Mantle hydration and the role of water in the generation of large igneous provinces

Jia Liu1,2, Qun-Ke Xia1, Takeshi Kuritani3, Eero Hanski4 & Hao-Ran Yu2

The genesis of large igneous provinces (LIP) is controlled by multiple factors including anomalous mantle temperatures, the presence of fusible fertile components and volatiles in the mantle source, and the extent of decompression. The lack of a comprehensive examination of all these factors in one specific LIP makes the mantle plume model debatable. Here, we report estimates of the water content in picrites from the Emeishan LIP in southwestern China. Although these picrites display an island arc-like H2O content (up to 3.4 by weight percent), the trace element characteristics do not support a subduction zone setting but point to a hydrous reservoir in the deep mantle. Combining with previous studies, we propose that hydrous and hot plumes occasionally appeared in the Phanerozoic era to produce continental LIPs (e.g., Tarim, Siberian Trap, Karoo). The wide sampling of hydrous reservoirs in the deep mantle by mantle plumes thus indicates that the Earth’s interior is largely hydrated.
Multiple physical and chemical factors contribute to the production of large igneous provinces (LIP): abnormally high mantle temperatures, fusible components in the mantle source, a large extent of decompression and the presence of volatiles (especially H2O)\(^1\)-\(^2\). One group of researchers suggests that the melting anomalies originate by decompressional melting of hot, deep-sourced mantle plumes\(^3\)-\(^4\), while some others propose that they are due to the presence of high proportions of easily fusible, recycled or delaminated crustal material\(^5\). Another group of researchers attributes the melting anomalies to the presence of pyroxenities in the source\(^1\), the role of the mantle potential temperature (\(T_p\)) and the presence of pyroxenites in the source have been suggested to play a significant role in the generation of the Siberian Traps\(^8\), the contribution of volatiles remains ambiguous, as the primary water content of magmas may be underestimated\(^9\). Moreover, although the H2O content of the primary basaltic magma in the Tarim LIP has been found to be up to 4.8 \(\pm 1.0\) wt.%\(^10\), the role of the mantle potential temperature and pyroxenite in the source have not been investigated simultaneously.

The Permian Emeishan LIP (ELIP), one of the largest continental LIPs in the world, is located in the western margin of the Yangtze Craton, Southwest China. It has been widely suggested to be related to a mantle plume\(^11\)-\(^13\), and the mantle potential temperature (\(T_p\)) estimated for some picrites seems to be higher than 1700 °C under dry conditions\(^14\). Pyroxenite in the mantle source has been suggested to be a direct source of some picrites\(^15\)-\(^16\). In addition, a fast kilometre-scale crustal uplift prior to the eruption of ELIP basalts, which may imply fast decompression of the mantle source, has been suggested\(^17\), although it was recently questioned by ref\(^18\). However, the role of water in the initiation of the ELIP has not been carefully examined so far. The only existing estimation of the primary water content of the ELIP, ~4.0–5.6 wt.%\(^10\), is from ref\(^19\). The authors investigated the water content of the primary magma (equilibrium with olivine with Fo\(_{91}\)) based on the correlation between H2O/Ce and Ba/La, Ba/Nb and Rb/Nb ratios, which were calibrated for global oceanic arcs. However, this estimation still needs caution to take into account for two reasons. Firstly, this primary magma water content is similar to that of the rather evolved magma when plagioclase was among the liquidus phases (H2O \(\sim 4.4\) wt.%\(^1\)), MgO of the bulk rock <8 wt.%\(^1\)); and secondly, none of the primary magmas of the ELIP show typical arc-like trace element signatures, which argues against a subduction zone setting\(^13\).

In this work, we investigated the water content of the picrite lavas from Dali, which are located stratigraphically at the bottom of the Binchuan section in the interior zone of the ELIP, representing the initial stage of the ELIP volcanism\(^14\) (Supplementary Fig. 1). Major and trace element analyses of melt inclusions in olivine phenocrysts and major and minor element (Ca, Mn, Ni, Al) compositions of the host mineral phases were used to constrain the source lithology and the crystallisation temperature of olivine. In addition, we compiled estimates of the water content, the proportion of pyroxenite-derived melt (\(X_{px}\)) and \(T_p\) from other continental LIPs. These data provide us so far the most comprehensive demonstration of the controlling factors for the melting anomaly in the generation of LIPs.

