

# Recycled dehydrated lithosphere observed in plume-influenced mid-ocean-ridge basalt

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**A substantial uncertainty in the Earth's global geochemical water cycle is the amount of water that enters the deep mantle through the subduction and recycling of hydrated oceanic lithosphere. Here we address the question of recycling of water into the deep mantle by characterizing the volatile contents of different mantle components as sampled by ocean island basalts and mid-ocean-ridge basalts. Although all mantle plume (ocean island) basalts seem to contain more water than mid-ocean-ridge basalts, we demonstrate that basalts associated with mantle plume components containing subducted lithosphere—'enriched-mantle' or 'EM-type' basalts—contain less water than those associated with a common mantle source. We interpret this depletion as indicating that water is extracted from the lithosphere during the subduction process, with greater than 92 per cent efficiency.**

Quantifying the Earth's global geochemical water cycle is important for modelling physical properties of mantle materials<sup>1</sup>, melt generation<sup>2</sup> and planetary evolution<sup>3</sup>. Water is added to oceanic crust at or near mid-ocean-ridge crests via hydrothermal alteration, and some or most of this water is lost during dehydration of subducting lithosphere, contributing to flux-melting of the overlying mantle wedge, generation of island arc magmas, and addition of water to the atmosphere–ocean system<sup>4</sup>. However, the amount of water that survives subduction and is transported to the deep mantle, perhaps contributing to subsequent 'wet' plume generation and ocean island volcanism<sup>5</sup>, is poorly known.

## Recycling of crustal materials and mantle heterogeneity

Chemical diversity within the mantle is closely related to recycling of oceanic crust and sediments into the mantle by the plate tectonic process of subduction<sup>6</sup>. On the basis of radiogenic Pb, Nd and Sr isotopes in ocean island basalts, five isotopically extreme mantle components have been defined<sup>7–9</sup>: (1) DMM (depleted MORB mantle); (2) HIMU ('high  $\mu$ ' where  $\mu = {}^{238}\text{U}/{}^{204}\text{Pb}$ ); (3) EM1 (enriched mantle 1); (4) EM2 (enriched mantle 2); and (5) LOMU ('low  $\mu$ ') with very low time-integrated U/Pb ratio; MORB indicates mid-ocean-ridge basalt. In this context, 'enriched' refers to time-integrated Rb/Sr, Sm/Nd and/or (U + Th)/Pb ratios higher than primitive mantle (bulk silicate Earth). The origin and location of these end-members are actively debated, but it is generally accepted that the shallow upper mantle is the source of depleted MORB. HIMU is believed to represent recycled, old, hydrothermally altered oceanic crust, dehydrated and metamorphosed to eclogite during subduction. HIMU sources are depleted in Pb and K and enriched in U, Nb and Ta (refs 10, 11) relative to MORB. EM1 includes either recycled oceanic crust plus a few per cent pelagic sediment<sup>10–12</sup> or metasomatized subcontinental lithosphere<sup>13</sup>. EM2 includes recycled oceanic crust containing a few per cent of continent-derived sediment<sup>11</sup>. LOMU is distinguished from EM1 by its unusually high  ${}^{87}\text{Sr}/{}^{86}\text{Sr}$  and  ${}^{207}\text{Pb}/{}^{204}\text{Pb}$  ratios, and very low  ${}^{143}\text{Nd}/{}^{144}\text{Nd}$  and  ${}^{177}\text{Hf}/{}^{176}\text{Hf}$  ratios, suggesting an ancient continental source<sup>9,14,15</sup>. Here we will refer to EM1, EM2, LOMU and mixtures of these simply as EM components, as all seem to include recycled materials of continental derivation.

Whereas the five end-members constrain the compositional

extremes, most data from ocean islands form linear mixing arrays that converge in a limited region of isotopic space that has been given various acronyms, including C ('common' mantle component; ref. 16) and FOZO ('focus zone'; refs 17, 18), used here. FOZO has moderately depleted Sr and Nd signatures, radiogenic Pb isotopes, and elevated  ${}^3\text{He}/{}^4\text{He}$  ratios<sup>18</sup>. The high He isotope ratios of FOZO suggest an origin in the lower mantle<sup>16,19</sup>. However, radiogenic isotopic compositions and trace-element ratios are inconsistent with FOZO being primitive mantle, and suggest involvement of a HIMU component<sup>6,10,20–25</sup>.

