The Ontong Java and Manihiki oceanic plateaus are believed to have formed through high-degree melting of a mantle plume head. Boninite-like, low-Ti basement rocks at Manihiki, however, imply a more complex magma genesis compared with Ontong Java basement lavas that can be generated by ~30% melting of a primitive mantle source. Here we show that the trace element and isotope compositions of low-Ti Manihiki rocks can best be explained by re-melting of an ultra-depleted source (possibly a common mantle component in the Ontong Java and Manihiki plume sources) re-enriched by ≤1% of an ocean-island-basalt-like melt component. Unlike boninites formed via hydrous flux melting of refractory mantle at subduction zones, these boninite-like intraplate rocks formed through adiabatic decompression melting of refractory plume material that has been metasomatized by ocean-island-basalt-like melts. Our results suggest that caution is required before assuming all Archaean boninites were formed in association with subduction processes.
Large igneous provinces are formed over a relatively short time period (several million years) through massive volcanism related to pressure-release melting of upwelling mantle plume heads1–3. Some basement lavas from the Ontong Java (OJP), Manihiki and Hikurangi Plateaus, located in the Southwest Pacific Ocean (Fig. 1), have similar chemical compositions and ages (~118–125 Myr), consistent with their derivation from a common source through high degrees (~30%) of mantle melting4–7. It has been proposed that they represent fragments of a single ‘super’ plateau8,9 and that this magmatic event, the largest in the Phanerozoic, covered ~1% of Earth’s surface5.

The primitive Kroenke and more evolved but isotopically identical and dominant Kwaimbaita basement lavas from OJP6,10,11 are thought to be derived from a primitive, ancient, lower-mantle reservoir12. These lavas have flat, primitive-mantle-normalized incompatible-element patterns. The stratigraphically younger and minor Singgalo lavas10,11 at OJP have geochemical characteristics similar to Manihiki high-Ti basement lavas4, for example, drilled at DSDP Site 317 (ref. 5). Owing to their possibly younger stratigraphic age, we do not consider these lavas further in this paper.

In contrast to OJP, a major part of the Manihiki Plateau is composed of relatively low-Ti, high-MgO rocks, dated at 118–125 Myr (refs 4,13), and related to the basement (main) phase of plateau formation similar to OJP Kroenke/Kwaimbaita lavas. These low-Ti rocks have variable contents of the most incompatible elements, positive relative Nb-Ta anomalies, and most of them have U-shaped patterns on primitive mantle- and mid-ocean-ridge basalt (MORB-) normalized incompatible element diagrams4,13. The boninite-like, U-shaped patterns are unique and enigmatic for plume-derived intraplate magmas, indicating depletion and re-enrichment processes involved in their genesis. In previous studies, the origin of the low-Ti rocks was explained by high-degree melting of a mixed source containing depleted mantle wedge material and small amounts of subducted volcaniclastic sediments13 and by extensive melting of a hybrid mantle source comprising FOZO-type peridotite and recycled oceanic crust1.
Here we present geochemical data from rare, fresh glass samples and additional major element data from bulk rock samples from the Manihiki Plateau obtained by dredging during the R/V Sonne SO193 (ref. 4) and SO225 expeditions (Fig. 1). Glass samples from the SO193 cruise yielded ages of 122.9 ± 1.6 and 124.5 ± 1.5 Myr (ref. 4). The fresh glasses provide a unique opportunity for precise geochemical characterization of the parental Manihiki melts, not possible with phenocryst-bearing whole rock samples variably affected by seawater alteration. We show that the origin of the low-Ti Manihiki rocks is related to re-melting of an isotopically distinctive, highly depleted plume source beneath Manihiki and possibly the OJP, comprising small and variable amounts of a recycled HIMU (high time-integrated 238U/204Pb ratio)-like component.