**Results**

**Pyroxenite-bearing mantle source.** All the studied samples are massive and show a typical porphyritic texture, with olivine, clinopyroxene and spinel being the phenocrysts (Supplementary Fig. 2). Their bulk MgO contents range from 18.6 to 24.0 wt.% (calculated on anhydrous basis, see Supplementary Data 1), which are comparable to the previous analyses on bulk rocks and melt inclusions in olivine (Supplementary Data 1, 2, Supplementary Fig. 3). The olivine grains in these samples have significantly higher NiO and Fe/Mn than those expected for olivine from global mid-ocean ridge basalt (MORB) (Supplementary Data 1), which are comparable to the previous analyses on bulk rocks and melt inclusions in olivine (Supplementary Data 1, 2, Supplementary Fig. 4), suggesting a contribution of melts derived from a pyroxenitic source\(^20\). On the basis of the Fe/Mn ratios of high-Fo olivines and the method of ref\(^20\), the amount of pyroxenite-derived melts for the Dali picrites is estimated to be

![Fig. 1 Comparison of water contents in the Dali picrites and other primary magmas from different geological settings. The water abundance data for oceanic basalts and komatites are from refs. 26-28, 45, and the data source for other LIPs are given in Supplementary Data 3. The Dali picrite data are from this study. NMORB, normal mid-ocean ridge basalt; EMORB, enriched mid-ocean ridge basalt; OIB, oceanic island basalt; BABB, back-arc basin basalt; CRB, Columbia River basalt; SRPB, Snake River Plain basalt](image)
~40–50 wt.% (Supplementary Data 1). This is consistent with the recent results from melt inclusion studies: the CaO content in the primary magmas of the Dali picrites increases slightly with decreasing TiO₂, which requires a significant role of pyroxenite in the source.

Island Arc-like water content of the primary magma. The H₂O content of the magma was recovered from the H₂O content of clinopyroxene (cpx) phenocrysts and the partition coefficient of H₂O between cpx and melt (D_water^{cpx/melt})21–23. The H₂O content of the primary Dali picrite was estimated to be 3.44 ± 0.89 wt.% (See Methods for details), reaching the range of island arc basalts (IAB) (Fig. 1). Even if the uncertainty (~40%) is taken into account, the lower-limit H₂O content is still as high as 2.04 wt.%.

Discussion
The bulk-rock and melt inclusion compositions show considerable positive Pb anomalies (Supplementary Fig. 3b), which may point to significant contamination with continental crust. However, the following observations argue against this possibility:
Fig. 3 Correlation between H$_2$O/Ce and proportion of pyroxenite-derived melts in primary magmas of LIPs and komatiites. The $X_{px}$ values were calculated based on the Fe/Mn ratios of olivine phenocrysts (Supplementary Data 1, 3). The error bars for $X_{px}$ and H$_2$O/Ce represent 1 and 2 standard deviations, respectively. H$_2$O/Ce ratios of global MORB and pyroxenite xenoliths from Hawaii (SCL) are also shown for comparison. The H$_2$O/Ce ratio of pyroxenite-derived melt is equal to that of the source pyroxenite if the degree of partial melting is larger than 10%, which is commonly reached in mantle plumes. The H$_2$O/Ce ratios of global MORB and pyroxenite xenoliths from Hawaii (SCL) are also shown for comparison. The H$_2$O/Ce ratio of pyroxenite-assumed to be dry. When the effects of H$_2$O content are considered, the corrected highest temperature is $\sim$1460 ± 43 °C (Supplementary Fig. 6). The Al thermometer gives a similar estimate for the maximum olivine liquidus temperature (Supplementary Fig. 6). It is not easy to accurately assess the mantle potential temperature ($T_p$) due to the complexity caused by the incorporation of volatiles and pyroxenite in the mantle source. Recently, Trela et al. applied the relationship between the olivine liquidus temperature and $T_p$ for the peridotite system (equation 17 in ref. 32) to estimate the mantle potential temperature for many LIPs. Here, we test this approach by applying it to a series of pyroxenite partial melting experiments (Methods). The results show that it can recover $T_p$ within an uncertainty of ±70 °C for most of these experimental runs (Supplementary Fig. 10). Thus, according to the estimated olivine liquidus solidus temperature ($\sim$1460 ± 43 °C), we estimate the upper limit of the $T_p$ to be around $\sim$1500 ± 70 °C (Methods), which is considerably higher than that of the average MORB source. The large (40–50%) proportion of pyroxenite-derived melt coupled with an island arc-like H$_2$O content and elevated $T_p$ indicates that the ELIP was formed by an extensively hydrated mantle plume rich in fusible components.

