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Connections between the bulk composition, geodynamics and habitability of Earth

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The bulk composition of the silicate part of Earth has long been linked to chondritic meteorites. Ordinary chondrites—the most abundant meteorite class—are thought to represent planetary building materials. However, a landmark discovery showed that the ^{142}Nd/^{144}Nd ratio of the accessible parts of the modern terrestrial mantle on Earth is greater than that of ordinary chondrites. If Earth was derived from these precursors, mass balance requires that a missing reservoir with ^{142}Nd/^{144}Nd lower than ordinary chondrites was isolated from the accessible mantle within 20 to 30 million years of accretion. This reservoir would host the equivalent of the modern continents' budget of radioactive heat-producing elements (uranium, thorium and potassium), yet has not been discovered. We argue that this reservoir could have been lost to space by ablation from early impactors. If so, Earth's radiogenic heat generation is between 18 and 45% lower than estimates based on a chondritic composition. Calculations of Earth's thermal history that incorporate such reduced radiogenic heating are consistent with a transition to the current plate tectonic mode in the past 2.5 billion years or so, a late onset of the dynamo and an evolving rate of volcanic outgassing consistent with Earth's long-term habitable climate. Reduced heat production compared with Venus and Mars could also explain aspects of the differences between the current climatic regimes of these planets and Earth.

The growth, internal differentiation, and geodynamic evolution of our planet can be partly constrained by the average composition of the silicate part of Earth (bulk silicate Earth). This basic constraint on Earth's history is difficult to infer, however, because geochemists cannot adequately sample a planet composed of oceanic and continental crust, a compositionally heterogeneous mantle, and a core. Owing to the heterogeneous make-up of Earth and necessarily incomplete sampling of the accessible parts of Earth, one approach to predict the bulk silicate Earth composition is to use models for Earth's formation. A long-standing conceptual picture for Earth's composition assumes that it formed by accretion of chondritic precursors, which are the most primitive, undifferentiated objects in the solar system (Box 1). All classes of chondrites have relatively constant ratios of elements that are both refractory (elements with high condensation temperatures) and lithophile (elements that remain in the silicate portion of Earth, including the crust and mantle), such as Samarium (Sm) and Neodymium (Nd). These elements are not fractionated during condensation from a hot nebular gas[1–4] or during separation of a metallic core with relatively low sulphur concentrations[5]. Therefore, ratios of the refractory lithophile elements in the silicate Earth have long been assumed to be the same as in chondrites, and the bulk silicate Earth has chondritic Sm/Nd ratios (ref. 2). The ^{146}Sm–^{142}Nd decay scheme (^{146}Sm half-life = 68 to 103 million years; ref. 6) provides a way to test this model: if the bulk silicate Earth and the chondrite reservoir have the same Sm/Nd, the ^{142}Nd/^{144}Nd of Earth and ordinary chondrites should be the same.

The discovery that the accessible, modern terrestrial mantle has ^{142}Nd/^{144}Nd that is 18 ± 5 ppm (0.018 ± 0.005‰) higher than ordinary chondrites, which exhibit isotopic compositions representative of planetary building material[4,7,8], challenges the assumption that Earth has chondritic Sm/Nd ratios (refs 9–12). While there are other models for the origin of the superchondritic ^{142}Nd/^{144}Nd in the bulk silicate Earth (Box 1), we explore the hypothesis that the higher ^{142}Nd/^{144}Nd in the modern terrestrial mantle relative to ordinary chondrites relates to the decay of ^{146}Sm. This model exploits a tendency for Nd to be concentrated in mantle melts relative to Sm, because Nd is more incompatible in the solid mantle than Sm during mantle melting. Following mantle melting, the melt has lower Sm/Nd than the mantle from which it was extracted, and the melt-depleted mantle residue has higher Sm/Nd. The magnitude of the terrestrial ^{142}Nd/^{144}Nd excess can thus be explained if an initially chondritic Earth (or the planetesimals that accreted to make Earth, implied hereafter) differentiated into crust and mantle by silicate melt extraction from mantle during the first 20–30 million years (Myr) of Solar System history[9,10,13]. To generate the ^{142}Nd/^{144}Nd excess observed in the accessible modern mantle compared with ordinary chondrites[9,14,15], the Sm/Nd ratio of the early-formed geochemically depleted mantle reservoir — referred to as the early-formed depleted mantle reservoir — must be 5–7% higher than chondritic values (Supplementary Information). The early depleted reservoir (EDR) is also depleted in, and therefore has low concentrations of, incompatible elements (including uranium, U; thorium, Th; and potassium, K) that partitioned into the early enriched crustal reservoir[9–11] (Figs 1,2). This early enriched reservoir (EER) has high concentrations of these incompatible elements (Fig. 2) and ratios of Sm/Nd and ^{142}Nd/^{144}Nd that are lower than ordinary chondrites.