It has also been proposed that EM components are associated with mantle metasomatism<sup>26</sup>, implying concentrations of water and/or carbon dioxide greater than those in 'normal' mantle, if the metasomatic agent is a hydrous or carbonate phase. However, Dixon and Clague<sup>27</sup> showed that  $\text{H}_2\text{O}/\text{Ce}$  in Loihi summit glasses correlates negatively with  ${}^{206}\text{Pb}/{}^{204}\text{Pb}$ , and interpreted this as evidence for a relatively 'dry' EM component in the Hawaiian plume. Here we report  $\text{H}_2\text{O}$  and  $\text{CO}_2$  concentration data (measured by transmission infrared spectroscopy on MORB glasses from ridges influenced by various mantle plume components in the North and South Atlantic oceans); our aim is to see if the Hawaii result is unique, or if it represents a global EM characteristic.

## $\text{H}_2\text{O}/\text{Ce}$ as a tracer of magmatic and nonmagmatic fractionations

Previous workers<sup>28,29</sup> have found it useful to compare water concentrations to concentrations of elements or oxides of similar incompatibility, such as  $\text{K}_2\text{O}$ ,  $\text{P}_2\text{O}_5$ , La and Ce. Water has a bulk distribution coefficient ( $D_{\text{H}_2\text{O}}$ ) of  $\sim 0.01$  (refs 28, 29), slightly higher than  $\text{K}_2\text{O}$  and La and lower than Ce and  $\text{P}_2\text{O}_5$ . For virtually all chemical species in oceanic basalts, ratios of more-incompatible to less-incompatible elements or oxides correlate positively. Thus  $\text{H}_2\text{O}$  ratioed to a slightly more compatible species (Ce,  $\text{P}_2\text{O}_5$ ) correlates positively with other trace-element ratios indicative of source region enrichment or depletion (such as  $(\text{La}/\text{Sm})_n$ ,  $\text{K}_2\text{O}/\text{TiO}_2$ ), as has been observed at the Easter microplate (EMP) and at the Easter–Salas y Gómez seamount chain (ESC)<sup>30</sup>, and for the East Pacific Rise and near-rise seamounts<sup>29</sup>. These correlations are thought to represent mantle source characteristics, because as long as the extent of melting ( $F$ ) is greater than the bulk distribution coefficient ( $D$ ), trace-element ratios of incompatible elements in

basaltic melts will be similar to those of the source region. These data show that for areas such as the Easter microplate, water behaves as other incompatible elements and appears to be controlled by magmatic processes.

Shallow level processes introduce scatter into these correlations through degassing (which decreases  $H_2O/Ce$ ) or assimilation of seawater-derived components (which increases  $H_2O/Ce$ ). These modifications of water concentrations can be identified by examining

water concentration as a function of partial melting, differentiation, eruption depth, vesiculation, and chlorine concentration<sup>27–32</sup>. For example, to correct for water degassing, bulk water concentrations can be estimated by adding the amount of water in vesicles to that dissolved in the glass<sup>27,31</sup>.

Once shallow level processes have been accounted for, deeper processes can be investigated. For example, addition of hydrous fluid phases by mantle metasomatism, or addition of a mantle component containing hydrous phases, should increase  $H_2O/Ce$ , whereas incorporation of severely dehydrated components will decrease  $H_2O/Ce$ . If variations in  $H_2O/Ce$  correlate with radiogenic isotopic compositions, then the hydration or dehydration event probably occurred at the same time as the fractionation between parent and daughter elements.