As shown in Figs. 1 and 2, for the Siberian Traps, Karoo LIP, Tarim LIP, Yellowstone hotspot track (Columbian River basin), and Snake River Plain basin) and Caribbean LIP, the H$_2$O content of their primary magma vary from 0.25 to 4.8 wt.% Thus, the mantle source of many other Phanerozoic LIPs also seems to have been extensively hydrated. The calculated H$_2$O content and H$_2$O/Ce ratios of the mantle sources are from 900 to >6000 p.p.m. and $\sim$160–400 to >2000 (Supplementary Data 3), respectively, i.e., significantly higher than those of the MORB and oceanic island basalt (OIB) sources (Fig. 2a, b) and falling in the range of the IAB sources. However, their trace element signatures do not show obvious depletions in Nb and Ta (Supplementary Fig. 7), arguing against a direct contribution of the fluids released from a subduction zone. The $T_p$ after correction for the depression effect on
the liquidus temperature by H₂O varies from that of an average MORB to higher than that of most of the OIBs (see Method, Fig. 2c, Supplementary Data 3).

In Fig. 3, the H₂O/Ce ratios and the possible proportion of pyroxenite-derived melts in their primary magma (Xpx, which is directly related to the Mn/Fe ratio of olivine, see Methods for details) were compared. For many continental LIPs that were generated by hydrous and pyroxenite-involved mantle plumes, the Xpx values correlate negatively with the H₂O/Ce ratios (Fig. 3). It should be noted that although the variation in Fe/Mn ratios of olivine can be alternatively explained by partial melting of a peridotite source under different P–T conditions (at higher P–T, the partial melts would have a higher MgO content, and thus the olivine-melt partition coefficient of Mn becomes lower leading to lower MnO and higher Fe/Mn in crystallised olivine, refs. 33, 34), the heterogeneity in Xpx shown in Fig. 3 reflects the fertile nature (proportion of pyroxenite) of their mantle sources. This is supported by the following observations: firstly, the Tortugal lavas in the Galápagos plume have been suggested to be results of partial melting of a peridotite source at ~7 GPa and ~1800 °C34, which should have much higher Ni contents and higher Fe/Mn ratios than MORBs according to the suggestion of ref. 33; however, as shown in Fig. 3, the Xpx values of the Tortugal olivine are comparable to those of MORB; secondly, the lithospheric mantle for the Loihi and Koolau lavas in Hawaii and the post-caldara and syn-caldara lavas in the Snake River Plain has a similar thickness, but the lavas show distinct calculated Xpx (Fig. 3). Actually, the recent investigation on the trace element concentration in olivines from the Tuli and Mwenezi picrites in the Karoo Continental Flood Basalt (CFB) and the Horninghaai low-Ti picrites in the Etendeka CFB, all of which were erupted in regions of thickened (>90 km) lithosphere in southern Africa, shows that Karoo picrite olivines have systematically higher Fe/Mn ratios and higher Ni contents than Etendeka picrites35. The other factor affecting the Fe/Mn ratios of the crystallised olivine would be the oxygen fugacity (fO₂) of the magma36. However, the difference in fO₂ could not explain the observed variation in Xpx. The Siberian meichene has a considerably higher H₂O content and fO₂ than the Gudchikhinsky formation picrite (3.88 wt.% vs. 0.25 wt.% H₂O, +1.5 vs. −1.5 to −2 ΔQFM)37, 38, while its Xpx is much lower than that of the latter (0.03 vs. 0.94). Thus, we suggest that the calculated Xpx values in Fig. 3 reflect the source heterogeneity or at least they can be considered as the maximum estimate of the pyroxenite-derived melt.

