Ultra-depleted melts in olivine-hosted melt inclusions from the Ontong Java Plateau.


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Abstract

The Ontong Java Plateau (OJP) represents the largest large igneous province (LIP) preserved in the geologic record. The most voluminous volcanic types of the OJP—the Kroenke and Kwaimbaita groups, which dominate the accessible portions of the plateau—have relatively flat primitive mantle normalized rare earth element (REE) patterns. With the exception of relatively small volumes of late-stage melts—referred to as the Singgalo group—that are characterized by slightly enriched REE patterns relative to a chondritic pattern, the volcanic groups that dominated the eruptive history of the OJP exhibit remarkably homogeneous, flat REE patterns.

Here we isolate, for the first time, olivine-hosted melt inclusions from OJP. We show that the melt inclusions have two clear populations defined by distinct trace element
characteristics. The first population has relatively flat trace element patterns that are similar to those observed in whole rock lavas from the most voluminous volcanic groups (Kroenke and Kwaimbaita) recorded in the OJP. In contrast, a second group of melt inclusions, referred to as UDM (ultra-depleted melt) inclusions, exhibit (light-REE) LREE-depleted patterns relative to a chondritic pattern; these trace element patterns are far more depleted than any previously reported lava from OJP. The UDM have unique trace element signatures that preclude an origin by re-melting the depleted mantle source left over after melt extraction during construction of the OJP. We interpret the new UDM compositions to be the result of melting a previously unrecognized (in lavas) ultra-depleted component hosted in the OJP mantle source.

1. Introduction

Large igneous provinces (LIPs) represent the largest outpourings of lava in the geologic record (Coffin and Eldholm, 1994). Ontong Java Plateau (OJP) is the largest LIP preserved on Earth and has an estimated volume of 44.4 million km$^3$ (Coffin and Eldholm, 1994; Coffin and Eldholm, 2000), a crustal thickness of approximately 30 km (Richardson et al., 2000; Miura et al., 2004), and a surface area that is roughly equivalent to Western Europe (Fitton and Godard, 2004). The bulk of the plateau was extruded at ~120 Ma (Mahoney et al., 1993, 2001; Tejada et al., 1996, 2002, 2004, 2013; Parkinson et al., 2001; Chambers et al., 2004) on top of young (15-30 Ma) oceanic crust (Larson,
1997), but the Pacific lithospheric upon which the OJP was erupted may have been as old as 40 Ma at the time of eruption (Ishikawa et al., 2011). A later stage of volumetrically less extensive volcanism may have occurred at 90 Ma (Mahoney et al., 1993; Tejada et al., 1996, 2002), but the occurrence of the 90 Ma episode is still debated (Chambers et al., 2002). Taylor (2006) argued that the OJP represents a portion of an even larger LIP that was composed of the OJP, Manihiki (8.8 million km$^3$) and Hikurangi Plateaus (2.7 million km$^3$), and following eruption, this “super LIP” rifted apart into these three separate plateaus. The origin of the OJP is the source of significant controversy. The OJP has been suggested to be a product of melting a thermally-buoyant mantle plume (Mahoney and Spencer, 1991; Richards et al., 1991; Tejada et al., 2004; Fitton and Godard, 2004; Ito and Clift, 1998), melting of a largely primitive (but non-chondritic) mantle component (Jackson and Carlson, 2011), entrainment and melting of eclogite-bearing mantle near a spreading center (Korenaga et al., 2005), or melting that resulted from a giant bolide impact (Rogers, 1982; Ingle and Coffin, 2004).

Lavas from the OJP have been sampled at eight deep sea drilling sites (Mahoney et al., 1993) and along a > 3.5 km thick section in the Solomon Islands which was thrust upwards when the OJP “docked” with the Solomon arc at 27 to 23 Ma (Coleman and Kroenke, 1981; Cooper and Taylor, 1985; Neal et al., 1997; Petterson et al., 1997; Tejada et al., 2002). OJP lavas record three distinct geochemical types (e.g., Tejada et al., 1996; 2002; 2004; Neal et al., 1997; Fitton and Godard, 2004). The Kwaimbaita- and Kroenke-type lavas dominate the bulk of the OJP. Kwaimbaita-type lavas are voluminous but fractionated, while Kroenke-type lavas are less evolved (9-10.5 wt.% MgO) and may be parental to the Kwaimbaita lavas, which have identical radiogenic isotopic signatures.
Kroenke-type lavas have been found in just two drill sites, ODP Sites 1185 and 1187. The Kroenke and Kwaimbaita-type lavas have relatively flat primitive mantle normalized rare earth element (REE) patterns (Tejada et al., 2004; Fitton and Godard, 2004), Sr and Nd isotope ratios that are less geochemically depleted than MORB (mid-ocean ridge basalt; Gale et al., 2013), and Pb-isotopic compositions that plot near the geochron (Tejada et al., 2004; Jackson and Carlson, 2011).

The trace element and isotopic characteristics indicate that the Kwaimbaita and Kroenke-type lavas are derived from a mantle source that is less geochemically depleted than the depleted MORB mantle (DMM) (Tejada et al., 2004). This mantle source may actually be a primitive (but non-chondritic) mantle domain (Jackson and Carlson, 2011) if the superchondritic $^{142}\text{Nd}/^{144}\text{Nd}$ in accessible terrestrial mantle rocks is the result of higher Sm/Nd in the bulk silicate Earth relative to chondrites (Boyet and Carlson, 2005; Caro et al., 2008; Caro and Bourdon, 2010; Jackson et al., 2010; Jackson and Jellinek, 2013).

Singgalo-type lavas represent a volumetrically smaller volcanic type at OJP, forming a thin late-stage veneer over the Kroeneke and Kwaimbaita-type lavas, and are thought to be the result of melting a slightly more enriched mantle source (lower $^{143}\text{Nd}/^{144}\text{Nd}$, higher $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{206}\text{Pb}/^{204}\text{Pb}$, and a slight relative enrichment in incompatible trace elements) than sampled by Kroeneke and Kwaimbaita-type lavas (Tejada et al., 2002, 2004; Fitton and Godard, 2004). While Singgalo lavas sample a mantle source that is slightly more enriched than Kroenke and Kwaimbaita-type lavas, to date there is no geochemical evidence in OJP lavas for the presence of a more
geochemically-depleted component than observed in the Kroenke and Kwaimbaita-type lavas.

Here we present a major, trace, and volatile element study of olivine-hosted melt inclusions hosted in a single Kroenke-type OJP basaltic sample from a drill core at ODP site 1187. Melt inclusions can trap heterogeneous melts prior to complete melt mixing, and thus provide an opportunity to characterize more of the chemical diversity that exists in melts that is not detectable in whole rock compositions. However, melt inclusion studies of the OJP have been hampered by a general lack of olivine-bearing basalt throughout the plateau. Olivines are extremely rare in OJP lavas, and when present, they are often small and/or altered (see Supplementary Materials). Here we report fresh olivines that host small (from 13 to 94 microns, long axis dimension) melt inclusions (Supplementary Fig. 1 and Supplementary Table 1). To our knowledge, these represent the first olivine-hosted melt inclusions identified in the OJP. The inclusions are of two types: The “normal-type” inclusions exhibit relatively flat primitive mantle normalized REE patterns that are similar to those observed in whole rock analyses of Kroenke-type lavas, while the second type of inclusions, UDM (ultra-depleted melt) inclusions—which exhibit greater incompatible element depletion than observed in the host whole rock composition—are evidence for a previously unrecognized geochemical component in the OJP lavas.