**Results**

**Composition of low-Ti glasses.** Relics of fresh glasses were found in strongly palagonitized hyaloclastites and pillow-lava margins. The glasses contain very rare vesicles and fresh olivine micro-

phenocrysts with inclusions of chromium-rich spinel. The glasses are tholeiitic (SiO2 = 51.1–52.4 wt%; Na2O + K2O = 1.5–1.8 wt%), characterized by very low TiO2 (0.27–0.44 wt%) and relatively high MgO (9.0–9.8 wt%) contents (Fig. 2a,b, Supplementary Table 1). Some glass and whole-rock samples have SiO2 contents above 52 and as high as 56 wt% at MgO > 8 wt%, which is characteristic for boninites14. High CaO contents (12.9–13.2 wt%) reflect insignificant clinopyroxene fractionation consistent with its absence as a phenocryst phase. The low-Ti glasses also have low but variable K2O contents (0.02–0.17 wt%) at relatively constant and high Mg# (molar Mg/(Mg + Fe)) = 0.65–0.67. Compared with primitive Kroenke lavas from the OJP basement with similar MgO content (9–10 wt% MgO; ref. 15), the low-Ti Manihiki glasses have higher SiO2 (51.4–52.4 versus ~48.9–50.4 wt%) and lower TiO2 (0.27–0.44 versus ~0.68–0.78 wt%) contents. The low-Ti Manihiki glasses contain 0.13–0.25 wt% H2O, 350–546 p.p.m. K2O) have high Cl/K2O (0.10–0.14, H2O/K2O = 0.02 wt% for the Troodos upper pillow lavas on Cyprus26, indicating their origin from a clinopyroxene-bearing, deformed lherzolite or harzburgite source27.

A major process for generating the characteristic compositional features of boninites is melting of highly depleted (through previous melt extraction) peridotitic mantle, triggered through addition of a hydrous slab-derived fluid or melt, enriched in incompatible elements25. The hydrous fluid/melt lowers the solidus temperature of the deformed peridotite, causing it to melt24,28. Several geochemical characteristics of the low-Ti Manihiki magmas, however, are not consistent with a subduction origin. There is no evidence of strong, selective enrichment in highly fluid-mobile elements (for example, Rb, Sr, U, Pb). Further, the strong enrichment in Nb andTa compared with other incompatible elements is unusual for subduction-related magmas (Fig. 2c). In addition, the Manihiki glasses have low H2O contents (0.13–0.25 wt%, see Supplementary Table 1 and ref. 4). Finally, palaeo-reconstruction studies indicate that the plateau basement formed in an oceanic intraplate setting, possibly near a mid-ocean-ridge spreading centre, but far away from a subduction zone8,29.

In contrast to the enriched fluid or melt component in boninites, which is derived from the subducting slab, we show in the following discussion that the re-enrichment of the ultra-depleted mantle source at Manihiki most likely occurred through addition of an enriched HIMU-like mantle plume component to the source. Unlike hydrous fluids involved in boninite petrogenesis, the small amounts (≤ 1%, see below) of this HIMU

more depleted in moderately incompatible elements (Lu to Zr) than pristine Kroenke lavas, whereas more incompatible elements (for example, light rare earth elements (LREE), Nb, Ta, Th, U, Ba, Rb) in low-Ti Manihiki glasses range from being more depleted to more enriched (Fig. 2c). Both, low-Ti Manihiki and Kroenke/Kwaimbaita lavas show strong relative depletion in K relative to LREE and relative enrichment in Nb-Ta in the normalized incompatible-element patterns that distinguishes them from subduction-zone-related boninites from Troodos and Tonga, as does the lack of strong relative Pb enrichment of the low-Ti Manihiki glasses (Fig. 2c).

Isotope compositions of the low-Ti glass samples fall into two clusters forming positive correlations on the 87Sr/86Sr versus 143Nd/144Nd and the Pb isotope diagrams, and negative correlations on 208Pb/204Pb versus 143Nd/144Nd and 87Sr/86Sr isotope diagrams (Fig. 3, Supplementary Fig. 1). The most incompatible-element-depleted low-Ti theoleiites have isotopic compositions similar to enriched mid-ocean-ridge basalts (E-MORB; Fig. 3, Supplementary Fig. 1). Glasses with the strongest enrichment in the most incompatible elements have the most radiogenic Pb (Supplementary Table 1) and the least radiogenic Sr and Nd isotope signatures, and trend towards the compositions of some HIMU-like ocean-island basalts (OIBs).