Significantly, only the EDR has been observed. Although the existence of the EER is required to satisfy the mass balance of a chondrite-based[3] Earth, no evidence of such a reservoir exists. If the modern bulk silicate Earth has a chondrite-based composition, the missing EER must have remained in the deep Earth, completely hidden, for >4.5 billion years (Gyr) of convective mantle stirring, melting, and volcanism.

However, if the EER does not exist within the planet, this reservoir was lost to space by collisional erosion by large impactors[16–19]. If so, Earth's mantle is far more depleted than commonly suggested. In such a scenario, and contrary to the canonical view of continental extraction from a chondrite-based primitive mantle, a significant fraction of highly incompatible elements must have been extracted

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Box 1 | Models for the origin of $^{142}Nd/^{144}Nd$ signatures in the modern terrestrial mantle.

Chondrites are the most primitive, undifferentiated objects in the solar system. There are several classes of chondrites — the three main types are ordinary, carbonaceous and enstatite chondrites — that are classified based on differences in bulk composition, redox state and petrographic attributes. Hundreds of analyses of chondrites reveal that the least metamorphosed, freshest chondrites have (with few exceptions) constant refractory lithophile element ratios, including Sm/Nd, that vary at most by a few per cent[1]. Therefore, observed variability in $^{142}Nd/^{144}Nd$ among the different chondrite classes has important implications for compositional models of Earth.

A subset of enstatite chondrites have $^{142}Nd/^{144}Nd$ ratios similar to the accessible modern terrestrial mantle[70]. Therefore, if Earth accreted from these chondrites, no early differentiation (into early enriched and early depleted reservoirs) and concomitant fractionation of Sm/Nd is required to generate the $^{142}Nd/^{144}Nd$ in the modern terrestrial mantle. Indeed, enstatite chondrites have been suggested to be the building blocks of the Earth[26]. However, constructing the silica-poor (peridotitic) terrestrial mantle from such silica-rich enstatite chondrite precursors is problematic[71].

Carbonaceous chondrites exhibit heterogeneous, but generally low $^{142}Nd/^{144}Nd$ relative to the modern terrestrial mantle and ordinary chondrites: Carbonaceous chondrites appear to have inherited nucleosynthetic anomalies from the incorporation of presolar material, but they have the same Sm/Nd as the other chondrite classes[4]. One explanation for this observation is that incomplete mixing of nucleosynthetic anomalies in the chondritic reservoir generated solar system $^{142}Nd/^{144}Nd$ variability (including Earth) without a contribution from ^{146}Sm decay[72], and this is the subject of ongoing work[7,8,22,73]. If this model is correct, the modern bulk silicate Earth and the various chondrite classes all have the same Sm/Nd ratio, but they inherited different $^{142}Nd/^{144}Nd$ via the incorporation of incompletely mixed nucleosynthetic anomalies[72]. Therefore, no early differentiation of the silicate Earth is required to explain the terrestrial $^{142}Nd/^{144}Nd$ result. One problem with this model is that ordinary chondrites exhibit no significant difference in the incorporation of nucleosynthetic anomalies compared with the modern terrestrial mantle, yet Earth has significantly higher $^{142}Nd/^{144}Nd$ anomaly (for example, ref. 4), suggesting that the modern terrestrial mantle $^{142}Nd/^{144}Nd$ relates to ^{146}Sm decay.

The hypothesis explored in this Perspective (and elsewhere)[9,14,15,18] is that the 18 ± 5 ppm $^{142}Nd/^{144}Nd$ excess in the accessible modern terrestrial mantle relative to ordinary chondrites results from ^{146}Sm decay. According to this model, early differentiation of the Earth raised the Sm/Nd ratio in the accessible mantle by 5–7% relative to ordinary chondrites, and ^{146}Sm decay generated the 18 ± 5 ppm $^{142}Nd/^{144}Nd$ excess in the first 20–30 Myr following accretion. A primary problem with this model is that mass balance requires the early differentiation event to generate an early enriched reservoir (EER) with low Sm/Nd and low $^{142}Nd/^{144}Nd$, but this reservoir has not been observed. It may be hidden in the deep mantle, in the core[47] or could have been lost to space by collisional erosion[16]. However, the EER has not been observed. We explore the consequences of the collisional erosion hypothesis here.

from the mantle to form the EER and expelled from the planet before the extraction of Earth's current volume of continental crust. In fact, the fraction of incompatible elements — including U, Th, and K — lost to space would have been equivalent to the modern continents' budget of these elements (Fig. 1). This twofold incompatible element depletion of the terrestrial mantle, as well as the presence (or absence) of an EER in the deep Earth, would have undoubtedly influenced the evolution of plate tectonics, the geodynamo, and the habitability of the planet.