2. Methods
The inclusions analyzed in this study are all hosted in olivines that were separated from a single whole rock sample (ODP drill core sample 192-1187A-006R-06W [110-129 cm]). We hand crushed 100 g of lava (representing most of the available, olivine-rich material) in a mortar and pestle and obtained just 60 mg of olivine grains. Twenty-eight olivine grains hosted visible inclusions, and only 15 olivine grains (hosting 19 inclusions; Supplementary Table 1) had sufficiently large inclusions for homogenization, exposure and analysis. Images of each melt inclusion analyzed in this study are shown in Supplementary Figure 1.

Unfortunately, all melt inclusions in the studied hand sample were crystalline. Melt inclusions were individually homogenized on a Vernadsky-style heating stage mounted under a microscope at the Laboratoire Magmas et Volcans at the Université Blaise Pascal in Clermont-Ferrand, France. This allowed us to visually confirm homogenization of the inclusion and discard inclusions that burst or leaked and annealed during the heating process. As described in Le Voyer et al. (2008), the homogenization was carried out at 1 atm, the temperatures were monitored with a thermocouple, and the samples were bathed in purified helium gas during homogenization and kept at an oxygen fugacity between $10^{-10}$ and $10^{-9}$ atm. The inclusions were raised from room temperature to the liquidus temperature within a span of 20 minutes, and then quenched. Chen et al. (2011) and Gaetani et al. (2012) demonstrated that homogenization, following the Clermont procedure on the heating stage, does not result in measurable hydrogen loss from the inclusion. Following homogenization, the inclusions were mounted on glass slides and individually exposed using silicon carbide paper, followed by polishing using diamond suspension and 0.3 µm alumina paste. Following exposure and polishing, each
olivine-hosted inclusion was pressed into an aluminum mount filled with indium. The mount was cleaned using milliQ water and ethanol prior to volatile, trace and major element analyses.

Trace element analyses were carried out using the Cameca 6F ion microprobe at Arizona State University (ASU) and the analytical protocols follow those detailed in Wanless et al. (2014) and Cabral et al. (2014). A $^{16}$O$^{-}$ primary beam was accelerated to 12.5 kV with a current of 10 nA. The sample was held at 9 kV, and an “energy filtering” window of 75 ± 20 eV was used to reduce molecular ions; this approach has been used successfully in other labs (e.g., Shimizu et al., 1978; Zinner and Crozaz, 1986) and at ASU (Wanless et al., 2014; Cabral et al., 2014). Samples were pre-sputtered for 200 seconds prior to analysis, and each analysis consisted of 20 individual cycles of analyses of the following isotopes with the following dwell times: $^{28}$Si (1 s), $^{47}$Ti (2 s), $^{88}$Sr (2 s), $^{89}$Y (2 s), $^{90}$Zr (2 s), $^{93}$Nb (2 s), $^{138}$Ba (2 s), $^{139}$La (3 s), $^{140}$Ce (3 s), $^{141}$Pr (3 s), $^{144}$Nd (3 s), $^{147}$Sm (3 s), $^{174}$Yb (5 s), and $^{180}$Hf (5 s). Four basaltic reference glasses (KL2-G, BCR-2G, BHVO-2G, and ALV519-4-1; Gale et al., 2013; Jochum and Nohl, 2008; Melson et al., 2002) were measured to generate working curves, and ALV519-4-1 was also used as a secondary standard to monitor drift. Fifteen analyses of glass sample ALV-519-4-1 (trace element abundances reported in Gale et al. [2013] and Melson et al. [2002]) were carried out during the course of the analytical session, and are reported in Supplementary Table 2, together with reproducibility for trace element analysis: Ti ($±$2.5% of the value reported, 2σ standard deviation), Sr ($±$5.3%), Y ($±$2.4%), Zr ($±$4.0%), Nb ($±$8.9%), Ba ($±$8.8%), La ($±$4.3%), Ce ($±$4.5%), Pr ($±$9.6%), Nd ($±$9.5%), Sm ($±$18.3%), Yb ($±$10.7%), and Hf ($±$16.6%).
Volatile ($\text{H}_2\text{O}$, $\text{CO}_2$, F, S, Cl) and P analyses were carried out at the Department of Terrestrial Magnetism, Carnegie Institution of Washington, using the 6F Cameca ion microprobe (Supplementary Table 1). In short, a 14nA Cs+ primary beam was used to sputter samples, and an electron gun was used to compensate for charge buildup. Samples were pre-sputtered for five minutes to eliminate surface contamination prior to analysis, and the masses of interest were measured five times with the following dwell times: $^{12}\text{C}$ (10 s), $^{17}\text{O}$ (5 s), $^{19}\text{F}$ (5 s), $^{30}\text{Si}$ (5 s), $^{31}\text{P}$ (5 s), $^{32}\text{S}$ (5 s), and $^{35}\text{Cl}$ (5 s). A $^{12}\text{C}$ ion image of each melt inclusion was examined prior to analysis to avoid any visible surface contamination, and analyses that exhibited drift in $^{12}\text{C}/^{30}\text{Si}$ over the course of an analysis, indicative of surface contamination, were discarded. ALV519-4-1 was used as a secondary standard to correct for drift. Five analyses of submarine glass sample D52-5 (volatiles are reported in Simons et al., 2002) were carried out during the course of the analytical session, and are reported in Supplementary Table 2. Following correction for drift and offset, we report the following reproducibility for each of the following elements in D52-5: $\text{H}_2\text{O}$ (±9.9%, 2σ standard deviation), $\text{CO}_2$ (±10.3%), F (±6.8%), S (±3.8%), Cl (±2.8%), and P (±1.7%).

Electron microprobe measurements were carried out using the electron microprobe facility at the University of Toronto on a Cameca SX-50, and the major element data are presented in Supplementary Table 1. Olivine analyses were carried out using a focused beam. For glass analyses, a defocused beam was used and employed a 15 kV accelerating voltage and a 10 nA beam current. We report the following precision for major element analyses of glass by electron microprobe: $\text{SiO}_2$ (±0.65 wt.%, 2σ standard deviation), $\text{TiO}_2$ (±0.16 wt.%), $\text{Al}_2\text{O}_3$ (±0.26 wt.%), $\text{FeO}$ (±0.32wt.%), $\text{MgO}$ (±0.25%),
CaO (±0.28 wt.%), Na₂O (±0.12 wt.%), MnO (±0.08 wt.%), K₂O (±0.04 wt.%), P₂O₅ (±0.06 wt.%).

CO₂ analyses by ion microprobe preceded electron microprobe analyses in order to avoid surface contamination from the carbon coat that is required for major element analyses by electron probe. Unfortunately, there was insufficient melt inclusion material remaining for electron probe analyses following ion probe analyses for inclusions 2B and 9C in this study (which lack major element data; Supplementary Table 1).

Whole rock major and trace element analyses of a portion of the same sample from which the olivines (and their inclusions) were separated were performed at the GeoAnalytical Lab at Washington State University (WSU). Major elements were measured by X-ray fluorescence (XRF), and trace elements were measured by inductively-coupled plasma mass spectrometry (ICP-MS). Precision for the analyses of SiO₂, Al₂O₃, TiO₂ and P₂O₅ in basalts is 0.11 – 0.33% (1σ) of the amount present, and 0.38 – 0.71% (1σ) of the amount present for FeO, MgO, CaO, Na₂O, MnO and K₂O (Johnson et al., 1999). Trace element analyses by ICP-MS have a precision of 0.77 – 3.2% (1σ) (Knaack et al., 1994).