**Discussion**

Manihiki low-Ti theoleiites share a number of characteristics with boninites from subduction-related settings, which are defined as rocks with > 52 wt% SiO2, > 8 wt% MgO and < 0.5 wt% TiO2 (ref. 14). Two glass samples, as well as a significant number of whole rock samples, fulfil the major element criteria for boninites in terms of SiO2, TiO2 and MgO content (Fig. 2a,b, Supplementary Table 1, 2). In addition, both the low-Ti Manihiki rocks and boninites have U-shaped incompatible element patterns with low Sm/Yb but high La/Sm (Fig. 2c,d), and low Ti/V (<12) ratios. Based on high CaO/Al2O3 ratios (0.83–0.88), the maﬁc low-Ti Manihiki theoleiites are similar to high-Ca-boninites24, such as, for example, those from the Tonga Arc25 and the Troodos upper pillow lavas on Cyprus26. Indicating their origin from a clinopyroxene-bearing, deformed lherzolite or harzburgite source27.

A major process for generating the characteristic compositional features of boninites is melting of highly depleted (through previous melt extraction) peridotitic mantle, triggered through addition of a hydrous slab-derived fluid or melt, enriched in incompatible elements25. The hydrous fluid/melt lowers the solidus temperature of the deformed peridotite, causing it to melt24,28. Several geochemical characteristics of the low-Ti Manihiki magmas, however, are not consistent with a subduction origin. There is no evidence of strong, selective enrichment in highly fluid-mobile elements (for example, Rb, Sr, U, Pb). Further, the strong enrichment in Nb and Ta compared with other incompatible elements is unusual for subduction-related magmas (Fig. 2c). In addition, the Manihiki glasses have low H2O contents (0.13–0.25 wt%, see Supplementary Table 1 and ref. 4). Finally, palaeo-reconstruction studies indicate that the plateau basement formed in an oceanic intraplate setting, possibly near a mid-ocean-ridge spreading centre, but far away from a subduction zone8,29.
mantle component probably did not have a major affect on the degree of mantle melting, and instead were mainly responsible for the variability in the concentrations of highly incompatible elements and Sr-Nd-Pb isotope ratios in low-Ti Manihiki magmas.

Variations of radiogenic isotope ratios (Fig. 3; Supplementary Fig. 1; Supplementary Table 1) in the low-Ti Manihiki glasses indicate that they do not simply represent different melt fractions from a single homogeneous mantle source. Following the criteria of ref. 30, linear correlations between incompatible element and isotope ratios with the same denominator (Supplementary Fig. 2) allow us to narrow down the range of possible scenarios for the origin of Manihiki magmas, indicating either mixing of two magmas from different sources ('magma mixing') or fixed degree of melting of a heterogeneous mantle source, comprising different proportions of depleted and enriched components ('source mixing'), for example, metasomatism of a depleted source with variable amounts of an enriched component. Although these two petrogenetic scenarios cannot be distinguished solely on the basis of incompatible-element (Supplementary Fig. 3) and isotope systematics30, they imply different mass fractions of the two components and consequently different effects on the major element composition of the magmas.

Before we can determine the compositions of the depleted and enriched end members, we need to calculate the compositions of primary Manihiki magmas from the composition of the low-Ti glasses. We calculated the primary magma compositions using the PRIMELT2 model31. The glasses are saturated with olivine

![Figure 2](image_url)
and spinel, which are the only liquidus phases, and thus the application of the model, involving incremental addition of olivine to the evolved melt, is straightforward. The calculated primary magmas are in equilibrium with olivine Fo91.1–91.3, have high MgO (15.7–17.0 wt%) and CaO (10.4–11.0 wt%), and are peridotite-derived compositions (Supplementary Table 3). Concentrations of incompatible elements in the primary magmas were then calculated by dilution of the trace element concentrations in glasses proportional to the amount of olivine added to the glass compositions.