The above discussion indicates that, except for the depleted-MORB mantle (DMM), two end-members are responsible for H₂O/Ce in the primary magmas in LIPs. One is pyroxenite, which is more fusible than peridotite and contains a higher H₂O content but lower H₂O/Ce than the DMM38. The other is a reservoir in the deep mantle, which is extensively hydrated and has a major element composition close to that of peridotite. This kind of mantle reservoir has been deduced for several hydrous Archaean and Cretaceous komatitites26–28 (Fig. 3). This end-member could be the solid segments or partial melts of wadzlyeite or ringwoodite in the MTZ or the recycled serpentinitised peridotite26, 28. Although the proportion of pyroxenite-derived melts could be affected by the thickness of the lithosphere and the degree of melting of pyroxenite, the complementary contribution of this hydrous reservoir and pyroxenite in the genesis of a LIP could also be explained by that when the water is in the hydrous plume for a LIP mainly resides in the less fertile and fusible part (low Xpx)26, 28, it starts melting earlier and preferentially than pyroxenite. If so, the decreasing proportion of pyroxenite-derived melts during a short time period does not necessarily mean a catastrophic thinning of the lithosphere3, but would be due to the variation of the H₂O content in the mantle plume (Fig. 3). Overall, we propose that the mantle sources of the Phanerozoic LIPs are generally extensively hydrated and contain abundant fusible components, which, together with a higher mantle potential temperature4, resulted in a much higher melt productivity and eruption rates in comparison with those of OIBs.

More broadly, our studies lead to new perspectives for the ancient water recycling into the deep Earth. The non-arc-like hydrous mantle represented by the Archaean komatitites (ie, Abitibi and Belingwe) has been explained by the incorporation of a hydrous reservoir from the deep mantle, the hydrous MTZ25, or ‘carbonated wetsps’ formed by the early ingassing of surface water into the deep Earth in the Hadean40. The widespread komatite production at 2.7 Ga has been regarded as the consequence of outgassing of this substantial volatile-rich mantle reservoir and the decline of komatite eruptions after this time as a reflection of purging out of volatiles from the mantle40. The general hydration of mantle plume sources of several Phanerozoic LIPs that were not related to the direct involvement of fluids released in a subduction zone (Supplementary Fig. 6) indicate that the Earth’s interior during the Phanerozoic was still occasionally extensively hydrous. One possible such reservoir would be the MTZ, which have been demonstrated to be regionally hydrous41. Alternatively, the water was entrained by the mantle plume derived from the large low-shear-velocity provinces (LSSVPs), which is a unique thermochemical structure in the lower mantle and would probably also be modified/incorporated by the volatile elements transported into the deep Earth by residual subducted plates42. The regassing of the deep mantle would be explained by that, at least before the end of the Proterozoic, the mantle had cooled enough for the water to be carried into the MTZ or the lower mantle through the subduction of oceanic lithosphere43. This is comparable to the recent suggestion by Korenaga et al.44 that there is a net water transport from the oceans to the mantle, with a long-term (at least back to ~3 Ga) average rate of 3–4.5 × 10⁻¹⁸ g per year, which is based on the most complete modelling of the continental freeboard so far.

Methods

Major and trace element analysis of bulk-rock samples. After the weathered crust was removed, the samples were crushed into small fragments (≤5 cm in diameter). Then, they were cleaned with deionised water and ground to 200-mesh powder. Major and trace element concentrations of bulk-rock samples were analysed at ALS Chemex (Guangzhou, China) Co., Ltd. Loss-on-ignition was determined before X-ray fluorescence (XRF) analysis. Major element compositions were measured by XRF spectrometry on fused glass disks. The precision for element concentrations of >1 wt.% was 1–3% and ~10% for element concentrations of <1 wt.%. For trace elements, two methods were employed to check the accuracy of the analytical results against each other. In the first method, lithium metaborate flux was added to the sample powder, and the mixture was fused at 1000 °C and dissolved in 100 ml of 4% nitric acid. The powder was then analysed using a PerkinElmer inductively coupled plasma mass spectrometer (ICP-MS). In the second method, the sample powder was dissolved in a Teflon bomb using an HNO₃–HF–HClO₄ mixture, diluted by nitric acid after being dried on a hot plate and then analysed by ICP-MS. The precision is generally better than 5% for most trace elements. These two methods gave rather consistent results with 95% confidence.