3. Results and Observations

3.1 Major element abundances in OJP melt inclusions

Like all whole rock lava and glass compositions obtained from OJP drill sites, the melt inclusions are tholeiitic (Fig. 1). The melt inclusions are hosted in olivines with
forsterite compositions ranging from 86 to 89, except for one Fo83 olivine (Supplementary Table 1). After the major element compositions of the inclusions are corrected to be in equilibrium with the host olivine by equilibrium olivine addition or subtraction (assuming an olivine-melt $K_d$ of 0.3 [Roeder and Emslie, 1970; Ford et al., 1983] and 10% of the total Fe is Fe$^{3+}$), the inclusions have MgO abundances that are similar to those previously identified in Kroenke-type lavas (Fig. 1 and Supplementary Table 1; unless stated otherwise, melt inclusion major, trace and volatile element abundances presented in the text and figures are adjusted for this olivine fractionation correction). With the exception of inclusion #2—which has the lowest MgO in the inclusion suite—SiO$_2$ abundances of the inclusions fall in the range previously identified for Kroenke-type lavas (Supplementary Table 1). Two inclusions (#25 and #27) have anomalously high alkali abundances compared to the whole rock and the other inclusions; we do not have an explanation for the alkali element enrichment, but we note that these two inclusions plot well within the tholeiite field defined by OJP whole rocks and glasses in Fig. 1. A group of inclusions have anomalously low (La/Yb)$_N$ (where N represents normalization to the primitive mantle composition of McDonough and Sun, 1995) compared to previously analyzed whole rocks and pillow glasses from the OJP. The inclusions with low (La/Yb)$_N$ values are discussed below, and are referred to as UDM inclusions hereafter. In major element variation diagrams (Fig. 1), the UDM inclusions do not exhibit clear major element compositional differences compared to the inclusions that have “normal” (La/Yb)$_N$ values, except for the possible exception of TiO$_2$, which tends to be lower in the UDM inclusions. The slightly lower TiO$_2$ in the UDM inclusions relative to the inclusions with normal (La/Yb)$_N$ is reflected in higher Na$_2$O/TiO$_2$ in the
former group (Fig. 1). In a plot of CaO/Al₂O₃ versus Na₂O/TiO₂ (Fig. 1), the UDM inclusions are resolved from the normal-type inclusions and from previously examined whole rocks and pillow glasses from the OJP.

Finally, Nb and La concentrations in the melt inclusions are plotted against MgO in Fig. 1. These two highly incompatible trace elements are depleted in the UDM inclusions compared to the normal type inclusions, even thought both types of inclusions span a similar range of MgO. The normal type inclusions have Nb and La concentrations that are similar to concentrations observed in whole rock analyses from the OJP. In contrast, the UDM inclusions have Nb and La concentrations that are lower than previously observed in OJP lavas.

3.2. Incompatible trace element patterns in OJP melt inclusions

Primitive mantle (McDonough and Sun, 1995) normalized trace element patterns reveal two groups of melt inclusions. The first group of inclusions has trace element patterns that are most similar to those of whole rock analyses of Kroenke-type OJP lavas (Fig. 2). The observation of these “normal-type” (i.e., Kroenke-type) inclusions is expected, as the olivines hosting the melt inclusions were isolated from a Kroenke-type lava. However, seven of the melt inclusions, referred to as UDMs, exhibit (La/Yb)ₙ ratios (0.18-0.32) that are up to four times lower than previously observed in any lava erupted at the OJP. Like the Kroenke-type lavas, Kwaimbaita lavas exhibit trace element patterns that are relatively flat, but shifted vertically relative to the Kroenke-type lavas (Fig. 2); this supports the hypothesis that Kroenke-type lavas are parental to (and therefore have lower incompatible trace element concentrations than) the more evolved Kwaimbaita-
type lavas (Fitton and Godard, 2004). Singgalo-type lavas have trace element patterns
that exhibit slight enrichment in the incompatible trace elements relative to Kroenke and
Kwaimbaita-type lavas (Figs. 2 and 3).

Two different melt inclusions hosted in the same olivine (inclusions 10A and 10B
from olivine 10; Table 1) have the same normal-type trace element patterns. Similarly,
two different sets of melt inclusions from two different olivines are UDM inclusions
(inclusions 7A and 7B from olivine 7, and inclusions 9B and 9C from olivine 9;
Supplementary Table 1). No examples of inclusions where normal-type and UDM
inclusions are hosted in the same olivine were found.

There are several trace element ratios in the melt inclusion suite that clearly
resolve the UDM inclusions from the normal-type inclusions, and demonstrate that the
UDM inclusions are more depleted in incompatible trace elements than any melts
previously identified in the OJP. In addition to having lower \((\text{La}/\text{Sm})_N\), the UDM
inclusions have lower \(\text{Nb}/\text{Zr}\) and higher \(\text{Ti}/\text{Zr}\) than the normal-type inclusions (Fig. 3).
The trace element ratios of the normal-type inclusions overlap with the ratios identified in
the freshest Kroenke and Kwaimbaita-type lavas, while Singgalo-type lavas define a level
of incompatible trace element enrichment that is greater than observed in the melt
inclusion suite and in the Kroenke and Kwaimbaita-type lavas. In summary, no previous
melts from the OJP have been observed to exhibit the level of extreme incompatible
element depletion observed in the UDM inclusions.

One inclusion, UDM inclusion #25, has a large positive Sr anomaly on a primitive
mantle normalized trace element pattern (Fig. 2). This inclusion is also enriched in Ba.
Large positive anomalies of Sr and Ba are common in gabbros, which relates to enrichment of Sr and Ba in plagioclase, an abundant phase in gabbros (e.g., Sobolev et al., 2000; Saal et al., 2007; Danyushevsky et al., 2003). Additionally, there is a general shift towards more plagioclase-like (low) CaO/Al₂O₃ ratios in the OJP inclusions with positive Sr anomalies. The inclusions with the largest positive Sr-anomalies (i.e., the highest Sr/Sr* values, where \( \text{Sr/Sr}^* = \frac{\text{Sr}_{\text{N}}}{(\text{Sm}_{\text{N}}^* \text{Nd}_{\text{N}})^{0.5}} \)), all with values from 1.23 to 1.44, also have the lowest CaO/Al₂O₃ ratios (Fig. 3). The Gabal Gerf plagioclase composition from Sobolev et al. (2000) has low CaO/Al₂O₃ (0.40) and high Sr/Sr* (3.3), and anchors the low CaO/Al₂O₃ and high Sr/Sr* portion of the melt inclusion trend (Fig. 3). We find no relationship between indicators of trace element depletion, like \((\text{La/Yb})_\text{N}\), and trace element proxies for a plagioclase-rich lithology, like Sr/Sr* (Fig. 3). A role for a plagioclase signature in the OJP melt inclusions is discussed below.

### 3.3. Volatile abundances in OJP melt inclusions.

#### 3.3.1. Chlorine

Cl/K ratios range from 0.19 to 4.3 over the entire melt inclusion suite. Cl/K ratios > 0.07 have been suggested to be the result of assimilation of hydrothermally altered material (Jambon et al., 1995; Kent et al. 1999a, 1999b; Lassiter et al., 2002; Michael and Schilling, 1989; Michael and Cornell, 1998; Stroncik and Haase, 2004; Kendrick et al., 2013). A similar range of elevated Cl/K ratios (0.22 to 2.8) was identified in pillow glasses obtained from a drill core of the OJP (Michael, 1999; Roberge, 2004). Both UDM and normal-type inclusions have similarly high Cl/K.

