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An ancient recipe for flood-basalt genesis

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Large outpourings of basaltic lava have punctuated geological time, but the mechanisms responsible for the generation of such extraordinary volumes of melt are not well known[1]. Recent geochemical evidence suggests that an early-formed reservoir may have survived in the Earth's mantle for about 4.5 billion years (ref. 2), and melts of this reservoir contributed to the flood basalt emplaced on Baffin Island about 60 million years ago[3–5]. However, the volume of this ancient mantle domain and whether it has contributed to other flood basalts is not known. Here we show that basalts from the largest volcanic event in geologic history—the Ontong Java plateau[1,6,7]—also exhibit the isotopic and trace element signatures proposed for the early-Earth reservoir[2]. Together with the Ontong Java plateau, we suggest that six of the largest volcanic events that erupted in the past 250 million years derive from the oldest terrestrial mantle reservoir. The association of these large volcanic events with an ancient primitive mantle source suggests that its unique geochemical characteristics—it is both hotter (it has greater abundances of the radioactive heat-producing elements) and more fertile than depleted mantle reservoirs—may strongly affect the generation of flood basalts.

The discovery of a surviving portion of the early-formed, homogeneous silicate Earth that existed immediately after formation of the core—referred to as primitive mantle—would place constraints on the earliest chemical evolution of the Earth and help to clarify the means by which the Earth arrived at its present geochemical state (see, for example, refs 8–10). Most models for this primitive mantle are based on the assumption that it should have relative abundances of refractory lithophile elements similar to those of carbonaceous chondrites—the presumed building blocks of the Earth[11–13]. However, the recent discovery of small (18 ± 5 parts per million, p.p.m.) differences in the ^{142}Nd to ^{144}Nd ratio (^{146}Sm decays to ^{142}Nd with a half-life of 106 million years, Myr) between the Earth and chondrites suggests that the Earth's primitive mantle may not have chondritic relative abundances of the refractory lithophile elements[14–16].

Instead, all known modern terrestrial mantle reservoirs may have evolved from a primitive precursor with Sm/Nd ratios 4.2–7.3% higher than that of chondrites, leading to a present-day ^{143}Nd/^{144}Nd of 0.51290–0.51309, which translates to a present-day ε^{143}Nd of $+5.3$ to $+9.0$, relative to the chondritic ^{143}Nd/^{144}Nd ratio of 0.51263 (ref. 17); the stated uncertainty arises from the range of ^{142}Nd/^{144}Nd found in modern terrestrial lavas and chondrites—18 ± 5 p.p.m.—that propagates into uncertainty in the Sm/Nd ratio and hence into the value of the present-day ^{143}Nd/^{144}Nd of the primitive precursor. If the expectation of chondritic relative abundances of refractory lithophile elements is removed, the only remaining signatures of primitive mantle are Pb-isotopic compositions on the geochron (the line in Pb-isotopic space defined by samples with constant U/Pb ratios over the Earth's age) and enrichment in the primordial isotope of helium, ^{3}He, relative to the largely radiogenic isotope, ^{4}He. All three (Nd, Pb and He) of the isotopic characteristics expected for a primitive terrestrial reservoir were identified in 62-Myr-old flood basalts emplaced on Baffin Island and West Greenland (BIWG)[2–5]. Employing the geochemical insights gained from BIWG, we examine some of the largest large igneous provinces (LIPs)—volcanic provinces characterized by anomalously high rates of mantle melting that represent the largest volcanic events in the Earth's history—to determine whether they are associated with a primitive (albeit non-chondritic) mantle source.

Located in the southwestern Pacific, the Ontong Java Plateau (OJP) is the largest LIP on the Earth[1,6,7]. The average ε^{143}Nd(t) of these lavas[6,7] plots close to the BIWG lavas (Fig. 1) and within the range predicted for the non-chondritic primitive mantle. Excluding the most incompatible and fluid mobile elements, the OJP lavas have relatively flat primitive-mantle-normalized trace-element patterns (Fig. 2) similar to the relatively flat patterns identified in the two highest ^{3}He/^{4}He lavas from BIWG (Fig. 2). The flatness of the trace-element patterns[18] led Tejada *et al.* (ref. 7) to suggest that the OJP mantle is "almost" primitive, but not actually primitive because of the higher-than-chondritic ^{143}Nd/^{144}Nd in the OJP lavas.

However, the discovery of a difference in ^{142}Nd/^{144}Nd between modern terrestrial rocks and chondrites suggests that the ^{143}Nd/^{144}Nd measured in OJP lavas overlaps with the primitive (albeit non-chondritic) terrestrial mantle. Additionally, the 120-Myr-old early-stage (Kwaimbaita- and Kroenke-type lavas[6,7]) lavas plot near the 4.43-billion-year (Gyr)-old Pb-isotope geochron, and close to the BIWG lavas (which plot closer to the 4.5-Gyr-old geochron), an observation that is consistent with these lavas sampling an ancient mantle source (Fig. 1). Although there are minor differences in the Nd and Pb isotopic composition of the OJP and BIWG lava sources, the overlapping trace-element patterns of the two LIPs suggest an origin from compositionally similar sources whose isotopic compositions are within the range expected for an early-formed reservoir.