### Water in plume-influenced MORB from the South Atlantic

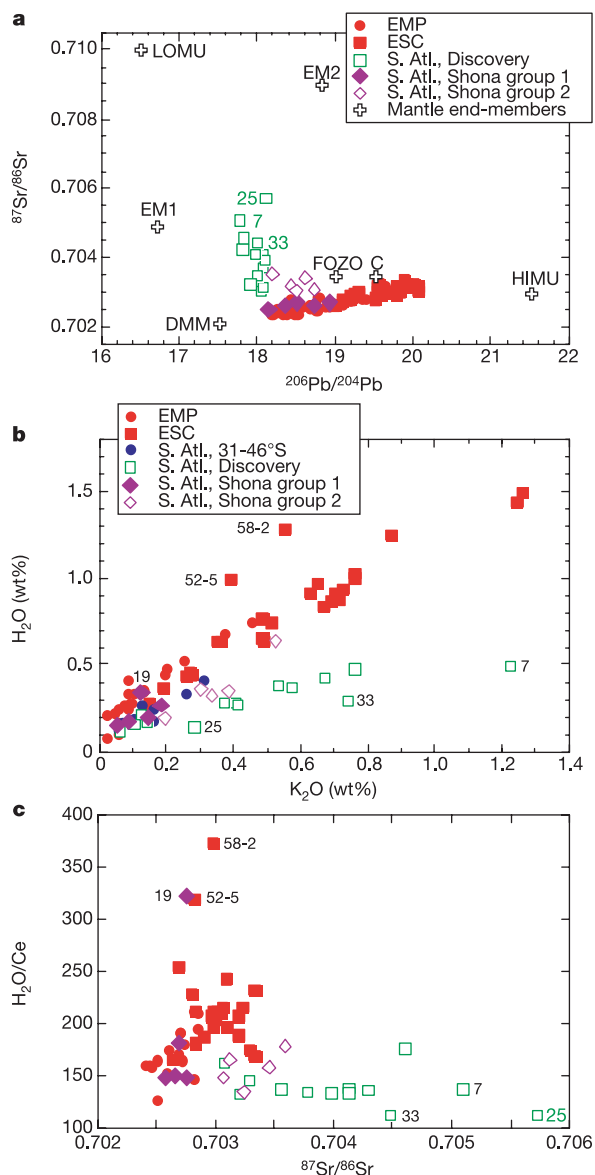
South Atlantic samples were dredged along the Mid-Atlantic Ridge between 40°S and 54°S during the RV *Maurice Ewing* EW93-09 cruise (see Supplementary Table S1). This region contains two distinct geochemical, gravity and bathymetric anomalies. The northern 'Discovery' anomaly is centred at 47.5°S and is influenced by the Discovery plume<sup>9,33</sup>. The southern 'Shona' anomaly is centred at 51.5°S (refs 9, 33, 34).

We compare the South Atlantic samples to EMP and ESC glasses because both areas involve plume–ridge interaction, and Pacific and South Atlantic MORB have similar regional  $H_2O/Ce$  ratios<sup>23</sup>, and thus similar depleted end-member compositions. Radiogenic isotopic data for EMP–ESC basalts (Fig. 1a) have been interpreted as the result of binary mixing between depleted MORB and mildly-HIMU FOZO (Salas y Gomez plume) sources<sup>35,36</sup>.

Isotopic compositions of Discovery glasses show a wide range of  $^{87}Sr/^{86}Sr$  at a relatively constant  $^{206}Pb/^{204}Pb$ , consistent with pseudo-binary mixing of DMM, FOZO and an EM component, specifically LOMU<sup>9</sup> (Fig. 1a). Contribution of this EM component is least for samples 26, 28, 34 and 40, and greatest for sample 7, 9, 33 and 25 (ref. 37)<sup>37</sup>. Whether this component is recycled in the upper or lower mantle is not known. However, the nearly solar  $^{21}Ne/^{22}Ne$  ratios and high  $^3He/^4He$  in some of the Discovery MORB glasses (samples 2–5) suggest recycling at least to the 660-km discontinuity, where more primitive mantle could have been entrained by the Discovery plume<sup>38</sup>. Shona glasses form two groups in Sr–Nd–Pb–Hf isotopic space. Shona group 1 samples (dredges 11, 14, 15, 17 and 19) show mixing between DMM and FOZO with mild HIMU influence, similar to the Easter trend. Shona group 2 samples (dredges 18, 20, 21, 22 and 23) show additional influence of an EM component (EM1–EM2) thought to represent recycled oceanic crust + pelagic sediments<sup>15</sup>.