Evidence for a highly depleted mantle

If the EER has been removed from the planet, then the EDR is the bulk silicate Earth. Critically, several recent compositional models for the EDR consistent with the aforementioned $^{142}Nd/^{144}Nd$ result indicate that when the 'missing' incompatible elements were extracted into the EER and lost to space, the planet became ~18–45% depleted in the most incompatible elements relative to a chondritic-based[3] bulk silicate Earth (Fig. 2 and Supplementary Table 1). This astonishing result implies that the equivalent of the entire highly incompatible element inventory of the modern continents was extracted from the early mantle before the modern continents were formed. If this model for a 'twice depleted' silicate Earth is accurate, the geochemistry of the depleted mid-ocean ridge basalt (MORB) mantle[10,11,20], the deep mantle sampled by hotspots[12,14,15], and modern continental crust[4,14,21] should exhibit geochemical evidence for a mantle that has twice experienced the equivalent of continent-scale extraction and incompatible element depletion (Fig. 2).

In early-developed models for continental extraction from a chondritic Earth, $^{143}Nd/^{144}Nd$ isotopic systematics suggested that only the depletion of upper mantle (to ~660 km depth) was necessary to form the continents[4], and the lower mantle remains primitive with chondritic Sm/Nd (Fig. 1(i)). One problem with this model is the lack of observed primitive chondrite-based bulk silicate Earth compositions in hotspot lavas, related to mantle plumes rising from the core–mantle boundary region. An additional problem with this class of model is that if the mantle is not layered at 660 km, and if continental crust is extracted from the entire mantle (one with a chondrite-based composition), then the depleted MORB mantle would be insufficiently depleted in incompatible elements and would have a $^{143}Nd/^{144}Nd$ ratio that is too low to serve as the time-integrated mantle source for MORB[4,14]. However, if the silicate Earth has the composition of the EDR, the modern continents were extracted from a mantle that already experienced depletion to form the EER, and >74% (ref. 11) to >82% (ref. 20) of the mantle must be depleted to generate the incompatible element budget of the modern continents (Fig. 1(ii, iii)). While recent work suggests that the incompatible element budget of the EDR is not sufficient to accomodate continental extraction[22], which argues against the formation of the EDR, uncertainties in the composition of continental crust and depleted MORB mantle do permit continental extraction from the EDR[20]. If the early extraction hypothesis[9] for the formation of the EDR is correct, the terrestrial mantle is vastly more depleted in incompatible elements than is suggested by chondrite-based models for the bulk silicate Earth[14], and a large depleted reservoir (depleted MORB mantle) comprises most of the mantle's mass.

Several lines of evidence in the isotopic record support this twice-depleted model for Earth's mantle (Fig. 2). First, ocean island basalts (OIB) erupted at hotspots — thought to be fed by deeply sourced mantle plumes — ought to sample predominantly geochemically depleted material if most of the mantle is comprised of the EDR and the depleted MORB mantle (Fig. 1(ii)). OIB geochemistry indeed indicates that the deep mantle is largely depleted: ~90% of OIB samples analysed have $^{143}Nd/^{144}Nd$ that is geochemically depleted relative to the chondritic value[12]. Second, the superchondritic $^{143}Nd/^{144}Nd$ of Archaean juvenile mafic and ultramafic rocks favours continental extraction from an early and pervasively depleted mantle, and extraction of continental crust from the early depleted mantle better describes the $^{143}Nd/^{144}Nd$ evolution of the