Owing to eruption through oceanic crust, contamination of OJP lavas by the chemically and isotopically evolved material of the continental crust does not complicate the interpretation of their mantle source to the degree seen in LIPs erupted through continental lithosphere (see Methods). In contrast, several of the largest LIPs, including the BIWG, were erupted in continental settings where assimilation of continental lithosphere can obscure the primary mantle signature of the lavas. Although continental assimilation can drive the Pb-isotopic composition of lavas towards either more or less radiogenic values, this mechanism will almost certainly lower magmatic ^{143}Nd/^{144}Nd (ref. 19). To test the hypothesis that the least-contaminated LIPs that erupted in continental settings contain lavas that, like the OJP and BIWG, have Pb isotopic compositions on the geochron, we examined only the subset of LIP magmas with high ε^{143}Nd(t) ($>+5.2$) that fall closest to the range suggested for a non-chondritic primitive mantle. Such lavas are least likely to have suffered from assimilation of continental crust (see Methods).

The $\sim$180-Myr-old Karoo lavas are typical of continental LIPs in that they exhibit evidence for continental crust and lithospheric mantle contamination[20]. However, the high-MgO lavas recently discovered in the Antarctic portion of the Karoo host high ε^{143}Nd(t) ratios ($\varepsilon^{143}\mathrm{Nd}_{180\,\mathrm{Myr}} = +7.3$ to $+8.4$), and these lavas plot near the Pb geochron[21] (Fig. 1).

The $\sim$251-Myr-old Siberian Traps generally have too much of a lithospheric overprint to enable us to discern primary mantle compositions[22].

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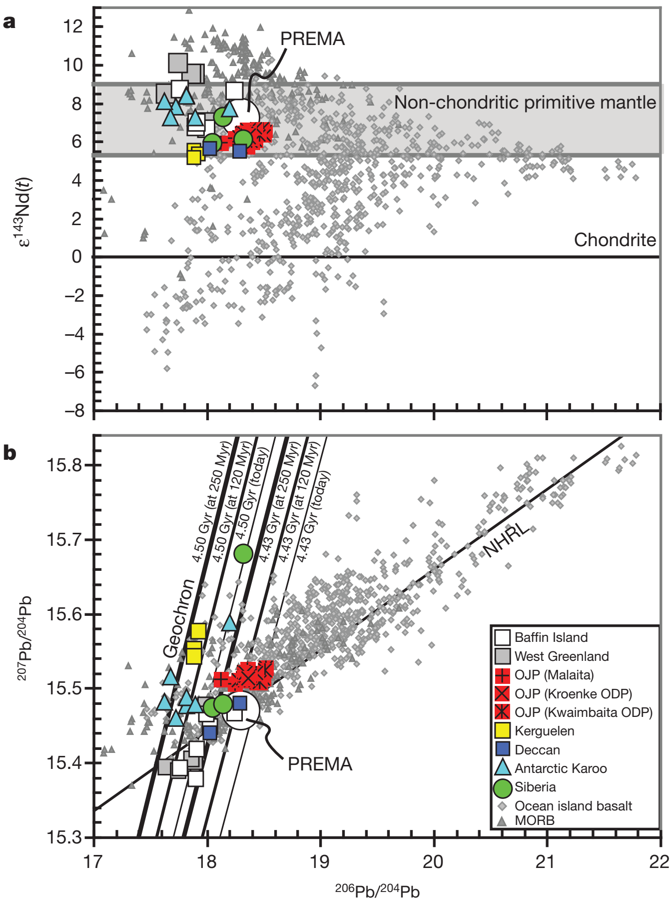

Figure 1 | Lavas from LIPs that have Nd isotopic compositions within the range expected for a non-chondritic primitive mantle exhibit Pb isotopic compositions that plot near the geochron. In addition to having Pb-isotopic compositions and U–Pb concentrations measured on the same samples (excluding the Deccan), all samples plotted also have paired Nd-isotopic compositions and Sm–Nd concentrations. Excluding the Pb-isotopic compositions of the Deccan lavas, all isotopic compositions are age-corrected to the time of eruption and the positions of representative age-corrected geochrons are also shown. **a**, To minimize the effects of continental assimilation, only flood basalt lavas with $\varepsilon^{143}Nd(t) \geq 5.2$ are plotted. **b**, The OJP plots closest to the 4.43-Gyr geochron at the time of eruption (120 Myr). Data for the OJP include lavas from Malaita island and ODP Leg 192 drilling sites[6,7]; late-stage Singgalo lavas are not plotted. Data sources for the other LIPs are in the text. Ocean-island-basalt and MORB data are from Georoc (http://georoc.mpch-mainz.gwdg.de/georoc/). The Northern Hemisphere reference line (NHRL) is shown[30]. $\varepsilon^{143}Nd(t) = [(^{143}Nd/^{144}Nd)_{sample}/(^{143}Nd/^{144}Nd)_{reference} - 1] \times 10{,}000$, where the isotopic ratios are calculated at the eruption age of the basalt (t) using the chondritic reference[17].

However, high-MgO meimechites[22] have the highest $\varepsilon^{143}Nd(t)$ ratios ($\varepsilon^{143}Nd_{251\,Myr} = +5.9$ to $+7.3$) associated with the Siberian Traps. These high-MgO lavas have not been affected by the continental crust contamination that is common in most Siberian Trap lavas (Fig. 1a), and have Pb isotopic compositions near the geochron.