To estimate the composition of the depleted source component, we first carried out forward modelling of pooled fractional melting, using a primitive mantle composition32 and bulk partition coefficients for peridotite melting33 to derive melts with similar concentrations of moderately incompatible elements, for example, heavy rare earth elements (HREE), to those in the calculated low-Ti primary melts (Fig. 4, Supplementary Fig. 4). The results of the forward modelling show that up to 15% fractional melting of fertile or moderately depleted mantle peridotite cannot explain the strong depletion of the Manihiki melts in moderately incompatible elements (Fig. 4a). The required depletion can only be achieved with multi-stage melting, when a significantly depleted source (through previous melting) is re-melted, and the magmas produced during the second stage of melting do not mix with magmas of the initial stage of melting, implying a time gap between these two melting events. The best-fit parameters of the two-stage melting scenario obtained by the least-squares fitting of the HREE concentrations in the modelled melts to the Manihiki primary magmas are ~11% melting of fertile peridotite during the first stage and ~9% melting of the residual mantle during the second stage. Modelling with more depleted sources than primitive mantle (for example, Depleted MORB Mantle (DMM) type source33) results in decreasing the total extent of melting. Taking into account the uncertainties in the physical parameters of melting and the initial source composition, the estimates in Fig. 4a only provide a possible (but not unique) origin for the depleted end member of the low-Ti Manihiki primary melts.

Although the degrees of melting of the individual melting stages cannot be fully constrained, the conclusion about the necessity of two (or multi)-stage melting to explain the concentrations of moderately incompatible elements in primary Manihiki magmas is robust. In conclusion, the modelling results show that the low-Ti Manihiki magmas could be highly depleted peridotite (that is, ultra-depleted mantle, UDM; Supplementary table 4) residual after ~11% fractional melting and melt removal.

Re-melting of residual mantle peridotite (and subsequent re-enrichment in incompatible elements) points to a similar type of origin for the low-Ti intraplate rocks and subduction-related boninites24. Since the low-Ti rocks do not show any evidence for a subduction-related origin as discussed above, elevated temperature and further decompression melting related to the emplacement of a hot mantle plume head are likely to have driven the melting under the Manihiki Plateau rather than a hydrous fluid/melt. The overall lower SiO2 content of the low-Ti tholeiites compared with boninites can also be explained through dry refractory lherzolite melting, since hydrous melting of refractory lherzolite would increase the contribution of orthopyroxene to the melt resulting in a higher SiO2 melt content28.

A recent study described ultra-depleted melt inclusions in olivines from a Kronenke-type lava (Fig. 2a,b,d), which were proposed to originate from a previously unrecognized ultra-depleted component in the OJP mantle source16. Since OJP, Hikurangi and Manihiki Plateaus are likely to have formed as a single plateau originally8,9, they presumably shared some similar source material. The recognition of UDM in the source of the low-Ti Manihiki magmas suggests that this mantle component may be involved in the origin of both OJP and Manihiki magmas.

The isotopic composition of the UDM end member can place important constraints on its origin. Since the modelled UDM incompatible element pattern shows systematically decreasing...
abundances of elements as they become more incompatible (Rb through Ta) showing near zero abundances (<0.001; Fig. 4a, Supplementary Table 4), the most-depleted samples cannot serve as the depleted end member, due to their U-shaped patterns. Following the approach of ref. 30, the isotope composition of the UDM was estimated from linear correlations of the Manihiki low-Ti lavas on plots of x/Pb versus Pb isotope ratios, x/Nd versus \( \text{Nd}^{143}/\text{Nd}^{144} \) and x/Sr versus \( \text{Sr}^{87}/\text{Sr}^{86} \) (where x is a highly incompatible element, for example, Ba, which has a negligible—near zero—concentration in the residual mantle after fractional melting). Since the Ba concentration in the UDM is near to zero, ratios of Ba/Pb, Ba/Nd and Ba/Sr will also approach zero and thus the UDM will have the following isotopic composition: 143Nd/144Nd and x/Sr versus \( \text{Sr}^{87}/\text{Sr}^{86} \) (where x is a highly incompatible element, for example, Ba, which has a negligible—near zero—concentration in the residual mantle after fractional melting). Since the Ba concentration in the UDM is near to zero, ratios of Ba/Pb, Ba/Nd and Ba/Sr will also approach zero and thus the UDM will have the following isotopic composition: 143Nd/144Nd and x/Sr versus \( \text{Sr}^{87}/\text{Sr}^{86} \) (where x is a highly incompatible element, for example, Ba, which has a negligible—near zero—concentration in the residual mantle after fractional melting).