Electron microprobe analyses. Chemical compositions of olivine and clinopyroxene phenocrysts and chrome spinel hosted by olivine were measured by a Shimadzu electron probe microanalyzer (EPMA 1600) at the CAS Key Laboratory of Crust-Mantle Materials and Environments (CA-CMME) of the University of Science and Technology of China (USTC). Back-scattered electron images were used to check the homogeneity of the minerals. During the quantitative analysis of clinopyroxene (cpx) phenocrysts and spinel inclusions in olivine, the operating conditions were the following: 15 kV accelerating voltage, 20 nA beam current and 1 μm spot size. Only the spinel grains located in the central zone of the host olivine phenocrysts were analysed. For olivine, the analytical method described by ref. 19 was used, employing an accelerating voltage of 20 kV, a beam current of 300 nA and a spot size of 5 μm. Natural minerals and synthetic oxides were used as standards, and a programme based on the ZAF procedure was used for all data correction. All the analysed points in cpx phenocrysts were set within the olivine.

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transform infrared spectroscopy (FTIR) analysis region. Some electron probe micro-analyses (EPMA) of cpx were conducted with a JEOL electron probe microanalyzer in the Hefei University of Technology. Analytical conditions were similar to those used in USTC.

**Major and trace element analysis of melt inclusions.** Major elements of the melt inclusions and their host olivine grains were analysed using a JEOL Superprobe JXA-8200 electron microprobe at the Max Planck Institute for Chemistry, Mainz, Germany. The analytical conditions for were the following: 15 kV accelerating voltage, 12 nA electron beam current and defocused to 5-μm-sized beam. For olivine, the conditions were similar to those for cpx phenocrysts described above. Trace element concentrations in melt inclusions were analysed by LA(laser ablation)-ICP-MS at the University of Tasmania. This instrumentation comprises a New Wave Research UP213 Nd:YAG (213 nm) laser coupled to an Agilent 4500 quadrupole mass spectrometer. For this study, analyses were performed in a He atmosphere by ablating 20–70 μm-diameter spots at a rate of five shots per s using laser power of ~12 J/cm². See Supplementary Data 2 for the data.

**Analysis of the H₂O content of single clinopyroxene.** The water contents of the picrite melts from which clinopyroxene phenocrysts crystallised were calculated by the following steps:

First, the cpx/melt partition coefficient ($D_{\text{cpx/melt}}$) of water was calculated based on the major element composition data determined by EPMA (Electronic probe micro-analyzer) analysis of cpx and the following equation from ref. 45:

$$\ln D_{\text{cpx/melt}} = -4.2(\pm 0.2) + 6.5(\pm 0.5)X_{\text{Mg}}^{-1}(\text{cpx}) - 1.0(\pm 0.2)X_{\text{Mg}}^{-1}(\text{melt}).$$

Second, the water content of the basaltic melt was calculated based on the water content in the cpx determined by FTIR and the calculated $D_{\text{cpx/melt}}$.

The water content of a single cpx phenocryst was measured following the approach of refs. 33, 34, in which the unpolarised fourier-transform infrared spectroscopy (FTIR) beam was focussed on a randomly orientated thin slices of cpx. Both theoretical calculations and experimental tests21, 46 have shown that this method allows an estimation of the water content in those cpx grains that have crystals along specific principal directions; ref. 47). Combining the uncertainty of the OH absorption coefficients and the base line correction, the total uncertainty in the water content measured by this method is ≤30%, which is comparable to the uncertainty in the secondary iron mass spectrometer measurements21. Considering the typical uncertainty of the water partitioning coefficient predicted by the equation 10 of O’Leary et al.46 (~20%), the total uncertainty of the calculated water content in the melt is around 40%. All the cpx phenocrysts in this study contain these three groups of OH bands (Supplementary Fig. 8a), and their highest linear absorptions are less than 0.3, allowing us to apply such an unpolarised method confidently. For the FTIR spectrum of O'H in cpx phenocrysts, the evaluation of possible H diffusion in cpx and the choice of cpx to calculate the final water content of magma.