Basalts from the Kerguelen plateau were erupted on submerged continental crust and exhibit evidence for continental crustal assimilation. Nonetheless, ~113-Myr-old Kerguelen lavas from Ocean Drilling Program (ODP) leg 120 site 749 (ref. 23) with the highest $\varepsilon^{143}Nd(t)$ values ($\varepsilon^{143}Nd_{113\,Myr} = +5.2$ to $+5.6$) and the lowest $^{87}Sr/^{86}Sr$ values appear to be least affected by crustal assimilation, and their Pb isotopic compositions plot close to the 4.50-Gyr-old geochron (at 120 Myr).

Most formations of the ~65-Myr-old Deccan LIP are pervasively contaminated with crust and/or lithospheric mantle[24]. Lavas from the Ambenali formation have the highest $^{143}Nd/^{144}Nd$ of the Deccan basalts and are thought to best represent mantle compositions. The subset of Ambenali lavas with the highest $\varepsilon^{143}Nd(t)$ ratios ($\varepsilon^{143}Nd_{65\,Myr} = +5.5$ to $+5.6$) have Pb isotopic ratios that straddle the geochron[25].

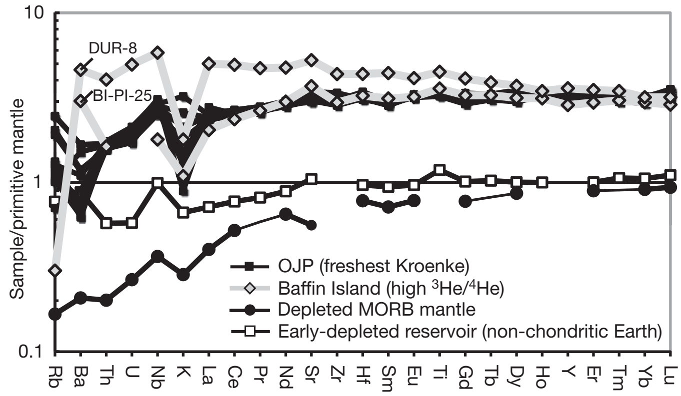

Figure 2 | Primitive mantle[13] normalized trace-element patterns of OJP lavas compared to high $^3He/^4He$ lavas from BIWG. For the primitive mantle composition to be consistent with past usage of this term, we use the values from ref. 13, because these have served as the model, chondrite-based, primitive mantle compositions with which the scientific community is most familiar. The lavas from Baffin Island with highest $^3He/^4He$, BI-PI-25 and DUR8, represent the normal (N) type and enriched (E) type lavas found in the BIWG LIP, respectively. Rb was not reported for BI-PI-25, and Pb concentrations were not reported for the Baffin Island or the OJP lavas[5,18]. The variability in Rb and Ba (and probably K) in OJP[18] and BIWG[2] lavas is probably due to alteration, and U has been dramatically modified by alteration in BIWG sample BI-PI-25 (and is not plotted). Only Kroenke-type OJP lavas are plotted, because they have probably experienced only olivine fractionation, whereas Kwaimbaita-type lavas are isotopically similar (Fig. 1) but are more evolved. All OJP and BIWG lavas are corrected for olivine fractionation to be in equilibrium with an olivine composition with a forsterite content of 92% (ref. 2). Only the freshest Kroenke-type lavas have been plotted, excluding the following samples (using the same filter as ref. 18): volcaniclastics and lavas with loss on ignition >0.5% and/or $K_2O/P_2O_5 > 2$. The non-chondritic primitive mantle[2] (or early depleted reservoir; see Supplementary Information) and depleted MORB mantle[15] are included.

The other test that can be applied to distinguish a primitive mantle source is high $^3He/^4He$. Unfortunately, owing to their age, post-eruptive radiogenic ingrowth of ^4He complicates identification of mantle source $^3He/^4He$ signatures[2,3,9].

Although many of the largest LIPs host lavas that have primitive Pb and Nd isotopic compositions, a number of large LIPs erupted in the past 250 Myr do not. This could be because of the absence of a primitive mantle component in their mantle sources or could be due to pervasive continental crust assimilation by lavas with initially primitive isotopic compositions; deconvolving the effects of crustal assimilation makes it difficult to assess the abundance of the primitive component in the mantle source of continentally erupted LIPs. Critically, however, the most frequent $^{143}Nd/^{144}Nd$ ratio in the global ocean-island basalt data set—that is, 0.5129–0.5130 (present-day $\varepsilon^{143}Nd = +5.3$ to $+9.0$; see Supplementary Information)[9]—is identical to that predicted for a non-chondritic terrestrial mantle and is also similar to the PREMA (Prevalent Mantle; see Supplementary Information) reservoir[9] (Fig. 1). This narrow range of Nd-isotopic ratios also overlaps with the $^{143}Nd/^{144}Nd$ identified in OJP and the least crustally contaminated continental LIPs (Fig. 1). If the large proportion of ocean-island-basalt lavas with present-day $\varepsilon^{143}Nd$ near $+5.3$ to $+9.0$ reflects a high proportion of non-chondritic primitive material in the mantle, then the early-formed reservoir must comprise a substantial portion of the modern terrestrial mantle. One problem with this interpretation is that many lavas with $^{143}Nd/^{144}Nd$ near 0.5130 (present-day $\varepsilon^{143}Nd = +7.2$) do not have Pb isotopic compositions that plot on the geochron (see Supplementary Information). This may be due to incorporation of recycled oceanic crust into the primitive reservoir, which would cause the mixture to be displaced to the right of the geochron[2], owing to the high Pb concentrations and high U/Pb ratios in recycled oceanic crust[26]. The high Pb/Nd concentration ratios in subducted oceanic crust relative to other mantle reservoirs, however, would lead to only slightly lower $^{143}Nd/^{144}Nd$ in the mixture.