#### 3.3.2. H₂O
The OJP melt inclusions have H$_2$O concentrations (0.11 to 0.70 wt.%, see Fig. 4 and Supplementary Table 1) that are similar to the range identified in pillow glasses from the OJP drill sites, where H$_2$O is 0.13 to 0.49 wt.% (Michael, 1999; Roberge et al., 2004, 2005). When H$_2$O is normalized to Ce, a non-volatile trace element that is thought to have similar solid-melt partition coefficients to H$_2$O during mantle melting and fractional crystallization (Michael, 1995; Dixon et al., 2002), the H$_2$O/Ce ratios extend to remarkably high values. The H$_2$O/Ce ratios in the normal-type inclusions range from 217 to 709, and the UDM inclusions have H$_2$O/Ce ratios that are even higher, ranging from 1853 to 2508. The higher H$_2$O/Ce in the UDM inclusions generally reflects lower Ce, not higher H$_2$O.

3.3.3. CO$_2$

The melt inclusions exhibit CO$_2$ concentrations (18-184 ppm, see Fig. 4) that fall within the range measured in OJP glasses (19-223 ppm; Michael, 1999; Roberge et al., 2004). Owing to the low solubility of CO$_2$ in silicate melts, most of the CO$_2$ in a primary melt is degassed prior to extrusion of melt on the seafloor or prior to entrapment of melts in olivines. When CO$_2$ is normalized to Nb, an incompatible trace element assumed to have mineral-melt partition coefficients similar to CO$_2$ during mantle melting and fractional crystallization (e.g., Saal et al., 2002), the CO$_2$/Nb ratios vary from 9 to 69 in the normal-type inclusions, and from 92 to 351 in the UDM inclusions. The CO$_2$/Nb ratios in the normal-type inclusions are all lower than the value of ~300 suggested for the depleted upper mantle (Koleszar et al., 2009). The higher CO$_2$/Nb ratios observed in the UDM inclusions extend above values proposed for the depleted upper mantle, but are still within the range suggested for CO$_2$-rich popping rocks dredged at mid-ocean ridge.
settings (Cartigny et al., 2008). Koleszar et al (2009) found an extremely high CO₂/Nb ratio (1879) in a UDM melt inclusion from the Galapagos Islands, and they suggested that such a high ratio is not driven by unusually high CO₂, but by the low abundances of incompatible trace elements.

3.3.4. Fluorine

The F abundances reported in the melt inclusion suite are the first reported in lavas from the OJP. Concentrations of F are lower in the UDM inclusions (56–60 ppm) than in the normal-type inclusions (74-131 ppm) (Fig. 4 and Supplementary Table 1). The average F/Nd ratio for the melt inclusion suite is 21.3±3.4 (1σ, standard deviation), and this is similar to the average F/Nd ratio of ~21 suggested for global oceanic lavas (Workman et al., 2006).

3.3.5. Sulfur

Previous work showed that S concentrations in OJP pillow glasses are in the range of 692 to 1156 ppm (Roberge et al., 2004). Roberge et al. (2004) observed that ratios of S to other incompatible elements (S/K and S/Ti) slightly decrease with decreased MgO. The concentrations of S in the OJP inclusions range from 327 to 948 ppm, and show a clear, positive relationship with MgO (Fig. 4). We note that sulfides have not been observed in the OJP inclusions.

4. Discussion
OJP lavas are noted for their trace element and isotopic homogeneity. Excluding the small volume Singgalo melts, which are slightly enriched geochemically (relative to the Kroenke and Kwaimbaita-type lavas) and thought to comprise a late-stage of volcanism on the plateau (Tejada et al., 2004; Fitton and Godard, 2004), the bulk of the accessible plateau is composed of Kroenke-type and Kwaimbaita-type lavas that have indistinguishable Sr-Nd-Pb-Hf isotopic compositions and relatively flat primitive mantle normalized REE patterns (Mahoney, 1987; Mahoney and Spencer, 1991; Mahoney et al., 1993; Tejada et al., 1996, 2002, 2004, 2013; Neal, 1997; White et al., 2004; Shafer et al., 2004). These melts are thought to be the result of 20-30% melting of a homogeneous mantle source that is less depleted than the depleted MORB mantle (Mahoney et al., 1993; Neal et al., 1997; Tejada et al., 2002, 2004, 2013; Fitton and Godard, 2004; Herzberg, 2004). There has never been a report of lavas from the OJP with strongly depleted light REE signatures. Thus, the discovery of the UDM inclusions hosted in a Kroenke-type OJP lava are all the more perplexing, and demonstrate that OJP magma compositions are more diverse than previously thought.

Based on the whole rock geochemical analyses of basalts, it has been known for decades that the mantle sources of hotspots and flood basalts host geochemically-depleted components (e.g., Zindler and Hart, 1986; Gee et al., 1998; Chauvel and Hemond, 2000; Kerr et al., 1995; Fitton et al., 1997; Salters et al., 2011; Shorttle et al., 2013). For example, the presence of a depleted component distinct from the normal MORB source has been identified in Hawaii (Frey et al., 2005). Similarly, the presence of a depleted component in the Iceland plume that is distinct from the upper mantle source of normal MORB was advanced by Thirlwall (1995) and Kerr et al. (1995) on the basis...
of Pb isotopes, by Fitton et al. (1997, 2003) using Nb-Zr-Y systematics, and by Kempton et al. (2000) and Fitton et al. (2003) using evidence from $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{176}\text{Hf}/^{177}\text{Hf}$. In fact, basalts erupted at most major hotspots exhibit evidence for sampling a mantle source that is geochemically depleted (Hart et al., 1992), and basalts erupted at LIPs globally exhibit evidence for sampling a geochemically depleted mantle (Zindler and Hart, 1986; Jackson and Carlson, 2011).

While geochemically-depleted lavas are not unusual at hotspot and flood basalt localities in the world’s ocean basins, UDM inclusions are unusual in that they exhibit greater degrees of incompatible trace element depletion than the whole rock from which they were separated. UDM melt inclusions have been reported in magmatic suites at ocean island hotspots (e.g., Sobolev et al., 2000; Koleszar et al., 2009; Gurenko and Chaussidon, 1995; Slater et al., 2001), mid-ocean ridge localities (e.g., Laubier et al., 2012; Sobolev et al., 2011; Sobolev and Shimizu, 1993; Danyushevsky et al., 2003; Kamenetsky et al., 1998) and komatiites (Shimizu et al., 2009; Kamenetsky et al., 2010).

With the exception of Iceland, the UDM inclusions from the OJP represent, to our knowledge, the first report of UDM inclusions at a LIP locality. Like the OJP melt inclusions here, Fig. 3 shows that Icelandic melt inclusions reveal a range of melt inclusion compositions that exhibit highly depleted trace element compositions. Indeed, the Icelandic melt inclusions trend to much more geochemically-depleted $(\text{La/Sm})_N$ values (~0.05) than identified in OJP inclusions (~0.18). Curiously, the Icelandic lavas also host melt inclusions with compositions that are have significantly more enriched $(\text{La/Sm})_N$ values (~6.5) than the OJP (~1.18) inclusions. Similarly, the Icelandic inclusions sample more extreme plagioclase signatures (i.e., higher Sr/Sr*) than
identified in the OJP inclusions. While we do not have an explanation for the greater
degree of geochemical variability observed in the Icelandic melt inclusions, we do note
that, compared to the number of melt inclusions analyzed from the OJP, many more
Iceland melt inclusions have been analyzed, from a larger suite of lavas. It is possible that
the relatively small number of OJP melt inclusions may not have captured the full range
of melt inclusion compositions present OJP lavas.