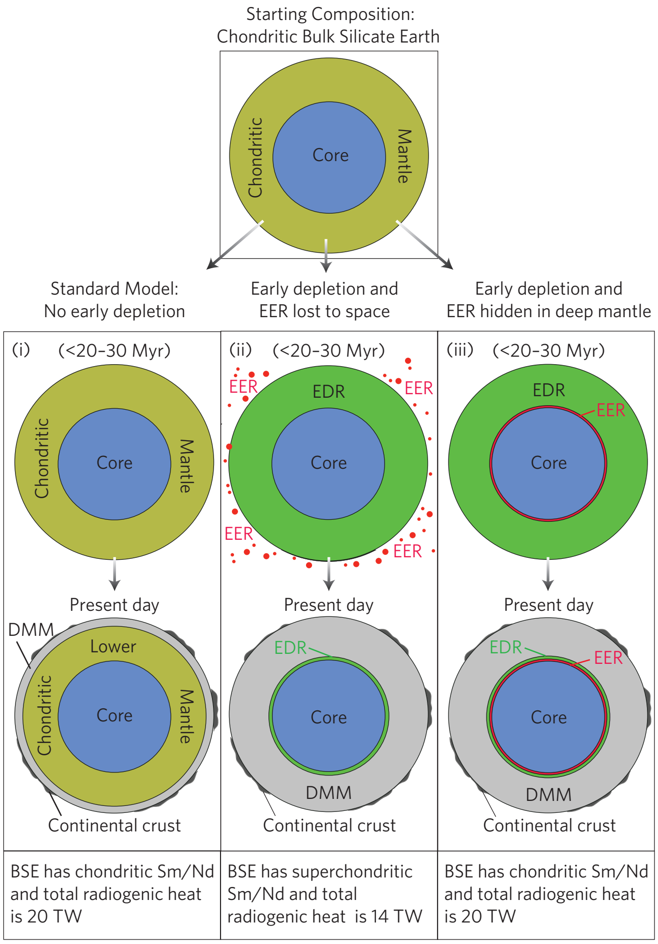

Figure 1 | Three scenarios for the differentiation of Earth from a chondrite-based starting composition. The canonical model for silicate Earth evolution does not satisfy the $^{142}Nd/^{144}Nd$ result; no early depletion occurs (i). The upper mantle is depleted by continental crust extraction; the lower mantle is chondrite-based compositionally[3]. If the silicate Earth underwent early depletion, consistent with the $^{142}Nd/^{144}Nd$ result, the early enriched reservoir (EER) would have been lost to space (ii); the planet generates only ~14 TW of radiogenic heat. The third model is similar, except that the EER is hidden in the mantle (iii). The planet generates 20 TW of radiogenic heat. In (ii) and (iii), the continental crust was extracted from the early depleted reservoir (EDR), generating a large depleted MORB mantle (DMM). Some EDR material may survive in the modern mantle[15] (Supplementary Information). BSE, bulk silicate Earth.

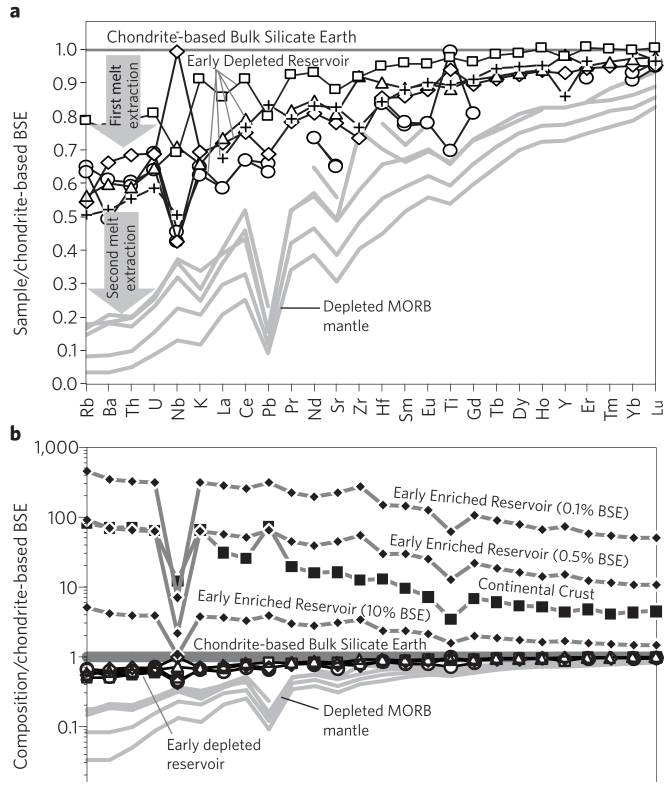

Figure 2 | Primitive mantle normalized trace element patterns illustrating two-fold depletion of Earth's mantle. a, The first melt extraction event resulted from extraction of the EER from a chondrite-based bulk silicate Earth (BSE) to generate the EDR. The second melt extraction event extracted continental crust from the EDR to make depleted MORB mantle. **b**, Enlarged version of **a**, showing estimates for the composition of the EER as a function of its mass; estimates for the EDR, continental crust and depleted MORB mantle are from the literature (Supplementary Information).

continents over the past 3.5 Gyr than models arguing for continental extraction from a chondrite-based mantle[4,14] (unless, in the latter case, the continents were extracted from the upper mantle only and the entire lower mantle is geochemically primitive with chondritic Sm/Nd ratios, which, as discussed above, is unlikely). However, the evolution of $^{176}Hf/^{177}Hf$ of Archaean juvenile mafic and ultramafic rocks may not be consistent with this picture, as the geochemically depleted $^{143}Nd/^{144}Nd$ compositions observed in Archaean rocks can be decoupled from their $^{176}Hf/^{177}Hf$ compositions (for example, refs 23 and 24), and further work will be required to resolve this issue.