If the Earth's primitive mantle currently has a $^{143}Nd/^{144}Nd$ of 0.5130 (present-day $\varepsilon^{143}Nd = +7.2$), then mass-balance calculations suggest that only 45–60% of the mantle was depleted to generate the chemically complementary continental crust and depleted mid-ocean-ridge basalt (MORB) mantle[2]. Recent dynamic convection models of the Earth's mantle suggest that, over the age of the Earth, 10–25% of the Earth's convecting mantle has never melted[27]. Mantle stirring and mixing is likely to have contaminated much of the surviving primitive reservoir with recycled material. This is consistent with the hypothesis that the ocean-island-basalt source mantle is largely composed of non-chondritic primitive mantle material that has been slightly modified by the incorporation of recycled material. Therefore, the present-day mass of surviving primitive material that has escaped melting and incorporation of recycled material may be small. The fact that the Earth's major LIPs have Nd and Pb isotopic compositions close to those expected for the non-chondritic primitive reservoir suggests that these LIPs may preferentially sample the uncontaminated portions of this reservoir.

A significant fraction of the world's largest volcanic events tap a mantle source that is similar to the primitive, non-chondritic mantle reservoir discovered in high $^{3}He/^{4}He$ lavas from BIWG, and the geochemical characteristics of a non-chondritic mantle may provide insights regarding its presence in LIPs. A (non-chondritic) primitive mantle has higher concentrations of the radioactive, heat-producing elements U, Th and K (0.012, 0.046 and 159 p.p.m., respectively[2]) than does depleted MORB mantle (0.0054, 0.016 and 68.4 p.p.m.; ref. 15), though still lower than for estimates of primitive mantle based on chondritic models (0.0203, 0.0795 and 240 p.p.m.; ref. 13). This higher heat-generating capacity would make the less-depleted mantle more prone to mantle upwelling and plume generation and also cause it to melt to a greater degree. Additionally, the bulk composition of a non-chondritic mantle would be more fertile and fusible than depleted MORB mantle. Therefore, under normal melting conditions, it would undergo greater degrees of melting. These two mechanisms—a hotter and more fusible mantle source—may work together to produce the extraordinarily large volumes of melt observed at LIPs.

The current distribution of non-chondritic primitive material in the mantle is not known, but a recently discovered palaeo-geographic relationship between Phanerozoic LIPs and the large low-shear-wave-velocity provinces (LLSVPs) in the deepest mantle might provide a clue. Torsvik *et al.* (ref. 28) showed that, using a reasonable plate reconstruction, most LIPs that erupted during the past 320 Myr plot directly over one of the two hot and dense LLSVPs, one beneath Africa and one beneath the Pacific. They suggest that the two near-antipodal LLSVPs have remained stable features in the mantle for up to 540 Myr. The geographic association of LIPs at the surface with LLSVPs at depth suggest that the mantle domain represented by the LLSVPs may be the source of the LIPs. If LIPs sample a primitive non-chondritic mantle source, then the results of Torsvik *et al.* suggest that the LLSVPs are clear candidates for hosting this ancient mantle source. At about 2% of the mantle's mass[29], the two LLSVPs are sufficiently large to source all LIP volcanism over the age of the Earth (see Supplementary Information), an observation that highlights their potential as reservoirs of early primitive material in the Earth.

METHODS SUMMARY

OJP lavas were erupted in an oceanic environment where assimilation of continental crust does not complicate the geochemical signatures of the lavas, making it possible clearly to identify their mantle source compositions. Although the OJP lavas potentially could have been contaminated by the oceanic crust through which they erupted, the relatively small difference in isotopic composition among the OJP lavas, and the low Nd and Pb concentrations of typical basaltic oceanic crust, would cause only minor isotopic shifts in the pre-contamination magmas, given reasonable amounts of contamination. Assimilation of oceanic pelagic sediments could more dramatically alter the isotopic composition of primitive OJP lavas, but such materials tend to have low $^{143}Nd/^{144}Nd$ and Pb isotope compositions plotting well to the right of the geochron. The OJP lavas display no trends consistent with the incorporation of pelagic sediments. In contrast, flood basalts erupted in continental settings are prone to contamination by assimilation of continental crust. In spite of being erupted in a continental setting, the subset of BIWG flood basalt lavas examined by ref. 2 exhibit little evidence for contamination by continental crust. In the Methods section, we examine a subset of lavas from each of four additional continental flood basalt provinces—the Antarctic portion of the Karoo flood basalt, the Siberian Traps, the Kerguelen Plateau and the Deccan—that, like the OJP and a subset of the BIWG, have suffered minimal crustal contamination and exhibit mantle source signatures predicted for a (non-chondritic) primitive mantle signature. Each of the four additional continental flood basalts have been extensively studied by others (see Methods), and the geochemical signatures associated with continental assimilation have also been thoroughly explored: the lavas that have suffered from the least continental crust assimilation also have the highest $^{143}Nd/^{144}Nd$ ($\varepsilon^{143}Nd$) ratios, and these ratios cluster near the range predicted for a non-chondritic primitive mantle.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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METHODS