The origin of the incompatible element depletion observed in UDM inclusions in
oceanic lavas globally is not well understood, but has been the subject of some
discussion. Below, we discuss the origin of the UDM inclusions from OJP in the context
of existing models for UDM formation. We argue that a distinct, depleted component
inherent to the OJP mantle plume generated melts that were trapped as UDM inclusions.

4.1. Origin of the depleted OJP mantle component sampled by UDM inclusions.

4.1.1. UDM inclusions generation by repeated melt extraction from the same portion of
upwelling mantle?

Following melt extraction and depletion of the OJP mantle source, subsequent
melts extracted from the same portion of (now highly depleted) mantle would be depleted
in incompatible elements (e.g., Sobolev and Shimizu, 1993; Thirwall et al., 2004), and we
examine whether this might explain the origin of the UDM inclusions at the OJP.

Sobolev and Shimizu (1993) showed that such a mechanism might explain the origin of
olivine-hosted UDM inclusions discovered in a MORB lava. They argued that the UDM inclusion represented the last fraction of melt produced by the upwelling mantle column beneath the ridge, and the same portion of the melting column had experienced continuous melt extraction, from greater depths beneath the ridge, to shallower depths where UDM is generated. As a result of melting a mantle source that has already experienced melt extraction and incompatible element depletion, the melt (i.e., the UDM) is depleted in incompatible elements. Sobolev and Shimizu (1993) suggested that MORB lavas are composed of mixtures of polybaric melts with different trace element characteristics, including inclusions with UDM characteristics. The UDM inclusions are generally mixed into bulk MORB magmas and their unique, incompatible element depleted signatures are lost during melt aggregation and homogenization with more geochemically-enriched melts. However, sometimes UDMs are trapped in growing olivines before melt homogenization, thereby preserving depleted instantaneous melts that are products of the final stages of polybaric melting of a highly depleted source.

One possible explanation for the formation of OJP UDM inclusions is that they were produced by a mechanism similar to that proposed by Sobolev and Shimizu (1993), whereby the UDM inclusions were formed by the final (shallower) stages of melting of a homogeneous upwelling OJP plume source that had become depleted in highly incompatible elements during earlier (deeper) stages of melting. In such a model, instantaneous melts of the final stages of melting would have been trapped in growing olivines in magma conduits beneath the OJP before mixing with earlier, deeper melts. The lower abundance of UDM inclusions (only just over one-third of the OJP inclusions are UDM inclusions; Supplementary Table 1) might be explained by such a model, as the
mantle source of the OJP would be expected to be more refractory during the final stages of polybaric melting, thereby producing a lower proportion of depleted melts compared to the less depleted melts extracted at greater depth. However, one potential problem with this model is that it does not explain why the OJP inclusions tend to cluster in two relatively separate groups: In trace element space (Fig. 3, panels A through D), the two inclusion types—normal-type and UDM inclusions—populate two relatively distinct groups, with perhaps one inclusion plotting between the two groups. However, if UDMs sample instantaneous polybaric melts from a homogenous upwelling OJP mantle plume, a continuous spectrum of melt inclusion compositions ranging from normal-type inclusions to UDM inclusions might be expected as the plume undergoes progressive depletion during upwelling. This is not observed.

4.1.2 A melt model to generated normal type inclusions at the OJP.

Before modeling the source of the UDM inclusions, it is first important to constrain the genesis of normal-type inclusions. Such a melt model can be used to place broad constraints on whether a single OJP mantle source can generate melts like the normal-type inclusions and, following depletion by melt extraction, generate melts similar to the UDM inclusions. The relatively flat REE patterns of the Kwaimbaita and Kroenke-type lavas, combined with the observation that the $^{143}\text{Nd}/^{144}\text{Nd}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ isotopic composition of the mantle source for these lavas is less depleted than the source for MORB, suggest that the trace element source of OJP Kroenke-type lavas is also less depleted than the MORB source (Tejada et al., 2004; Fitton et al., 2004).
Jackson et al. (2010) and Jackson and Carlson (2011) argued that the mantle sources of many LIPs globally, including the Kroenke lavas from the OJP, are sourced by an early-formed, depleted reservoir (EDR) generated by global differentiation event of the silicate Earth (Boyet and Carlson, 2005).

Adopting the model of Jackson and Carlson (2011), which argues that OJP lavas are melts of the EDR, we employ an aggregated near-fractional melt model of an EDR mantle source to match the trace element composition of Kroenke-type OJP lavas. We employ the alphaMELTS software (Smith and Asimow, 2005) and adopt a mantle source major element composition from Sun and McDonough (1989) and the EDR mantle source from Jackson and Jellinek (2013). The default trace element routine of alphaMELTS was used to calculate trace element fractionation, in which mineral-melt partition coefficients for clinopyroxene, garnet, and feldspar vary as a function of pressure, temperature and composition (Wood and Blundy, 1997; van Westrenen et al, 1999; Blundy and Wood 1994), while mineral-melt partition coefficients for spinel and orthopyroxene are constant values compiled by MacKenzie and O’Nions (1991; 1995).

The melting calculation starts at 1600°C and 40 kilobars and proceeds until the degree of melting reaches 25-30%. The trace element composition of Kroenke-type lavas (and therefore, the normal-type inclusions, which have trace element patterns that are similar to Kroenke-type lavas) are best matched when the degree of melting of the EDR mantle is 25-30% (see Fig. 5 for melt model details). This degree of melting is in agreement with previous suggestions that Kwaimbaita and Kroenke-type OJP lavas are the result of 20-30% melting (Mahoney et al., 1993; Neal et al., 1997; Tejada et al., 2002, 2004, 2013; Fitton and Godard, 2004; Herzberg, 2004); for comparative purposes, the EDR mantle
source used here (0.65 ppm Nb and 7.7 ppm Zr; Jackson and Jellinek, 2013) is similar to
a previously suggested source for Kroenke-type OJP lavas (~0.6 ppm Nb and 9.5 ppm Zr;
Fitton and Goddard, 2004). Notably, the EDR mantle source that generates the Kroenke-
type lavas and normal-type inclusions has concentrations of the most incompatible
elements (e.g., La) that are similar to or slightly higher than the UDM inclusions (Fig. 2),
and therefore cannot source the UDM inclusions. The UDM inclusions require a more
incompatible element depleted mantle source.

4.1.3. A distinct mantle source for the UDM melt inclusions?

While melting the EDR mantle source does a reasonable job of generating the
trace element patterns observed in the Kroenke-type lavas and the normal-type
inclusions, a key trace element signature of the UDM inclusions suggests that they
require a distinct mantle source unrelated to the EDR source: Unlike the normal-type OJP
inclusions, which are thought to represent entrapped portions of Kroenke-type lavas, the
UDM inclusions from the OJP have Zr/Zr* (where $Zr/Zr^* = Zr_N/(Sm_N^{*}Nd_N^{*})^{0.5}$) values
that are generally displaced to lower values than found in the normal-type OJP inclusions
(Fig. 6). The low Zr/Zr* in the UDM inclusions is difficult to generate from the same
mantle source that produces the normal-type inclusions, which have generally higher
Zr/Zr*.

While low Zr/Zr* values in UDM inclusions from other hotspot and mid-ocean
ridge localities have been attributed to a gabbro signature (e.g., Sobolev et al., 2000; Saal
et al., 2007; Danyushevsky et al., 2003), the low Zr/Zr* values in the OJP UDM
inclusions cannot be the result of interaction with gabbro: there is no relationship between Zr/Zr* and Sr anomalies (where the latter is an indicator of a gabbro signature). Thus, the lack of any relationship between Sr/Sr* and Zr/Zr* argues against the negative Zr anomalies in the UDM inclusions from the OJP resulting from interaction with gabbro melts. The low Zr/Zr* signatures in the OJP UDM inclusions are interpreted to be a primary signature of the melts.