Figure 4 | Two-stage mantle melting and source mixing to generate low-Ti primary Manihiki magmas. (a) Primitive-mantle-normalized multi-element plot of incompatible elements showing the compositions of primary low-Ti melts calculated from the compositions of Manihiki glasses (Supplementary Table 3; red circles); the ranges of melt compositions produced by pooled (aggregate) fractional melting from 1% to 15% of primitive mantle (PM) and of residual primitive mantle after 5% (PM-5%) and 10% (PM-10%) fractional melting; and residual mantle compositions after 5% and 10% previous melt extraction (yellow and green triangles, respectively). (b) The compositions of second stage melts produced by 8.7% pooled fractional melting of an UDM source. The UDM source was previously generated by 10.6% melt extraction from PM and subsequent enrichment/metasomatism with variable amounts (indicated in wt%) of melt corresponding in composition to the mafic Rurutu sample #RRT-B-30 from ref. 34. Details of the melt modelling are given in the discussion and input parameters in Supplementary Table 4.

The primitive-mantle-normalized incompatible element patterns of the most enriched low-Ti glasses show enrichment in the moderately to highly incompatible elements, relative enrichments in Nb and Ta and relative depletions in K, Pb and Zr-Hf, general characteristics of HIMU-type lavas (Fig. 4). Below we will test the source and melt mixing models to see which can best explain the compositions of the low-Ti melts.

First, we test the source-mixing model (Fig. 4b) using the composition of primitive (MgO > 10 wt%) HIMU-like lavas from the Rurutu Island, Austral archipelago, Central Pacific34, which have isotope compositions similar to the most LREE-enriched low-Ti rocks, to serve as the enriched end member. The model reproduces the general shape of the incompatible-element patterns and abundances of U, Nb, Ta and LREE in the primitive low-Ti Manihiki magmas well (Fig. 4b). Small discrepancies are however evident, primarily for fluid-mobile incompatible elements (Rb, Ba, U and Sr). A slightly better fit for the incompatible elements in the low-Ti Manihiki primary magmas can be achieved if the most enriched Macquarie Island ophiolite glasses35 (Supplementary Fig. 4a), which also have HIMU-like incompatible element compositions but distinct (Pacific-MORB-like) isotopic compositions, are assumed for the enriched end member. The addition of ~0.06 to 1% of the Rurutu or Macquarie enriched end members to the UDM source can reproduce the full range of low-Ti Manihiki incompatible-

\[
\text{Sample/primitive mantle} = 0.001, 0.01, 0.1, 1, 10, 100
\]

\[
\text{PM melts} = 0.001, 0.01, 0.1, 1, 10, 100
\]

\[
\text{PM-5% melts} = 0.001, 0.01, 0.1, 1, 10, 100
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\text{PM-10% melts} = 0.001, 0.01, 0.1, 1, 10, 100
\]

\[
\text{PM-10% residue} = 0.001, 0.01, 0.1, 1, 10, 100
\]

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\text{PM-5% residue} = 0.001, 0.01, 0.1, 1, 10, 100
\]

\[
\text{PM-5% melts} = 0.001, 0.01, 0.1, 1, 10, 100
\]

\[
\text{PM-10% melts} = 0.001, 0.01, 0.1, 1, 10, 100
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\[
\text{PM-10% residue} = 0.001, 0.01, 0.1, 1, 10, 100
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\[
\text{PM-5% residue} = 0.001, 0.01, 0.1, 1, 10, 100
\]
element patterns. A similarly good fit to the Manihiki magmas can be obtained by modelling direct mixing of ultra-depleted melt from the UDM source and an enriched Rurutu or Maquarie melt (Supplementary Fig. 4b,c). The melt-mixing model, however, requires an order of magnitude more enriched melt (1–10%) to contribute to the Manihiki primary magmas than the source-mixing model. The melt-mixing model was therefore rejected less probable due to the absence of correlations between major and trace elements in Manihiki glasses, expected from the relatively large mass fraction of the enriched melt required to fit the trace-element patterns. The origin of the magmas can thus be qualitatively attributed to melting ultra-depleted mantle metasomatized by the enriched melt component, present either cryptically or as a different lithology.