To establish a baseline for the composition of melts sampling a (non-chondritic) primitive mantle reservoir, this Letter relies on the conclusions drawn from the OJP data set, in large part to avoid the issue of the sensitivity of continental flood basalts to contamination by continental crust during emplacement and eruption. The OJP was erupted in an oceanic environment, and there is no evidence for continental fragments in the OJP. Although we cannot rule out small degrees of contamination from the oceanic lithosphere, the Pb-isotopic composition of OJP lavas is not at all consistent with a strong oceanic crust or sediment overprint. The tight clustering of the OJP Pb-isotopic data—which were measured on samples collected from Malaita and multiple drill core locations scattered over hundreds of kilometres across the plateau—is remarkable and argues against any systematic offset of the data caused by oceanic crust or sediment contamination. An important point regarding the OJP lavas is that we did not filter the data on the basis of any isotopic parameter. Figure 1 shows all available OJP lavas (excluding late-stage Singgalo lavas) that have both paired U–Pb concentrations and Pb-isotopic measurements and paired Sm–Nd concentrations and Nd-isotopic measurements.

In contrast, a specific isotopic filter was applied to the continental flood basalts, because the isotopic compositions of such lavas are often overprinted by continental crust. In selecting samples with the most radiogenic Nd-isotopic compositions, we are selecting samples with the lowest crustal input and it is those lavas that have Pb-isotopic compositions that plot close to the geochron. Although we cannot rule out the possibility that these basalts obtained their Pb-isotopic compositions through a haphazard mixture of continental crust and variable mantle sources, it is worth noting that all of the samples shown in Fig. 1—that were selected based solely on Nd-isotopic compositional characteristics—also plot exactly where expected in Pb-isotopic space for a melt of ancient primitive mantle. Below, we present additional geochemical evidence from the literature that supports our contention that continental flood basalts—including BIWG, the Kerguelen Plateau, Siberian Traps, Deccan Traps and the Antarctic portion of the Karoo—with the highest $^{143}Nd/^{144}Nd$ have suffered from the least crustal contamination and best represent mantle source compositions.

BIWG flood basalt lavas. Continental crust contamination had already been ruled out for a suite of lavas from BIWG examined by ref. 2. Larsen and Pederson (ref. 31) used trace-element indicators sensitive to continental crust assimilation to show that West Greenland lavas with the least crustal contamination have radiogenic $\varepsilon^{143}Nd(t)$ values and plot in a specific region of Pb-isotopic space. An evaluation of this data by ref. 2 showed that the region of Pb-isotopic space occupied by the least contaminated Baffin Island lavas corresponds with the 4.55–4.45-Gyr terrestrial geochrons.

Kerguelen Plateau basalts. Although originally viewed as an oceanic plateau, continental fragments have been identified in the Kerguelen Plateau using seismic methods (ref. 32). Clasts of garnet-biotite gneiss recovered from Elan Bank contain zircons with ages ranging from 534 to 2,547 Myr (ref. 33), clearly indicative of an old crustal basement beneath portions of the Kerguelen Plateau. Additionally, studies in the area have found geochemical evidence for continental assimilation in Kerguelen basalts, and workers in this area have spent considerable efforts showing which basalts are and are not contaminated in this province[23,34–37]. For example, Kerguelen lavas that have been contaminated with continental crust tend to have low Nb/La (for example, ODP leg 120 site 747, ODP leg 183 site 1137) or high $^{87}Sr/^{86}Sr$ (>0.7045; for example, ODP leg 119 site 738, ODP leg 120 sites 747 and 750, and ODP leg 183 site 1137). In contrast, a subset of the lavas from ODP leg 120 site 749 have low $^{87}Sr/^{86}Sr$ (<0.704) and Nb/La ratios (0.9–1.0) that are similar to oceanic lavas and low $^{87}Sr/^{86}Sr$ ratios[23]. Site 749 lavas are divided into two distinct groups: group 1 has lower Nb/La (0.80–0.85) and higher $^{87}Sr/^{86}Sr$ (>0.704) than group 2, which has higher Nb/La (0.9–1.0) and lower $^{87}Sr/^{86}Sr$. The site 749 lavas from group 1, with the lower Nb/La and higher $^{87}Sr/^{86}Sr$, are interpreted to have suffered from more assimilation of continental crust than the group 2 lavas. We note that the group 2 lavas from site 749 basalts, which we consider to be the least contaminated by continental crust, have the highest $\varepsilon^{143}Nd(t)$ in the Kerguelen Plateau suite, an observation that supports our contention that continental LIPs with the most radiogenic Nd-isotopic compositions best represent the mantle source in geochemically complex continental flood basalt provinces. These lavas also have Pb-isotopic compositions that plot close to the geochron.

Deccan flood basalt lavas. In the Deccan, the Ambenali formation flows are thought to best represent mantle compositions[24,38,39]. Several studies have documented the nature of crustal contamination in the Deccan and show that the least-contaminated members of the Ambenali are closest to mantle source compositions[24,38,39]. For example, ref. 38 used Ba/Y and Ba/Zr (where both ratios are high in continental crust) to identify lavas that have suffered from crustal contamination, and they found that lavas with the lowest Ba/Y and Ba/Zr are found in the Ambenali formation. Additionally, ref. 39 used Ba/Ti to evaluate continental assimilation (where high Ba/Ti is high in continental crust), and they found Ambenali lavas to have low Ba/Ti ratios. Ref. 39 also considered radiogenic Sr isotopic ratios to be a signature of crustally contaminated Deccan lavas, and although Ambenali lavas tend to have the lowest $^{87}Sr/^{86}Sr$ in the Deccan, some of the Ambenali lavas have elevated $^{87}Sr/^{86}Sr$—with correspondingly low $\varepsilon^{143}Nd(t)$—that are considered to be crustally contaminated. Like ref. 39, we exclude such lavas as having a mantle source composition. In summary, the least-contaminated units of the Ambenali formation, which is considered to be the least contaminated in the Deccan, also have the highest $\varepsilon^{143}Nd(t)$, and these lavas have Pb-isotopic compositions that plot close to the geochron.