**FTIR analysis.** The unpolarised FTIR measurements were conducted at the CAS Key Laboratory of Crust-Mantle Materials and Environments of the University of Science and Technology of China (USTC) with a Nicolet 5700 FTIR spectrometer coupled with a Continuum microscope using a KBr beam splitter and equipped with a liquid-nitrogen-cooled MCT-A detector. Double-polished thin sections of picrite samples were prepared with thickesses ranging from 120 to 150 μm. The light source and pathway, and the sample-holding cell were flushed with a purified air free of CO₂ and H₂O. For each cpx grain, unpolarised spectra ranging from 1000 to 4500 cm⁻¹ were obtained using a total of 256 scans with a resolution of 4 cm⁻¹. A square light spot with dimensions ranging from 30 by 30 μm to 100 by 100 μm was used, depending on the size and quality of the mineral grain. The optically clean, inclusion- and crack-free areas were chosen for measurement. A typical unpolarised IR spectrum of the OH bands in cpx is shown in Supplementary Fig. 8a. Profile analyses for a subset of cpx grains were also conducted to check the diffusion of H (Supplementary Fig. 9). The water content of cpx phenocrysts was calculated by the transformed Beer–Lambert law: $C = \frac{3A(1 + t)}{4t}$, where C is the water content of cpx in ppm, A is the unpolarised integral absorbance, t is the absorption coefficient (7.09 ppm⁻¹ cm⁻¹), and t is the thickness in cm.

**Calculation of the water content of primary magma.** Typical FTIR bands of cpx in clinopyroxene from the Dali picrites are shown in Supplementary Fig. 8a. These bands are rather consistent with that in mantle-derived cpx and cpx megacrys in kimberlites46, 47. Results of profile analyses are displayed in Supplementary Fig. 9. The $D_{\text{cpx/melt}}$ (water in melt) vs. Mg# of cpx plot shown in Supplementary Fig. 8d indicates a variable melt water content from ~1 to >6 wt.% at all Mg# values. The possible reasons for this large variation include: isobaric crystallisation of phenocrysts, which causes an increase in $C_{\text{melt}}$, Mg diffusion at depth, which reduces $C_{\text{melt}}$; and water loss through diffusion after crystallisation of cpx and emplacement of the magma in shallow crust. On the basis of the FTIR profile analyses shown in Supplementary Fig. 9, cpx in sample DL3-5 experienced obvious and prominent water loss (Supplementary Fig. 9c–d), whereas very few cpx grains in sample DL3-6 were affected by diffusion of H₂O (Supplementary Fig. 9a, b). Thus, the diffusional loss of water would be the reason why nearly all DL3-5 cpx grains and part of DL3-4 cpx grains contain systematically less water than the others. With the exception of these data, most of the other grains are within the range of modern island arc basalts (Supplementary Fig. 8d, light green and blue fields). Two lines of evidence indicate that the diffusion did not significantly change the water content in cpx in DL3-1, -4, and -5. First, most of the profile analyses on cpx show that the water concentrations are homogenous within individual grains (Supplementary Fig. 9a, b); (2) the calculated water contents in cpx are correlated with the atom numbers of Mg and Al, which diffuse several orders of magnitudes slower than H does (Supplementary Fig. 8b, c). In order to reduce the effects of magma crystallisation and degassing on the water content in melts, we used the data from the cpx grains with Mg# higher than 89 to calculate the water content of the ‘primary’ magma (Supplementary Fig. 8d), resulting in an average water content of 3.73 ± 0.89 wt.%.