A hidden reservoir or a geochemically depleted planet?

If the EER exists in the modern mantle, the high abundance of radioactive heat-producing elements should make this reservoir detectible by a mobile geoneutrino detector, particularly if this reservoir is concentrated in the large low shear-wave velocity provinces[25]. (A nearer-term goal of the geoneutrino experiments is to resolve whether Earth has chondrite-based or EDR-based U and Th concentrations[26].) In the absence of data from a long-term ocean-based geoneutrino experiment, however, the extraction of the EER from the early Earth has several testable implications, depending on whether: (1) the EER in the form of early-formed crust was lost to space as a result of collisional erosion[16]; or (2) the EER is a hidden reservoir in the deep mantle[9].

If the EER is hidden at the core–mantle boundary, it is most likely expressed as the thin (~10–50 km thick) partially molten parts (that is, the seismic ultra-low velocity zones) at the base of relatively large piles of dense, chemically distinct mantle[27,28], which are observed to extend vertically as far as ~1,000 km above the core–mantle boundary beneath the Pacific and Africa[29]. Thus, if the EER exists as deep mantle piles enriched in U, Th, and K, the local rate of heat production would be comparable to modern continental crust (Supplementary Table 1). This leads to testable predictions for the strength and structure of Earth's magnetic field over time, as well as for the isotopic compositions of OIBs and continental crust, which are challenging to reconcile with observations. Moreover, if there is an EER in the deep mantle, it has been argued that heat flux carried by mantle plumes will reflect the high thermal output of an enriched basal layer with >6 TW of radiogenic power[20]. But this is not observed[1] and thus presents an additional line of evidence against the presence of a hidden enriched reservoir within the deep Earth.

High-resolution core dynamo models suggest that whereas the present-day symmetric distribution of hot piles at the core–mantle boundary can enhance the observed (mostly dipolar) structure of Earth's magnetic field, this heat flux pattern may also stabilize the dynamo against the magnetic reversals that are a characteristic feature of the past 200 Myr of Earth's magnetic history[30]. Furthermore, bulldozing and merging of these piles by subducting slabs spreading at the core–mantle boundary[29] during formation of supercontinents Nuna, Rodinia, and Pangea would produce an asymmetric heat flux pattern at the boundary[31] that could weaken or terminate Earth's dynamo[32,33], which is not consistent with observations of magnetic field behaviour during the formation and breakup of Pangea[34].

Within the mantle, entrainment of dense, low-viscosity partial melt into plate-driven flow and into plumes ascending from the core–mantle boundary is expected to be small, but it will increase monotonically over Earth history as the effective viscosity of the mixture increases with solidification of the melt phase[35]. This picture is inconsistent with the survival of an EER over the majority of Earth's evolution because the geologic record provides no support for the gradual entrainment of such a layer: There is no observable shift in the $^{142}Nd/^{144}Nd$ of the continents for the past 2.7 Gyr toward the lower $^{142}Nd/^{144}Nd$ values predicted for the EER[36–38]. Similarly, OIBs exhibit no evidence for incorporation of a reservoir with lower $^{142}Nd/^{144}Nd$, which rules out entrainment of a deep EER by plumes[10,13,39–41].

Finally, ^{182}Hf-^{182}W isotopic systematics of the Earth–Moon system constrain the timing of the giant impact event to have occurred >60 Myr after accretion[42,43], which implies that the formation of the EER (<20–30 Myr after accretion) preceded the Moon-forming giant impact event[21]. This impact did not erase all early-formed mantle heterogeneity (as suggested by the survival of early-formed ^{182}W anomalies in Archaean crust[44,45]), but the existence of an EER in Earth during the Moon-forming giant impact would require that it somehow escaped mixing into the ambient mantle[1,14,21]. However, the size of the impactor and its impact trajectory may leave deep reservoirs (including the putative EER) relatively undisturbed, and resolution of this issue requires incorporation of deep mantle reservoirs in impact models[46].

In summary, it is difficult to reconcile a hidden EER with a growing number of geomagnetic, geochemical and geodynamic constraints. A hidden reservoir is by definition undetected and its presence cannot be excluded in the deep Earth. The hidden reservoir has even been suggested to reside in Earth's core, which, under extremely sulphur-rich conditions, may have fractionated Sm/Nd and strongly partitioned U (ref. 47), but the applicability of this result to early Earth conditions will no doubt be the subject of future work. We explore an alternative hypothesis in which an EER was instead lost to space by collisional erosion of early-formed crust[19]. In this model, the bulk silicate Earth is depleted in radiogenic heat-producing elements (U, Th, K), potentially resulting in remarkable geodynamic and climatic consequences.