Siberian flood basalt. The ~251-Myr-old Siberian Traps are generally too contaminated by continental crust assimilation to allow us to evaluate primary mantle compositions[22,40]. However, a recent study showed that the Siberian meimechites have the highest $\varepsilon^{143}Nd(t)$ of any Siberian flood basalt and have trace-element characteristics inconsistent with crustal contamination[22]. Together with having the highest $\varepsilon^{143}Nd(t)$, the meimechites also have the lowest Th/Ta in the flood basalt province. This is in contrast to the crustally contaminated Siberian flood basalt lavas that have high Th/Ta (continental crust has high Th/Ta) coupled with low $\varepsilon^{143}Nd(t)$ (ref. 22). The Siberian meimechites also have Os-isotopic compositions inconsistent with any significant crustal input[22]. Like the Deccan and Kerguelen flood basalts, the least crustally contaminated Siberian flood basalt lavas have the highest $\varepsilon^{143}Nd(t)$, and these lavas have Pb-isotopic compositions that plot close to the geochron.

Antarctic Karoo flood basalts. Using a data set similar to the Siberian lavas from ref. 22, similar arguments were used to argue for a lack of contamination in the picritic lavas in the Antarctic portion of the Karoo flood basalt province[21]. The lavas that are considered to be least contaminated by continental crust exhibit Os-isotopic signatures that are thought to reflect mantle signatures (age-corrected $^{188}Os/^{188}Os = 0.1257–0.1286$), while the crustally contaminated lavas have higher $^{187}Os/^{188}Os$ (0.1297–0.1426), consistent with continental crust assimilation. The crustally contaminated lavas also have higher $^{87}Sr/^{86}Sr$ (≥0.7036 after age correction) than the least crustally contaminated lavas (<0.7036). The least-contaminated Antarctic Karoo lavas also have the highest $\varepsilon^{143}Nd(t)$, and their Pb-isotopic compositions plot close to the geochron.

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SI Guide

Title of each file (in a merged PDF):

1. Supplementary Discussion
2. Supplementary Figures and Legends 1 and 2
3. Supplementary References

Supplementary Figure 1 shows a histogram of $^{143}Nd/^{144}Nd$ for the global ocean island basalt database. Supplementary Figure 2 shows that ocean island lavas with primitive (but non-chondritic) $^{143}Nd/^{144}Nd$ ratios do not generally plot on the terrestrial Pb-isotope geochron. The Supplementary Discussion presents some of the implications of a non-chondritic primitive mantle in the source of the largest igneous provinces (PDF size is 0.68 Mb)

Supplementary Information (Jackson and Carlson, 2011)

Supplementary Discussion

All known modern terrestrial mantle reservoirs evolved from a primitive precursor with superchondritic $^{143}Nd/^{144}Nd$. What is this reservoir?

The terms "primitive" or "primordial" mantle or "bulk-silicate Earth" refer to the hypothetical homogeneous average composition of the silicate portion of the Earth at the end of accretion and core formation. Until recently, this reservoir was assumed to have chondritic relative abundance ratios of refractory lithophile elements[1-3] and as a result, chondritic isotopic compositions of radioactive decay systems based on parent and daughter elements that are both refractory lithophile elements, e.g. Sm-Nd and Lu-Hf[4-6]. The discovery of an 18 ppm difference in $^{142}Nd/^{144}Nd$ between chondrites and modern mantle-derived rocks[7] suggests that, within a few tens of millions of years of Earth formation, the portion of Earth's mantle that serves as the source of modern volcanism was already characterized by a Sm/Nd ratio some 4 to 7% higher than chondritic. There are two models for the origin of this ancient non-chondritic reservoir. One is that it simply may represent a non-chondritic bulk-Earth composition, although the mechanism that results in an Earth with non-chondritic refractory lithophile element abundances is unclear[8,9]. Alternatively, a chondritic bulk mantle may have undergone an early differentiation event forming chemically complementary incompatible element depleted and enriched reservoirs given the labels "early depleted reservoir" (EDR) and "early enriched reservoir" (EER) by Boyet and Carlson (2005)[7]. In this case, the EDR became the predecessor to all modern terrestrial mantle reservoirs, and is therefore effectively a primitive mantle reservoir. In this paper, when we use the term "primitive mantle" we are referring to the mantle reservoir characterized by a superchondritic Sm/Nd and Nd isotopic composition, irrespective of whether that reservoir reflects a non-chondritic Earth or one mantle reservoir (EDR) formed in an early global differentiation event.

Floods basalts are melts of a chondritic primitive mantle?

The supposition that LIPs derive from primitive mantle sources was originally made on the basis of the clustering of some flood basalts with $^{143}Nd/^{144}Nd$ near chondritic[4]. This idea fell into disfavor on the argument that those flood basalts with near-chondritic $^{143}Nd/^{144}Nd$ obtained those isotopic compositions through crustal contamination of parental magmas that had higher, non-chondritic $^{143}Nd/^{144}Nd$ (ref. 10). Here we revive the idea that a primitive mantle reservoir is the source of the largest flood basalts, but unlike DePaolo and Wasserburg (1976)[4], we argue that the primitive source is not chondritic. Flood basalts that are the least crustally contaminated, and that exhibit superchondritic $^{143}Nd/^{144}Nd$ (0.5129-0.51309), have geochemical signatures predicted for a non-chondritic primitive reservoir[11].