The possible isotopic composition of the enriched component was calculated by solving the general mixing equations for isotope ratios to fit the estimated mass fraction of the enriched component in the UDM obtained from trace element modelling and assuming Sr, Nd and Pb concentrations in the enriched component equal to the Rurutu melt used for the mixing model (see Fig. 4b). The estimated initial isotope composition of the enriched component is $^{143}$Nd/$^{144}$Nd = 0.51279 ± 0.00001, $^{206}$Pb/$^{204}$Pb = 19.87 ± 0.16, $^{207}$Pb/$^{204}$Pb = 15.66 ± 0.03, $^{208}$Pb/$^{204}$Pb = 39.17 ± 0.11, $^{87}$Sr/$^{86}$Sr = 0.70280 ± 0.00007 (see Fig. 3, Supplementary Fig. 1, Supplementary Table 5). The end member ratios are very similar to those in the most-enriched low-Ti glass sample SQ225DR12-3 with $^{206}$Pb/$^{204}$Pb = 19.78, $^{207}$Pb/$^{204}$Pb = 15.65, $^{208}$Pb/$^{204}$Pb = 39.12, $^{87}$Sr/$^{86}$Sr = 0.70282 and $^{143}$Nd/$^{144}$Nd = 0.51279.

The enriched Manihiki end member has Sr-Nd-Pb isotopic ratios similar to lavas from sources with HIMU-type Ocean Island Basalt lavas from the Cook-Austral chain, such as those from Rurutu (young lavas) and Tubuai lavas at 120 Myr ago (Fig. 3; Supplementary Fig. 1). Following the prevailing point of view, the HIMU-like enriched component may originate from recycled oceanic crust.

On the basis of our new and previously published data, OJP and Manihiki Plateau, as well as possibly Hikurangi Plateau, were likely formed by melting of a compositionally heterogeneous plume source. The dominant plume component beneath the OJP and possibly the Hikurangi part of the original super-plateau (before breakup into individual plateau fragments) was the source of Kroenke/Kwaimbaita basalts lavas (Fig. 5), which possibly represented a nearly primitive mantle source from the lower mantle. The UDM component might also be present in the OJP source, but thus far has never been recognized in whole rock samples, but only as melt inclusions in olivine from one OJP Kroenke-type rock. The dominant plume component beneath Manihiki appears to be the UDM metasomatized by HIMU-like melts. Together the UDM (mantle from which melt has been previously extracted) and enriched HIMU-like (recycled ocean crust) end members may represent relatively young, subducted Indian-MORB-like oceanic lithosphere, which stalled in the transition zone. Such oceanic lithosphere could have been entrained and recycled by the OJP/Manihiki/Hikurangi plume head as it upwelled from the lower mantle. Incorporation of the dense subducted ocean lithosphere could also have served to reduce the buoyancy of the upwelling plume head, such that it did not cause major uplift of the seafloor. This could explain why the OJP, Manihiki and Hikurangi Plateaus remained largely submarine throughout their history on the seafloor. A piece of this entrained oceanic crust (eclogite) may still be located beneath OJP as proposed in a recent study to explain the fast shear wave velocity of 4.75 km s$^{-1}$ observed beneath OJP. Regardless of the origin of the UDM and HIMU-like components, the composition of the mantle source below OJP (Kroenke/Kwaimbaita with minor UDM) and Manihiki (mainly UDM with some HIMU-like component) was largely different (Fig. 5). In conclusion, our results indicate that melting of incompatible-element ultra-depleted and subsequently re-enriched mantle is possible on a large-scale in intraplate settings during the formation of large igneous provinces, especially under young, thin oceanic lithosphere.