We explore whether the lower Zr/Zr* values in OJP UDM inclusions is a geochemical signature can be generated by melting a mantle source residue left over following melt extraction of Kroenke-type lavas (and normal-type inclusions) from the EDR mantle. Fig. 6 shows the same aggregated fractional melt model of the EDR source that was explored in Fig. 5, and shows that the (La/Yb)N and Zr/Zr* compositions of the normal-type inclusions and Kroenke-type basalts are best matched with 25-30% aggregated fractional melting of the EDR source (blue line in Fig. 6), which is consistent with the melt model result shown in Fig. 5. Melts of the EDR source do not generate the low Zr/Zr* values observed in the UDM inclusions. However, the composition of the mantle residue (grey line in Fig. 6) following melt extraction from the EDR source has diminished (La/Yb)N, which is a feature observed in UDM inclusions. Unfortunately, Zr/Zr* in the melt model does not match the UDM inclusions: melts extracted from this depleted residue have higher Zr/Zr* than the residue (red line in Fig. 6), while the UDM inclusions have lower Zr/Zr* values than the residue. To demonstrate this effect, we employ the alphaMELTS software using similar assumptions employed above. However, instead of extracting melt from the EDR source, melt is re-extracted from the depleted residue following 10% fractional melting of the EDR source (red line in Fig. 6), and the
melt re-extraction starts at 29 kilobars and 1555°C and proceeds to lower pressures and temperatures. The melts have the low \((\text{La/Yb})_N\) values observed in the UDM inclusions, but the \(\text{Zr/Zr}^*\) of the model melts are higher than the UDM inclusions (Fig. 6). In general, a family of melt models show that re-melting the depleted mantle source left over after melt extraction during construction of the OJP does not generate the combination of low \(\text{Zr/Zr}^*\) and low \((\text{La/Yb})_N\) values observed in the UDM inclusions.

Multiple melt extraction events from the same portion of upwelling mantle may successfully explain the generation of an ultra-depleted source that gave rise to the UDM inclusion identified in a mid-ocean ridge basalt (Sobolev and Shimizu, 1993). However, given the generally lower \(\text{Zr/Zr}^*\) observed in the UDMs compared to normal-type inclusions and Kroenke-type basalts, the UDMs from OJP are not explained as melts extracted from the EDR or melt extracted from the depleted mantle residue left over following extraction of Kroenke-type melts (and the associated normal-type inclusions). Instead, the UDM melts must have been extracted from a mantle source that is unrelated to (and has lower \(\text{Zr/Zr}^*\) and \(\text{La/Yb}\) than) the mantle source of the Kroenke-type lavas and normal-type inclusions. Without isotopic information on the UDM inclusions, we cannot speculate on the timing of the melt extraction event that generated the depleted mantle source of the UDMs. However, based on the arguments above, this depletion event is unlikely to have occurred during melt extraction to form the lavas that constitute the OJP.

4.1.4. Distinct mantle sources for UDM and normal-type melt inclusions
Instead of representing melts of a single plume source that has undergone progressive depletion by polybaric melt extraction during plume upwelling, the two groups of melt inclusions may represent melts of two distinct mantle sources within the upwelling plume. Recent work on mantle xenoliths from the island of Malaita has identified several lithologies—depleted harzburgites, fertile lherzolites and pyroxenites—that were suggested to have sourced OJP melts at 120 Ma (Ishikawa et al., 2007, 2011). Ishikawa et al. (2011) argued that the lithological diversity of Malaita xenoliths indicate that the mantle upwelling beneath the OJP was heterogeneous. Ishikawa et al. (2011) suggest that the homogeneity in OJP lavas could result from mixing and homogenization of melts from these diverse lithologies. If their hypothesis is correct, and the OJP magmas sampled a heterogeneous mantle that is represented by the diverse xenoliths from Malaita, then the UDM inclusions may offer a first glimpse at some of the heterogeneity that exists in primary melts prior to melt aggregation. In this model, the UDM inclusions represent melts of a more depleted portion of a geochemically-heterogeneous OJP mantle source than the normal-type inclusions. A model in which there are two distinct mantle sources for the inclusions—normal-type and UDM—might explain why the melt inclusions tend to form two rather distinct groups in Figs 3 and 6.

Isotopic measurements of the OJP melt inclusions could constrain whether UDM inclusions are melts of a mantle source formed by the final stages of polybaric melting of a homogeneous OJP plume, or melts of a more depleted portion of a heterogeneous OJP plume. If UDM inclusions were formed by the final stages of melting of a homogeneous upwelling OJP plume source that had already been depleted in highly incompatible elements during the early stages of melting (Sobolev and Shimizu, 1993), the isotopic
composition of the UDM would be expected to be similar to the normal-type inclusions. However, if the UDM inclusions are melts of a more depleted portion of a geochemically heterogeneous OJP mantle source, then the two inclusion groups would be expected to have distinct isotopic compositions. Unfortunately, the OJP inclusions in this study were too small to permit a systematic isotopic study (e.g., Pb-isotopic analysis by ion probe; Saal et al., 1998; Cabral et al., 2014).

4.2. Incompatible trace element depletion in UDMs is the result from assimilation of plagioclase-rich (gabbroic) assemblages or altered oceanic crust?

Significant discussion surrounds the origin of the gabbro signature that is apparent in a subset of melt inclusions isolated from MORB and hotspot lavas. Sobolev et al. (2000) argued that the gabbro signature in rare Hawaiian inclusions results from melting recycled gabbro incorporated into the Hawaiian mantle. However, Danyushevsky et al. (2003) argued that UDM inclusions at some localities may result from assimilation of plagioclase-rich assemblages, including gabbros, during melt ascent. While we cannot distinguish between these two models for the origin of the gabbro signature in the OJP melt inclusions, we argue that the mechanism responsible for generating the gabbro signature did not generate the UDM signatures.

Gabbro cumulate xenoliths have been found at the OJP (Kinman and Neal, 2006), and gabbro cumulates are predicted to lie in the deep portions of the OJP (Neal et al., 1997). However, trace element evidence suggests that interaction of OJP melts with gabbros did not generate the UDMs. Only one UDM inclusion from the OJP has a large
positive Sr anomaly, which suggests interaction with a plagioclase-assembly, but the other UDM inclusions do not exhibit clear Sr anomalies within measurement error (Fig. 3). This observation indicates that the processes associated with the generation of the positive Sr anomaly (for example, gabbro assimilation in the Danyushevsky et al. [2003] model) are decoupled from the process that generates the incompatible element depletion noted in the UDM inclusions from the OJP. Danyushevsky et al. (2003) noted that, while some UDM inclusions at other localities might result from plagioclase-bearing gabbro assimilation, not all UDMs acquire their incompatible trace element depleted signature in this way. For example, they indicated that the lack of a positive Sr anomaly in the UDM measured by Sobolev and Shimizu (1993) argued against the UDM signature originating by gabbro assimilation. Laubier et al. (2012) made a similar argument for a suite of MORB melt inclusions, and argued that, while assimilation can generate positive Sr anomalies, it is unlikely to generate the incompatible trace element depletion observed in the same melt inclusions.

Similarly, Cl/K exhibits no relationship with indicators of incompatible element depletion (e.g., La/Yb) (Fig. 4). If elevated Cl/K ratios indicate interaction with hydrothermally-altered oceanic crust, then the lack of relationship between Cl/K and La/Yb argues against shallow-level assimilation of lithospheric material as the mechanism responsible for the trace element patterns in the UDM inclusions.