The dominance of superchondritic $^{143}Nd/^{144}Nd$ in ocean island basalts was recognized long ago[12]. This mantle source, with $^{143}Nd/^{144}Nd$ ~0.5129-0.5130, was called PREMA (Prevalent Mantle); it was suggested to be the depleted mixing end-member identified in flood basalts and ocean island basalts, but was isotopically distinct from, and less depleted than, the depleted MORB mantle (DMM)[12]. PREMA also was assigned Pb isotopic compositions close to the terrestrial geochron (Fig. 1), but the superchondritic $^{143}Nd/^{144}Nd$ made this reservoir distinct from the hypothetical primitive mantle reservoir that had chondritic refractory lithophile elements (and hence $^{143}Nd/^{144}Nd = 0.51263$). However, the discovery of a difference in $^{142}Nd/^{144}Nd$ between modern terrestrial rocks and chondrites suggests that the $^{143}Nd/^{144}Nd$ measured in OJP lavas overlaps with the primitive (albeit non-chondritic) terrestrial mantle, and we argue that this early, primitive (but non-chondritic) reservoir has sourced flood basalt volcanism over the past 250 Ma.

Lower limit on the size of volume of the unmodified (non-chondritic) primitive mantle.

While the quantity of surviving uncontaminated primitive mantle material is unknown, the large volume of LIPs with compositions similar to a non-chondritic primitive mantle can be used to place a lower limit on the volume of the unmodified primitive mantle that has survived until the past 250 Ma. The relatively homogeneous OJP has an estimated maximum eruptive volume of approximately $6*10^7$ km^3 (ref. 13), and if the melts resulted from 20-30% mantle melting[14], then a mantle reservoir with a volume of $2\text{-}3*10^8$ km^3 was required to generate this province. This represents just over 0.02-0.03% of the volume of the mantle. If we include the Manihiki Plateau[15,16], and include the maximum erupted volumes of the other 5 primitive-mantle-hosting LIP's[10,13] (and assume that they sample largely non-chondritic mantle sources that were subsequently overprinted by continental crust assimilation of magmas), then the required volume of mantle roughly doubles to $4\text{-}6*10^8$ km^3. This volume represents only 0.04-

0.06% of the mantle, or just 2.5-3.8% of a 100 km-thick layer at the core mantle boundary. If this rate of LIP formation remained constant over Earth history, melting the primitive mantle at a rate of 0.05% of the mantle per 250 million years would require processing of < 1% of the mass of the mantle in order to produce the LIP flux over the 4.5 billion year age of Earth. Therefore, the size of the surviving primitive mantle reservoir that has sourced flood basalt volcanism need not be a large fraction of the Earth's mantle.