### Geothermometers for the olivine liquidus temperature.

For the Fe/Mg thermometer, the crystallisation pressure of cpx phenocrysts is calculated first according to the approach in ref. 50. The result is around 1.3 GPa. To estimate crystallisation temperatures of olivine, we used partitioning of AI between olivine and spinel31 and Fe/Mg distribution between olivine and melt32. The olivines with Fo in the range of 81.6–91.9 mol.%, crystallised together with chrome spinel, were used in the olivine-spinel geothermometry. Only the spinel grains hosted in the central part of olivine phenocrysts were chosen. Unfortunately, the olivine grain with highest Fo (93.4 mol.%) has only spinel in its rim and was not applied in this geothermometry. The error of this thermometer is estimated to be ±25°C and includes the error arising from the precision of the olivine A₃O₂ measurement (0.003 to 0.007 wt.%). Before the application of the Fe/Mg olivine geothermometry, the equilibrium between the olivine and the bulk-rock composition was examined. Olivine shows a wide range of Fo, and assuming Kₑ(Fe-Mg) to be 0.30 ± 0.03, most of them are not in equilibrium with their bulk rock hosts. However, the maximum Fo contents of olivine are close to the equilibrium value. The PRIMELT3 software of ref. 31 was used to subtract the fraction of extra previously crystallised olivine from the whole-rock composition to obtain the liquid composition equilibrated with the observed most Fo-rich olivine. The Kₑ values calculated based on the obtained liquid compositions and maximum Fo fall in the range of 0.30–0.33. Then the olivine–glass-based thermometer of ref. 32 was used to calculate the olivine liquidus temperature (equation 22) with the experimentally determined water content. The standard error of this approach is around ±4°C.

### Estimation of mantle potential temperature.

In this study, it is shown that the mantle source of the Dali picrites was hydrous and contained pyroxene (Fig. 1, Supplementary Fig. 5). In this case, the models of refs. 31, 34, which were calibrated from experiments on peridotites, could not be directly applied to obtain mantle potential temperatures ($T_p$). For instance, an incorrect application of the PRIMELT2 model to lavas that formed from pyroxene sources is expected to result in an $T_p$ overestimation of ~30–70°C. Considering that we have determined the olivine liquidus temperature at a lower crust depth ($T_\text{liq}$) by an independent approach (AI-in-olivine thermometer), to recover the $T_p$, we use the correlation between olivine liquidus temperature at 1 atm ($T_\text{liq}(1 \text{atm})$) and $T_p$ calibrated by ref. 31 for peridotite-derived magmas:

$$T_p = 1.0497T^\text{liq}(1 \text{atm}) - 0.00019T^\text{liq}(1 \text{atm})^2 + 1.487 \times 10^{-7}T^\text{liq}(1 \text{atm})^3,$$

where $P$ is the olivine crystallisation pressure in GPa and all the temperatures in °C.

The errors of applying these equations to pyroxene sources were tested for a series of partial melting experiments conducted for pyroxene with a wide range of bulk compositions (Supplementary Data 4) at pressures of 1–7 GPa and temperatures of 1250–1750°C. In the test, the $T_\text{liq}(1 \text{atm})$ was calculated by the following equation32:

$$T_\text{liq}(1 \text{atm}) = 1020 + 24.4MgO - 0.161MgO^2,$$

where MgO is the content for the produced partial melts. As shown in Supplementary Fig. 10a (for data, see Supplementary Data 4), the calculated mantle
potential temperature (T_P-calculated) based on the above equations can recover T_p for pyroxene partial melt experiments (T_p-experimental), most of which are within the uncertainty of ±70 °C. The mantle potential temperature for Dali picrite is calculated as follows: (1) by Eq. (1), T_HK = 1460 °C is calculated from the measured T_OH_L (1460 °C) and crystallisation pressure of 1.3 GPa; (2) then Eq. (2) is used to calculate T_P. The calculated T_p for Dali picrite is ~1500 ± 70 °C. For the other LIPs, whose T_p values were determined by the Al-in-olivine thermometer51, Eq. (2) above is used to calculate their mantle potential temperatures. This calculation gives consistent T_p estimates based on the Fe-Mg equilibrium thermometer when the effect of water is considered25, 50. For those without Al-in-olivine-based T_p estimates based on the approach above, the T_p values for OIBs were estimated according to the previously determined value by ref. 4 and the water depression effect by ref. 39. See Supplementary Data 3 for the calculation results.

Data availability. All the data used in this study are reported in four Supplementary Data online.

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Author contributions

Q.-K.X. designed and led the project. J.L. and H.-R.Y. finished all analyses except the major and trace element data of the melt inclusions that were provided by E.H. J.L. and Q.-K.X. wrote the manuscript with inputs from T.K. and E.H. All authors contributed the interpretation of the results.

Additional information

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