4.3. Interpreting the water abundances in OJP inclusions
The H$_2$O contents of the OJP inclusions are not correlated with any incompatible element ratios or concentrations. The H$_2$O concentrations of the UDM and normal-type inclusions fall in a fairly narrow range (Fig. 4) that is similar to that measured in OJP glasses (Roberge et al., 2004), while the Ce concentrations in the UDM inclusions are lower than the normal type inclusions. This leads to large variations in H$_2$O/Ce. The best explanation for these observations relates to the high diffusivity of H$_2$O in olivine. Diffusion of H$_2$O (but not Ce) from the host liquid through the host olivine and into H$_2$O-poor UDM inclusions may elevate the H$_2$O/Ce ratio of the inclusion (Kolezar et al., 2009; Gaetani et al., 2012). If so, the inclusions may have started out with similar H$_2$O/Ce ratios when they were trapped, but addition of H$_2$O via diffusion into the olivine raised their H$_2$O/Ce ratios. If the host olivines experienced relatively long residence times in large magma chambers, it would have been difficult for inclusions to avoid such diffusive equilibration.

The high Cl/K ratios provide evidence for extensive assimilation of hydrothermally altered material in much of the OJP inclusion suite, consistent with previous suggestions of widespread assimilation in the OJP (Neal and Davidson, 1989; Michael, 1999; Roberge, 2004; Kinman and Neal, 2006); both UDM and normal-type inclusions have elevated Cl/K, indicating that assimilation occurred in both suites prior to melt aggregation (Fig. 4). Assimilation of altered, and therefore hydrous, crust can increase the H$_2$O abundances of affected melts (e.g., Kent et al., 1999a, 1999b).

Therefore, we do not argue that the H$_2$O abundances and the elevated H$_2$O/Ce ratios in the OJP melt inclusions reflect mantle source ratios, a conclusion made in Roberge et al.’s (2004) study of OJP pillow glasses. However, while the Cl/K is high in the OJP
inclusion suite, there is not a clear correlation between Cl/K and H₂O/Ce. Thus, it is
difficult to argue for assimilation as the sole cause for the elevated H₂O/Ce in the
inclusions. Therefore, we argue that diffusive incorporation of H₂O may operate alone or
in tandem with assimilation to increase the H₂O/Ce of the OJP inclusions, and that the
H₂O abundances in the inclusions do not reflect primary magmatic concentrations.

4.4. A widespread, but diluted depleted component in OJP lavas: evidence from UDM
inclusions

An important question is whether melts like those sampled in UDM inclusions are
relatively common in the OJP but were simply mixed together with Kroenke-type melts
and became obscured by magma mixing and dilution. The trace element patterns of the
least altered Kroenke-type lavas are generally smooth (Figs. 1, 2 and 3). However, the
extremely limited variability may permit a small proportion of melts like the UDM
inclusions to comprise (i.e., be “hidden” within) the bulk whole rock chemistry of
Kroenke-type basalts without causing their trace element patterns to deviate outside the
range of measured (La/Yb)ₙ ratios in whole rock basalts. If so, then mixing and
homogenization in magma chambers could have mixed the depleted component
thoroughly into the bulk lava such that the depleted component is only visible in the
UDM inclusions that were trapped before complete magma mixing. A mixture of
approximately 7% of a UDM melt component (using the average of the UDM inclusions)
and 93% of an average Kroenke-type melt component generates a primitive mantle
normalized trace element pattern that is similar to the pattern of the most depleted
Kroenke-type lava. This suggests that a small quantity of UDM melts may be “hidden” in the average bulk rock Kroenke-type lavas without forcing the trace element variability to depart from levels observed in whole rock Kroenke lavas.

The crustal portion of the OJP is estimated to be 30 km thick (Miura et al., 2004; Richardson et al., 2000), but only 3.5 km of the plateau’s stratigraphy is exposed in the Solomon islands and has been sampled (e.g., Petterson et al., 1997), while even less has been sampled by drilling. With nearly 90% of the stratigraphy of the OJP left unsampled, the possibility exists that melts like the UDM inclusions comprise a larger fraction than 7% of the bulk rock in samples from deeper in the plateau. However, only the upper stratigraphy of the OJP has been characterized. The bulk of the plateau is still beyond the reach of direct sampling efforts, and the Kroenke lava type (which we find to host UDM inclusions) was only recently discovered (Tejada and Mahoney, 2004; Fitton and Godard, 2004) as a result of a major ocean drilling effort. The deeper portions of the OJP have been suggested to be heterogeneous (Kerr and Mahoney, 2007; Kerr, 2014). If the UDM component reflects a more refractory mantle source (suggested by its trace element depletion), and if the earlier stages of OJP volcanism sampled a hotter portion of the upwelling plume, then earlier stages of volcanism at the OJP might sample this component in purer form. We suggest that, if sampled in purer form in as-yet-undiscovered OJP bulk lavas, this lava type be called Mahoney-type, to complement the Kroenke, Kwaimbaita and Singgalo-type lavas already discovered in the OJP.

5. Conclusions
We conducted the first geochemical study of melt inclusions from the OJP. All of the olivine-hosted melt inclusions were isolated from a single hand sample from ODP Site 1187. Measurements of major, trace, and volatile elements on the inclusions reveal that over one third of the inclusions are highly depleted in incompatible elements (with low (La/Yb)_N ratios, referred to as UDM inclusions), while the remaining inclusions have primitive mantle normalized trace element patterns that are similar to whole rock Kroenke-type lavas from the OJP. The inclusions all have elevated Cl/K (indicative of assimilation of altered oceanic crust or brines), and many of the inclusions have elevated Sr/Sr* (indicative of a gabbro component), but neither Cl/K nor Sr/Sr* correlates with indicators of incompatible element depletion, like (La/Yb)_N. Thus, we argue that the geochemically depleted signatures of the UDM inclusions are not the result of assimilation.

The trace element characteristics of the UDM inclusions suggest that their mantle source is not related to the mantle source of the normal-type inclusions or Kroenke-type lavas. First, the UDM inclusions have unique trace element signatures (e.g., low Zr/Zr* values) that preclude an origin by re-melting the depleted mantle source left over after melt extraction during construction of the OJP. Second, sampling of melts from a progressively depleted OJP mantle component during upwelling and polybaric melt extraction from a mantle plume might be expected to produce a continuous spectrum of inclusion compositions between normal-type and UDM inclusions. However, there is a distinct lack of inclusions that have compositions intermediate between the UDM and normal-type inclusions, which suggests the presence of two distinct mantle sources that give rise to the two groups of melt inclusions observed in this study. We argue that the
UDM inclusions are melts of a previously unrecognized depleted component in the OJP mantle source.

We argue that the two distinct groups of OJP inclusions sample two (perhaps lithologically) distinct mantle sources in the OJP plume. If the lithologically heterogeneous xenoliths previously reported from the Island of Malaita represent geochemical diversity in the OJP mantle source, the heterogeneous trace element compositions in the OJP inclusions represent the first hints of heterogeneity that exists in primary Kroenke and Kwaimbaita-type melts prior to melt aggregation.

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Fig. 1. Major and trace element compositions of the OJP melt inclusions compared to representative whole rock basaltic compositions (Fitton and Godard, 2004) and pillow glass compositions from OJP drill sites (Michael, 1999; Roberge et al., 2004). In order to avoid the effects of alteration, we follow the alteration filter of Fitton and Godard (2004) and have excluded whole rock basalts with LOI > 0.5 wt.% and K2O/P2O5 > 2. The composition of the Kroenke-type lava hosting the melt inclusions (192-1187A-006R-06W [110-129 cm]) is also shown. The major and trace element concentrations in the melt inclusions have been corrected for olivine fractionation to be in equilibrium with the host olivine. Whole rock and melt inclusion major element data are normalized to 100 wt.% on a volatile-free basis.