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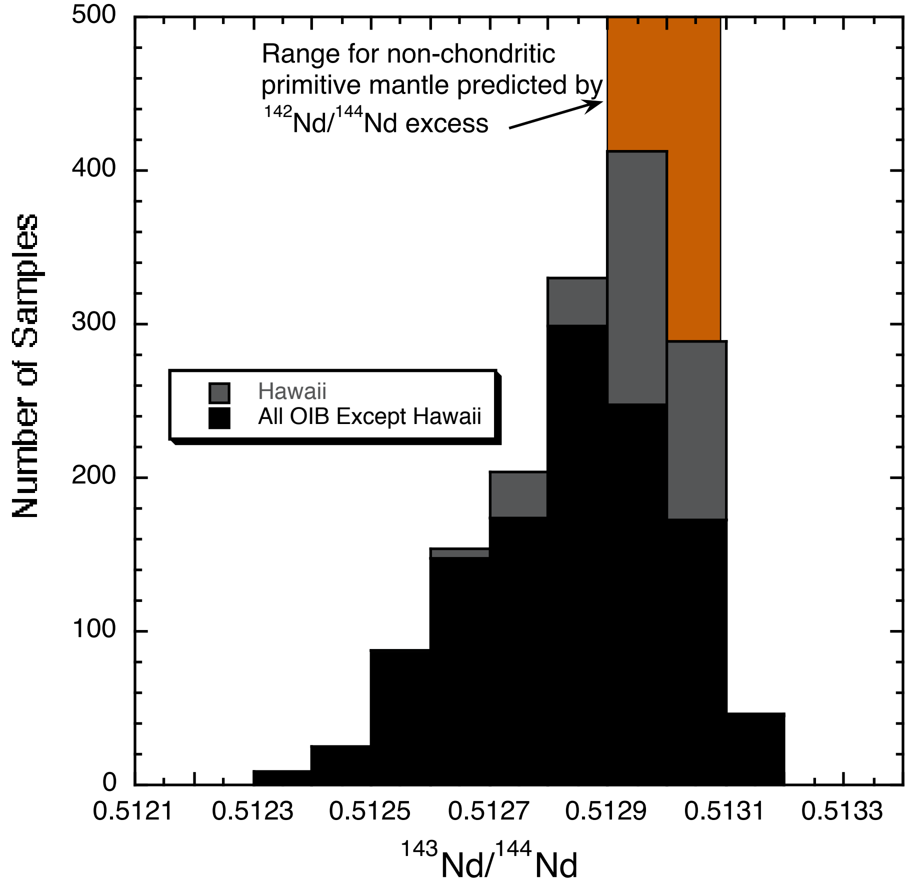
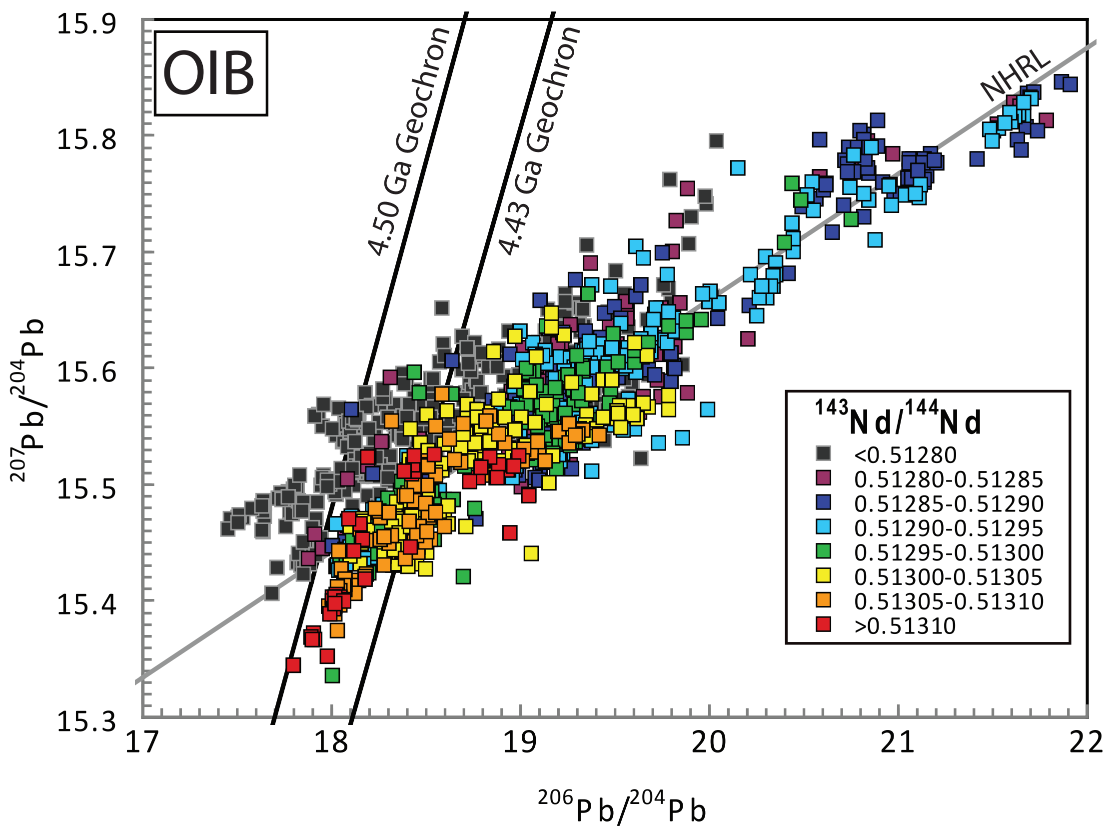


Supplementary Figure 1. Nd isotopic compositions for the global OIB dataset (from Georoc: http://georoc.mpch-mainz.gwdg.de/georoc/) peak in the range predicted for the primitive mantle (0.51290 to 0.51309) on the basis of its superchondritic ^{142}Nd/^{144}Nd. This peak in ^{143}Nd/^{144}Nd is referred to as PREMA (prevalent mantle) in Zindler and Hart (1986)[12]. Note that data from Hawaii are plotted separately, owing to the fact that Hawaii is over-represented in the OIB database, but the Hawaiian data do not dramatically change the peak of the ^{143}Nd/^{144}Nd. Most of the samples with Nd isotopic compositions in this range, however, have Pb isotopic compositions plotting to the right of the geochron (see Fig. S2). Although this has long be taken to reflect the consequences of crust formation and mantle-differentiation over Earth history, we suggest that an alternative explanation is that the source of OIB is non-chondritic primitive mantle with ^{143}Nd/^{144}Nd ~ 0.5130 and Pb isotopic composition plotting on the geochron that has been contaminated with a small percentage of recycled crustal material. The LIPs discussed in this paper that have Pb isotopic compositions near the geochron preferentially sample an uncontaminated portion of this primitive mantle.!



Supplementary Figure 2. The isotopic topology of the $^{143}Nd/^{144}Nd$ of basalts and OIBs in $^{206}Pb/^{204}Pb$ vs $^{207}Pb/^{204}Pb$ isotope space. Most OIB lavas with $^{143}Nd/^{144}Nd$ (0.51290 to 0.51309, the range possible for the EDR or a non-chondritic primitive mantle given a $^{142}Nd/^{144}Nd$ 18±5 ppm higher than chondritic), similar to PREMA, do not have Pb-isotopic compositions on the geochron. This demonstrates that PREMA is not a pure, non-chondritic primitive reservoir like the EDR. Instead, PREMA may be dominated by primitive material that has mixed with a small component of recycled material, where the latter perturbs Pb isotopes away from the geochron and causes the OIB Nd histogram to be skewed to lower values of $^{143}Nd/^{144}Nd$. OIB data are from Georoc (http://georoc.mpch-mainz.gwdg.de/georoc/).

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