocean. Such a model indicates that most of the terrestrial Pb and Xe was delivered by the asteroids that constituted the late veneer, and therefore that the young Pb–Pb and I–Xe ages of the Earth date, not the Earth, but events that affected the asteroids. It is suggested here that these events are those of the accretion to the Earth of the late veneer.

Figure 6 | Galena data and the young age of the Earth. Data are taken from ref. 54. The evolution of ^{206}Pb/^{204}Pb in conformable Pb deposits is linear in $\exp(\lambda_{238U} T) - 1$, where λ_{238U} is the decay constant of ^{238}U, which indicates that the mantle source of galenas behaved as a closed system since the early geological ages. The primordial Pb of the Solar System, represented by the 4.56-Gyr-old Canyon Diablo troilite[89], is not on the galena trend, which suggests that terrestrial Pb is younger than that of this meteorite. This condition reflects that either Pb segregated into the core at a late stage[89] or, as suggested here, that terrestrial Pb was largely inherited from the late accretion of volatile-rich material (late veneer) to the Earth.

reasonably consistent with the Pb–Pb age. Hence, arrival of the late veneer about 100 ± 50 Myr after the collapse of the nebula is supported by independent sets of geochemical observations.

The nature of the wet, late-accreting icy bodies from beyond the snow line, either identified meteoritic or so-far unsampled material, is not understood[1,41]. It is likely that any source of planetary material that significantly contributed to planetary accretion during the first 50 Myr of the Solar System is now exhausted. This makes the quest for a particular type of modern chondritic contributor intrinsically elusive.

Hydrating the mantle and setting off planetary dynamics

If water is a late addition to terrestrial accretion, the question arises of when and how modern mantle water was introduced into the solid Earth[4]. Solution in the primordial magma ocean (ingassing)[61] requires a very high atmospheric temperature ($>800\,°C$) to prevent mantle hydration. Foundering the hydrous crust of serpentine and other hydrous minerals[62] of the magma ocean is an alternative mechanism for early deep Earth hydration. In both cases, however, crystallization of the magma ocean is expected to concentrate water, a very incompatible molecule, in the residual melt and therefore acts to remove most of the water initially present in the upper mantle.

Water and all the other incompatible elements are particularly depleted in the upper mantle for two main reasons. First, orogenic volcanism at converging plate boundaries removes most of the volatile and incompatible lithophile elements from the hydrous lithospheric plates. Later, mid-ocean-ridge magmas remove from the upper mantle most of what survived the subduction 'filter'. In addition, it is a general feature that magma extraction under mid-ocean ridges and ocean islands is a rather shallow process (<100 km) that takes place during decompression of the mantle: the deeper into the mantle water and incompatible elements are buried, the less likely they are to become involved in melting and extraction, which is apparent in convection models dealing with geochemical tracers[63]. Water is continuously lost to the deep mantle by subduction of a post-serpentine hydrous phase known as phase D[64–66]. The presence of hydrous phases at the top of the lower mantle may actually account for stronger seismic attenuation at subduction zones than in the ambient mantle[67].

Water decreases the viscosity of major mantle minerals, notably olivine[68]. It reduces the strain before lithospheric failure and therefore affects mantle dynamics[69]. A strong reduction of mantle viscosity contingent on subtle olivine hydration is suspected to shift the elastic thickness of the lithosphere and to change mantle dynamics from a stagnant-lid regime (strong dry mantle) to a plate tectonic regime (soft wet mantle)[70].

The varying fates of water on the different terrestrial planets provide a relatively simple explanation of their contrasting evolution. Admitting that water and Ce have similar residence times of 6–8 Gyr (ref. 71) in the terrestrial mantle, ~50% of the ocean must have been subducted into the mantle after 4.5 Gyr, which is precisely what the widely held view of 'one ocean inside for one ocean outside' is predicting.

The status of water on Venus can be explained by conditions opposite to those on the Earth: hot surface vapour quickly reacts with the crust and is rapidly transported downwards because the more hydrous the mantle, the faster its convection. The loss of water from the surface is largely controlled by its reactivity and therefore by surface temperature. On both planets, the depletion of the upper mantle acts to hold water back in the lower mantle. The unique hypsometric maximum on Venus contrasts, however, with the bimodal distribution of elevations on Earth[72] and demonstrates its lack of true continents. Evidence of plate tectonics, if it existed in the past, was erased by resurfacing ~600–900 Myr ago[73,74]. Although some water is currently lost from the atmosphere of Venus[75], the relative abundances of atmospheric rare gases argues against hydrodynamic escape in the past[76]. If Venus and the Earth initially had oceans of similar sizes, an alternative may be found to atmospheric loss on Venus: water may simply have been dragged into the mantle by early

plate tectonics. Eventually, this may become the fate of the terrestrial oceans and continents as well, once enough water has been introduced into the mantle, making it softer than it is today.

It has been argued[77] that Martian water was delivered by asteroids and comets from beyond 2.5 AU. Also, it was suggested that Mars' interior is dry because, although the planet acquired a late volatile-rich veneer, it did not get folded into the mantle[78]. A dry mantle explains the early demise of plate tectonics on Mars. In contrast to the Earth and Venus, Mars lost its atmosphere to space by hydrodynamic escape during the first few hundred Myr after accretion[79]. Fractionation of the atmospheric $^{38}Ar/^{36}Ar$ ratio attests to hydrodynamic escape[76]. The weak gravity field due to the small planet radius has a triple effect: (1) escape from the atmosphere is much easier on Mars than on Earth; (2) because the pressure gradient is about three times weaker on Mars, the phase changes giving rise to the viscosity jump of the terrestrial transition zone are shifted to the bottom of the Martian mantle, thereby preventing significant accumulation of water at depth; and (3) the bending of plates and, hence, the onset of plate tectonics is made more difficult. It has been suggested that the mantle source of Martian shergottites could be wet[80,81], but this is only possible if these rocks are younger than a few hundred Myr, a point that was recently challenged on the basis of Pb–Pb ages in excess of 4 Gyr (ref. 82).

Contrasting dynamic regimes, and, therefore, the amount of water present in planetary mantles, have diverse effects on the dynamo: a plate tectonic regime allows heat to be evacuated more efficiently from the core than a stagnant-lid regime[83]. The Earth, and possibly early Venus, illustrates the former case with active plate tectonics. In the latter case, the dynamo chokes, the magnetosphere vanishes, and the atmosphere gets eroded by solar wind: this was probably the fate of Mars, initially triggered by a water-poor mantle and the weak gravity field of the planet, and may become the fate of Venus.

Future directions

Beyond the fascinating question of how the Earth formed and acquired its hydrosphere lies the question of the origin of life. Associating life on Earth with plate tectonics and the presence of continents, all of them being contingent on the presence of water, is tantalizing and justifies the 'follow the water' motto of space agencies. Although the reducing environments created on reduction of water by the magma ocean may have jump-started biological activity[84], it is not clear that a 'water world' can provide a steady source of nutrients and sustain life[85]. Both the timing of water delivery (relevant to the onset of plate tectonics) and the amount of water (for the persistence of a shallow ocean with subaerial reliefs) need to be understood. The detailed chemical reactions at work during the giant lunar impact[86] and even its timing remain poorly understood. New dynamical models of accretion will need to deal with radial transfer across the nebula and with hit-and-run impacts that severely affect planetary chemistry. The past decade witnessed major conceptual changes in our understanding of the early history of the terrestrial planets, and more surprises seem to be ahead of us.

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