The presence of boninites in Archaean rock formations has been cited as evidence that subduction, and thus plate tectonics, initiated in the Archaean. Recently, comparison of rock sequences including boninites from a modern arc system (Izu-Bonin-Mariana) and an Archaean greenstone belt in Canada suggested that subduction of oceanic crust has been operating since the Hadean. High degrees of alteration, however, are common in Archaean rocks, affecting in particular major and mobile trace elements. The results of our study show that rocks with affinities to boninites in terms of major and trace elements (Fig. 2) can also originate in intraplate settings. Such melts may have been more abundant in earlier Earth history due to a hotter geotherm or enhanced plume-related magmatism. Thus, it is important to distinguish Archaean boninites that formed in subduction versus intraplate settings. The principal difference between intraplate boninite-like and most subduction-related boninites may be whether the Nb-Ta anomaly is positive and if Nb/U normalized to N-MORB is greater or less than one. For example, in the Abitibi greenstone belt of Canada, some low-Ti rocks have trace element patterns very similar to those of the low-Ti Manihiki tholeiites (Supplementary Fig. 5). Thus, these Archaean sequences could possibly be plume-related unlike greenstones from the Nuvvuagtitq supracrustal belt in northern Quebec or Isua, Greenland, which have arc-like boninite signatures with low Nb/La.

Figure S1 | A schematic model for the formation of the Ontong Java and Manihiki Plateaus from a geochemically heterogeneous mantle-plume head. The presence of ultra-depleted melts at OJP and Manihiki (UDM) can be explained with a geochemically heterogeneous plume head containing different components beneath the two plateau segments. Beneath OJP, the dominant Kroenke/Kwaimbaita source component upwells and generates the dominant Kroenke/Kwaimbaita basement lavas with flat primitive-mantle-normalized incompatible element patterns. The presumed dominant source component beneath Manihiki is the UDM end member metasomatized by ≤1% HIMU-type melts. We propose that both components beneath Manihiki are derived through recycling of Indian-mantle-like oceanic lithosphere. Ultra-depleted melt inclusions in olivines in a Kroenke sample from OJP indicate that smaller proportions of a possibly common UDM source may also be present beneath the OJP.
Methods

Sample material. Analysed samples were dredged during the R/V Sonne 225 expedition at different locations along the flanks of the Danger Island and Suvorov Troughs (Fig. 1). Detailed information about sampling locations and sample descriptions can be found in ref. 44. All the glass samples contain fresh and partly altered olivine crystals, up to 0.3 mm in size. One relatively fresh, vesicular, olivine-phric basalt sample with fresh glass (sample SO225DR24-10) was recovered at the eastern flank of the Suvorov Trough, containing fresh olivine phenocrysts (0.25–1.00 mm size). Concentrations of mobile elements and oxides (e.g. Rb, Ba, U, Pb, K2O, P2O5) correlate with immobile elements such as Zr, Nb, La and Ce and thus do not appear to have been affected by seawater alteration. The glass samples from the SO193 expedition (ref. 4 and references therein) were re-analysed employing electron microprobe (EMP) and laser ablation inductively coupled plasma source mass spectrometry (LA-ICP-MS) using the same analysing conditions and standards for better data comparison. The sample SO225DR12-2 contained only small amounts of fresh glass material and thus it was not possible to replicate the radiogenic isotope composition. This sample shows slightly higher 143Nd/144Nd and 87Sr/86Sr ratios compared with the more-enriched glass sample.

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Glass shards were analysed with 60–80 multiple analyses was typically better than 3% rel. for most elements. Further details of the setup and calibration strategy can be found in ref. 52. The trace element data generated by laser ablation ICP-MS on glasses to account for H2O and CO2 background. The slightly variations in ref. 53. The trace element data generated by laser ablation ICP-MS on glasses to account for H2O and CO2 background. The slightly variations in ref. 53. The trace element data generated by laser ablation ICP-MS on glasses to account for H2O and CO2 background. The slightly variations in ref. 53. The trace element data generated by laser ablation ICP-MS on glasses to account for H2O and CO2 background. The slightly variations in ref. 53. The trace element data generated by laser ablation ICP-MS on glasses to account for H2O and CO2 background. The slightly variations in ref. 53. The trace element data generated by laser ablation ICP-MS on glasses to account for H2O and CO2 background. The slightly variations in ref. 53. The trace element data generated by laser ablation ICP-MS on glasses to account for H2O and CO2 background. The slightly variations in ref.
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Author contributions
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