Geodynamic, geomagnetic and climatic implications

Reduced U, Th and K in Earth implies that the ratio of radiogenic heating to the total heat flux out of the planet, referred to as the Urey ratio, is decreased. The mantle's radiogenic heating contribution to the present-day surface heat flux carried by plate tectonics (that is, excluding radiogenic heat from the continents) is, in turn, decreased by approximately 50% from the chondrite-based compositional estimate — from 12.8 TW (ref. 3) to 6.6 TW (ref. 20) (Supplementary Table 1). Integrating this effect backwards in time has potentially profound implications for Earth's thermal, tectonic, magnetic and climatic evolutions, as well as for the emergence of intrinsic differences between the present-day tectonic and climatic regimes of Earth, Venus and possibly Mars. We discuss aspects of these issues below (and in greater detail in Supplementary Information).

Consequences for Earth's tectonic regime. The mean internal temperature of Earth's mantle reflects a balance between the rate at which heat is generated internally and lost at the surface through plate tectonic-driven (that is, mobile lid mode) stirring. Presently, Earth's heat loss is driven primarily by a continual subduction and stirring of cold 'large plates' such as the Pacific. However, under reduced radiogenic heating in a planet with a lower Urey ratio, this large-plate cooling mode is ultimately too efficient at cooling Earth[20], which leads to difficulties in understanding the thermal evolution of the planet. For example, integrating thermal history models backwards in an Earth with a low Urey ratio with a large-plate mantle convective regime leads to thermal catastrophe in the form of global mantle melting within approximately the first billion years[48]. This timescale for thermal catastrophe increases for complex mantle and lithosphere rheologies[48], high core thermal conductivities[49] and if radiogenic heat production is added to the core[49,50], but this extreme solution is, nevertheless, hard to avoid, particularly if Earth has a low Urey ratio.

An evolving plate tectonic regime in response to Earth's cooling presents an alternative solution to averting early thermal catastrophe under low Urey ratio conditions. Recent studies suggest that the present-day large-plate regime was not favoured in the higher-temperature, lower-viscosity mantle of Earth's first 2 Gyr (refs 51, 52). Instead, early mantle cooling was modulated by the relatively sluggish motion of small plates comparable in size to the mantle depth, moving in response to relatively fast mantle flow driven by lateral temperature variations within a thin underlying low-viscosity asthenospheric channel[51–53]. Thus, there are two driving forces for Earth's so-called mobile lid tectonic mode with relative contributions to plate motions that evolve with Earth's cooling. Whereas plate buoyancy predominantly drives present-day Pacific-plate-scale flow, drag imparted by flow in the asthenosphere is expected to govern plate motions of the smaller plates in Earth's higher-temperature past. On this point it is important to be clear: Both tectonic regimes coexist with a gradual transition from an Earth dominated by small plates to one dominated by large plates after ~100–150 °C of mantle cooling[51] (Fig. 3). To avoid thermal catastrophe and still satisfy present-day mantle thermal conditions with reduced radiogenic heating requires that about 75% of Earth's cooling occurred in this small-plate regime[20] (Fig. 3), which on average slows cooling of the planet.

Consequences for Earth's geodynamo. The expected change in the plate tectonic regime of an Earth with relatively less radiogenic heat production leads to a testable prediction for the timing of the geodynamo, assuming that initiation is related to thermal convection and not to other mechanisms related to impacts or Earth's early rotational dynamics[54]. Core cooling is governed by the heat flux carried away from the core–mantle boundary by mantle convective motions. If this heat flux exceeds that which is conducted down the core adiabat, vigorous thermal convection can lead to dynamo action. Initially sluggish mantle cooling in an Earth with less radiogenic heat will consequently delay the onset of thermally driven dynamo action[20], potentially consistent with the delivery of terrestrial nitrogen to lunar far-side soils[55], the 3.4–3.45 Ga (billion years ago) dynamo age inferred from high-resolution palaeomagnetic intensity measurements[56] and models[34]. Additionally, when the core adiabatic heat flux exceeds the heat flux carried by mantle convective motions (that is, $(Q_{core}-Q_{critical}) < 0$, Fig. 3), partial melting at the base of the mantle is expected and may be a potentially important feature of Earth's mantle prior to the interval between 2.7 and 3.5 Ga (Fig. 3). Indeed the slow solidification of such a deep, early-formed partial melt is potentially consistent with the presence and longevity of well-documented 'ultralow-velocity zone' material observed presently in Earth's core–mantle boundary region[29] (Fig. 3, Supplementary Information).