Fig. 2. Primitive mantle (McDonough and Sun, 1995) normalized trace element patterns for ultra-depleted and normal-type OJP melt inclusions. UDM inclusions are shown as red lines and normal-type inclusions are shown as blue lines. The two inclusions with the largest Sr/Sr* values, one UDM inclusion (#25) and one normal-type inclusion (#23), are highlighted with diamond symbols. The melt inclusions are compared to whole rock trace element patterns measured on Kroenke-type lavas (top panel, solid grey lines), and Kawaimbaita-type (bottom panel, grey large-dashed lines) and Singgalo-type (bottom panel, solid black lines) lavas. The whole rock analysis for this lava from which inclusions were extracted is shown (top panel, bold black large-dashed line). In the bottom panel, several reference compositions are shown: MORB
(light grey thick solid line; Gale et al., 2013), depleted MORB mantle (DMM, dark bold grey large-dashed line; Workman and Hart, 2005), average Gabal Gerf gabbro composition (Zimmer et al., 1995; small-dashed black line). The EDR composition used in the melt model is shown (grey small-dashed lines). Whole rock lava data come from Fitton and Godard (2004), and we plot only the freshest lavas following the filter outlined in the caption of Fig. 1. The trace element concentrations of the inclusions have been adjusted to reflect major element correction for olivine fractionation/addition to be in equilibrium with the host olivine (see Fig. 1 caption).

**Fig. 3.** Major and trace element ratios are used to distinguish the UDM inclusions and the normal-type inclusions from the OJP and to evaluate interaction with plagioclase-rich (i.e., plagioclase-rich gabbro) lithologies. The expanded views show olivine-hosted melt inclusions from Iceland, for comparison. Panels A through D use incompatible trace element ratios to show that the UDM and normal-type inclusions form separate groups. In panels E and F, the Gabal Gerf plagioclase composition from Sobolev et al. (2000) plots off the figure, and has low CaO/Al$_2$O$_3$ (0.40) and high Sr/Sr* (3.3). Panels G and H show that there is no relationship between a plagioclase-rich gabbro signature (where high values of Sr/Sr* suggest the strongest gabbro signature) and (La/Yb)$_N$ signatures of the OJP inclusions. All whole rock data are from Fitton and Godard (2004). The whole-rock data (Kroenke, Kwaimbaita and Singgalo-type lavas) are filtered for alteration as discussed in the caption of Fig. 1. MORB is from Gale et al. (2013). The whole rock composition of the Kroenke-type lava hosting the melt inclusions is also shown. Error bars are 1σ, standard deviation. Symbols are the same as in previous
figures except for the addition of the Iceland melt inclusions (grey circles); Iceland data are from Gurenko and Chaussidon (1995, 1997), Slater et al. (2001) and Maclennan et al. (2003a, 2003b, 2008a, 2008b), Moune et al. (2012), Hartley et al. (2013, 2014) and Neave et al. (2014).

**Fig. 4. Plots showing the behavior of CO₂, H₂O, Cl, F and S in OJP melt inclusions.** Symbols as in previous figures. OJP pillow glass compositions are from Michael (1999) and Roberge et al. (2004). For all melt inclusion data, the trace element data are corrected for olivine fractionation/addition so that the major elements are in equilibrium with the host olivine (see Fig. 1 caption); thus, two samples without major element data (2B and 9C) are excluded from the three panels where elemental concentrations are plotted. Error bars are 1σ, standard deviation.

**Fig. 5. A melt model showing that the EDR mantle source (solid grey line, no symbols) from Jackson and Jellinek (2013) generates melts similar to the Kroenke-type OJP lavas (black lines) and normal-type inclusions (blue lines).** The UDM inclusions are also plotted (red lines). Two melt models are shown (described in Fig. 6 and Section 4.1.2 of the text): One represents 25% aggregated fractional melting of the EDR mantle source (grey line with circles), and the other represents 30% aggregated fractional melting of the same source (grey line with triangles). The details of the melt model are provided in the text. Kroenke-type lavas from Fitton and Goddard (2004) and the lava hosting the inclusions in this study are shown (black lines); whole rocks are filtered after Fig. 1, and are olivine fractionation corrected to be in equilibrium with Fo₉₂
olivine. Melt inclusions are also corrected for olivine fractionation to be in equilibrium with Fo$_{92}$ olivine to simulate primary mantle melts.

**Fig. 6. A melt model shows that the UDM inclusions cannot be extracted from the same mantle source as the normal-type inclusions or from the depleted residual mantle left over following extraction of normal-type melts.** The details of the melt model are provided in the text. The melt model mantle source (EDR) is shown.

Aggregated near-fractional melt extraction (0.05 to 2% residual porosity in mantle) from this mantle source (blue line with tic marks at 1% aggregated fractional melting intervals, starting at 0% on the far right) best matches the composition of the normal-type inclusions with 25-30% aggregated fractional melting. The composition of the mantle residue following melt extraction is shown as a grey line with tic marks marking 1% fractional melt extraction (with 15% fractional melt extraction on the far left, and 0% fractional melt extraction on the right) from the EDR mantle. Melts extracted from this residue have higher Zr/Zr* than the residue, and therefore have higher Zr/Zr* that the UDM inclusions from the OJP. Following extraction of 10% fractional melt from the EDR to make a depleted residue (grey line, starting at tic labeled F=10%), we extract aggregated fractional melt from this residue (red line with aggregated fractional melting intervals at 1%, starting at 0% on the far right): while the low (La/Yb)$_N$ values of the UDM inclusions are matched by melt extraction from a depleted source (red line), the Zr/Zr* of the model melt is too high. Error bar represents 1σ, standard deviation.
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Figures 1 to 6

UDM inclusions (this study)  Normal inclusions (this study)
Whole rock (this study)  Kroenke whole rocks
Kwaimbaita whole rocks Singgalo whole rocks
OJP glasses
Fig. 2
Fig. 3

A-C: Ti/Zr vs. (La/Yb)N for Depleted and Enriched samples.

D-F: Nb/Zr vs. (La/Yb)N for Depleted and Enriched samples.

G-H: CaO/Al₂O₃ vs. Sr/Sr* for Gabal Gerf plagioclase.

Legend:
- Red: UDM inclusions (this study)
- Black: Normal inclusions (this study)
- Gray: Whole rock (this study)
- White: Kroenke whole rocks
- Blue: Kwaimbaita whole rocks
- Green: Singgalo whole rocks
- Yellow: OJP glasses
- Light gray: Iceland melt inclusions
Fig. 5

Sample/Primitive Mantle

Melt Model (25% melt)
Melt Model (30% melt)
Normal-type inclusions
Kroenke-type lavas
UDM inclusions
EDR (source of Kroenke lavas)
Fig. 6

UDM inclusions (this study)  Normal inclusions (this study)
Whole rock (this study)  Kroenke whole rocks
Kwaimbaita whole rocks  Singgalo whole rocks

Zr/Zr*

0.01 0.1 1 10

(La/Yb)N

F=15%
Residue of EDR putting
F=10%
Melt of residue
EDR
Melt of EDR
F=0%

Kroenke whole rocks
Singgalo whole rocks
Whole rock (this study)
Kwaimbaita whole rocks

Kroenke whole rocks
Singgalo whole rocks
Whole rock (this study)
Kwaimbaita whole rocks