As a further cautionary remark, this thermally driven picture of dynamo onset is not required by observational data (which show only that a dynamo existed over the last ~3.5 Gyr; ref. 34). Indeed, our results point to an important and ambitious goal for future palaeomagnetic studies: To constrain not just the timing of an early dynamo but also distinguish the key underlying mechanism(s) for excitation. In particular, although core convection is almost assuredly required to sustain Earth's dynamo over long geological timescales, whether the dynamo was initiated by convective instabilities, through processes related to impacts or rotationally driven mechanisms, or through some combination of the three requires information about both the strength and the structure of Earth's early magnetic field. For example, rather than a convective onset mechanism, did the large impact leading to the formation of the Moon initiate Earth's dynamo, in turn? Although a daunting observational challenge[34], progress beyond parameterized thermal history models such as ours for an Earth with reduced heat production requires new palaeomagnetic intensity measurements on old rocks along with constraints on palaeomagnetic directions.

Consequences for Earth's climate and habitability. Over timescales greater than ~1 Myr, Earth's surface temperature largely reflects the greenhouse forcing resulting from a balance between the rates at which CO_2 is expelled from volcanoes and drawn down from the atmosphere as a result of chemical weathering processes at Earth's surface. The long-term evolution of Earth's climate will consequently be regulated by the changing style of plate tectonics and its effect on the rates of tectonically driven uplift and erosion, as well as mantle cooling and melting. Accordingly, we present a heuristic model for Earth's climate evolution that explores effects related to the coupled evolutions of volcanic degassing and the tectonic regime in our model Earth with reduced radiogenic heating (Fig. 3, Supplementary Information). Our aim is to provide a qualitative picture for how links between key sources and sinks for CO_2 might interact to modulate climate in an Earth with reduced radiogenic heat production.

Global rates of volcanism, and volcanic CO_2 outgassing (F_{outgas}), depend on the vigour of mantle resurfacing and melting, which depend, in turn, on a viscosity (μ) that increases by about 1 order of magnitude per 100 °C decline in the mantle temperature (T_{mtl}; Fig. 3). We assume that the present-day lengths of mid-ocean ridges and volcanic arcs are approximately preserved (which is probably an underestimate compared with an Earth with predominantly small plates) and thus obtain a plausible lower bound on the strength of volcanic forcing. Backward integrating our thermal history model beginning at well-constrained conditions for the present day, we predict the flux of volcanic CO_2 into the atmosphere at 4 Ga was 10–15 times greater than today (Fig. 3). This lower bound is conservative: recent work[57] shows that the flux of volcanic CO_2 from arcs increases with mantle temperature, particularly before 2 Ga, when the peak output of volcanic CO_2 was a factor of ~5 greater than today (Fig. 3).

Volcanic greenhouse forcing depends on the concentration of CO_2 in the atmosphere (that is, p_{CO_2}), which depends, in turn, on interactions between the atmosphere, land and oceans[58]. In particular, the dynamics governing major sinks for atmospheric CO_2 over Earth history involve time-varying and coupled links between tectonics, precipitation, ocean temperature and chemistry, and mechanical weathering, as well as biological processes that are distinct in the microbial-dominated world before 0.63 Ga and after the appearance of land plants about 0.4–0.5 Ga (refs 59, 60). Nevertheless, an abiotic weathering response to our predicted volcanic forcing is qualitatively instructive to explore (Supplementary Information), and predicts that, at 2 Ga, p_{CO_2} was 10 times higher in our model than present-day values (Fig. 3). Prior to the rise of atmospheric oxygen at 2.4 Ga, and in view of an obvious knowledge gap related to the mechanics of erosion and weathering in a small-plate world, such simple calculations are fraught; we can only conclude by extrapolation that p_{CO_2} rises continuously backward in time as the volcanic forcing climbs to a peak that is 10–15 times present-day values at 4 Ga. Indeed, understanding the evolution of the main controls on the chemical weathering feedback modulating Earth's climate backward in time is a seminal challenge.

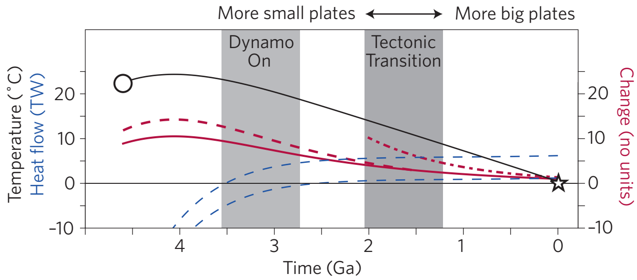

Figure 3 | Thermal, magnetic and climatic histories of a non-chondritic Earth. Reduced radiogenic heat production (see Fig. 1(ii)) leads to thermal histories for Earth's mantle (black line) characterized by recent emergence of predominantly large, Pacific plate-style subduction[20], to a delayed onset of Earth's dynamo (that is, $(Q_{core}-Q_{critical}) < 0$ with $Q_{critical}$ = 10–15 TW (ref. 69); blue dashed lines),and to the potential for mantle melting, not considered here[27,49,69]. Compared to present day (now), volcanic CO_2 outgassing, $F_{outgas}/F_{outgas,now}$ (solid red curve), is higher in the past and is enhanced by increased slab decarbonation efficiency before ~2 Ga (ref. 57, red dashed curve). Over the last 2 Ga, atmospheric $(p_{CO_2}/p_{CO_2,now}) \propto (F_{outgas}/F_{outgas,now})^2$ (red dash-dot line; Supplementary Information). Calculations assume 14 TW of radiogenic heat, an initial mantle temperature (open circle) T_{mtl} = 1,575 °C, a current $T_{mtl,now}$ = 1,350 °C, and that continents are insulating[20].

Although volcanic forcing increases backward in time from the present day, solar forcing declines as the Sun becomes younger. A remarkable feature of Earth's long-term climate record is a dearth of global glaciations during the Archaean and through much of the Proterozoic (in particular, between 2.22 and 0.72 Ga; refs 61, 62), which is attributed to lower solar output at that time. Solutions to this faint young Sun paradox must be consistent with observations that include an absence of iron carbonate in Archaean paleosols, which may limit p_{CO_2} levels to ~100 times the present-day level[62], although interpretation of these data remains contentious (Supplementary Information). Nevertheless, if the change in p_{CO_2} increases approximately with the square of the change in F_{outgas}, similar to Earth's recent past[63] (Supplementary Information), this p_{CO_2} condition is potentially satisfied in our model. Together with a decline in Earth's average surface albedo (because of an absence of continental surface area) and probable additional greenhouse forcing (from high H_2O clouds[58] and gases such as NH_3, H_2S, CH_4 and C_2H_6)[62], our predicted high volcanic CO_2 forcing (Fig. 3) contributes a provocative new element to the discussion of how to resolve the faint young Sun paradox. We suggest that the climatic expression of a tectonic regime evolving partly in response to the effects of collisional erosion may favour long-term habitability in comparison with a chondrite-based Earth (Supplementary information).

Finally, what might be the consequences for our model Earth of increasing heat production to a chondrite-based[3] value? An engaging prediction is that there is a greater likelihood that Earth will operate in an episodic or stagnant lid mode (below and Supplementary Information). In such regimes, volcanic outgassing is more likely to be intermittent[64] rather than continuous, leading potentially to large changes in p_{CO_2} and acute shifts in climate: there is a greater likelihood of a climate that varies strongly though time with, for example, protracted periods of globally glaciated icehouse, partially-glaciated and ice-free hothouse conditions (Supplementary Information).

Consequences for differences between Earth, Venus and Mars. A natural final question to consider is how variations in the efficiency of collisional erosion influenced the distinct tectonic and climatic regimes of Earth, Venus, and Mars. Theoretical[65] and numerical studies[66] show that enhanced radiogenic heat production (yielding higher mantle temperatures and lower mantle viscosities) will generally favour one-plate planets, with episodic or more complex multi-mode tectonic regimes (Supplementary Information)[67] characterized by intermittent volcanism (potentially like present-day Venus). This predicted behaviour is in stark contrast with the relatively steady mantle overturning and regular outgassing characteristic of modern plate tectonics on Earth. Looking forward, several key questions emerge. For example, the absence of plate tectonics and the climatic catastrophe that is the current greenhouse runaway on Venus could simply be a consequence of there being less collisional erosion on that planet at early times. Relatively greater radiogenic heat production may increase the likelihood of an episodic mode of tectonics characterized by extreme but infrequent volcanism related to intermittent global plate resurfacing events[67]. If so, the current state of Venus may be an inevitable outcome for a compositionally chondrite-based planet.

Conversely, Mars may have experienced relatively extensive collisional erosion that vastly reduced the budget of heat-producing elements, thereby reducing the vigour and longevity of mantle convective stirring and volcanism[68]. The planet may thus have escaped Earth-like plate tectonics and ultimately undergone a climate catastrophe ending in icehouse conditions. Such an alluring picture is potentially consistent with the elevated (geochemically depleted) ^{142}Nd/^{144}Nd character of Martian meteorites[18] and the planet's relatively small size.

Finally, if planetary habitability is dynamic and ultimately modulated though time by effects related to the amount of internal heat production, the bulk composition of a planet may play a critical role in its tectonic and climatic regimes, which can inform the search for habitable extrasolar worlds.

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Author contributions
Both authors contributed equally to the manuscript.

Additional information
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Competing financial interests
The authors declare no competing financial interests.