Water correlates positively with  $K_2O$  for the South Atlantic, but with very different slopes defined by Shona and Discovery samples (Fig. 1b). Linear correlations between  $H_2O$  and  $K_2O$  for Shona group 1, Easter, and other South Atlantic (31–46°S) MORB samples are indistinguishable (Fig. 1b). One outlier (sample 19) has more water at a given  $K_2O$  (about 0.1 wt% extra) than samples forming the main trend, with  $H_2O/Ce$  similar to several ESC samples, possibly related to serpentine assimilation during ascent<sup>23</sup>. For the remaining samples, water is more compatible than K and less compatible than Ce, consistent with the behaviour of these elements in magmatic systems. Thus, the characteristics of the plume and DMM end-members for the Shona group 1 samples are similar to those of the EMP–ESC<sup>30</sup>, for which the FOZO component has  $H_2O/K_2O = \sim 0.8$  and  $H_2O/Ce = 210 \pm 30$  and the DMM component has  $H_2O/K_2O = \sim 5$  and  $H_2O/Ce = 150 \pm 10$  (Fig. 1c).

Shona group 2 and Discovery samples ( $^{87}Sr/^{86}Sr > 0.703$ ) that contain an EM component have distinctly lower  $H_2O$  concentrations and lower  $H_2O/Ce$  than Shona group 1 and Easter samples. Shona group 2 data form trends sub-parallel to Shona group 1 data but at progressively lower  $H_2O$  content and  $^{206}Pb/^{204}Pb$ . The



**Figure 1** Comparison of radiogenic isotopic compositions,  $H_2O$ ,  $K_2O$  and  $H_2O/Ce$  in basaltic glasses. Data are from the Discovery and Shona anomalies<sup>9</sup> along the southern Mid-Atlantic Ridge, and from the Easter microplate and Easter–Salas y Gomez seamount chain (EMP–ESC) in the southeast Pacific<sup>35,36</sup>. **a**,  $^{87}Sr/^{86}Sr$  versus  $^{206}Pb/^{204}Pb$ . Isotopic compositions for mantle end-members are from ref. 51. Open symbols (Discovery and Shona group 2) represent samples having an EM-type mantle plume component. Filled symbols (Shona group 1 and EMP–ESC) represent samples containing a FOZO-type or mildly-HIMU plume component. **b**,  $H_2O$  versus  $K_2O$ . Water concentrations increase with increasing  $K_2O$  concentrations; however, EM-type basalts contain less water at a given  $K_2O$  than C-type basalts. **c**,  $H_2O/Ce$  versus  $^{87}Sr/^{86}Sr$  for the South Atlantic and Easter microplate. EM-type basalts have significantly lower  $H_2O/Ce$  than FOZO-type basalts. Several samples have high  $H_2O/Ce$  ratios ( $>300$ ) that do not correlate with major- or trace-element or isotopic compositions. These samples may have assimilated water during transport and eruption. Symbols are as in **b**.

Discovery samples form a distinct binary mixing line converging with that of the Easter group at the depleted source end (Fig. 1b, c). Discovery samples with the most definitive EM signature have  $\text{H}_2\text{O}/\text{K}_2\text{O}$  half that of the Easter samples. The observation that sample 25 has relatively low water concentration and  $\text{H}_2\text{O}/\text{Ce}$  is very important. Even though it has the highest  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio, reflecting a mantle source with time-integrated enrichment of incompatible elements (for example, high  $\text{Rb}/\text{Sr}$ ), it is not the most enriched in incompatible elements, perhaps related to a recent episode of

melting and melt extraction<sup>39</sup>. Sample 25 has only 0.15 wt% water. In order for this sample to have degassed significant quantities of water, it would have to have been erupted at or below the water solubility pressure of  $\sim 3$  bar (30 m water depth), much shallower than its actual eruption depth at 2,032 m. It is almost certain that its low water concentration is a primary magmatic characteristic. Samples most enriched in  $^{87}\text{Sr}/^{86}\text{Sr}$  (7, 25 and 33) have the lowest  $\text{H}_2\text{O}/\text{K}_2\text{O}$ . If these ratios were caused by the same type of (magmatic) process as observed for the Easter samples, then these samples should also have the highest  $\text{H}_2\text{O}/\text{Ce}$ . Instead, samples with the lowest  $\text{H}_2\text{O}/\text{K}_2\text{O}$  have low  $\text{H}_2\text{O}/\text{Ce}$ , suggesting control by a different process that selectively lowers water content.

Thus, the EM components in the mantle sources for the Shona and Discovery samples are associated with lower water concentrations and lower ratios of water to similarly incompatible elements compared to the common plume component (FOZO).

### Water in plume-influenced MORB from the North Atlantic

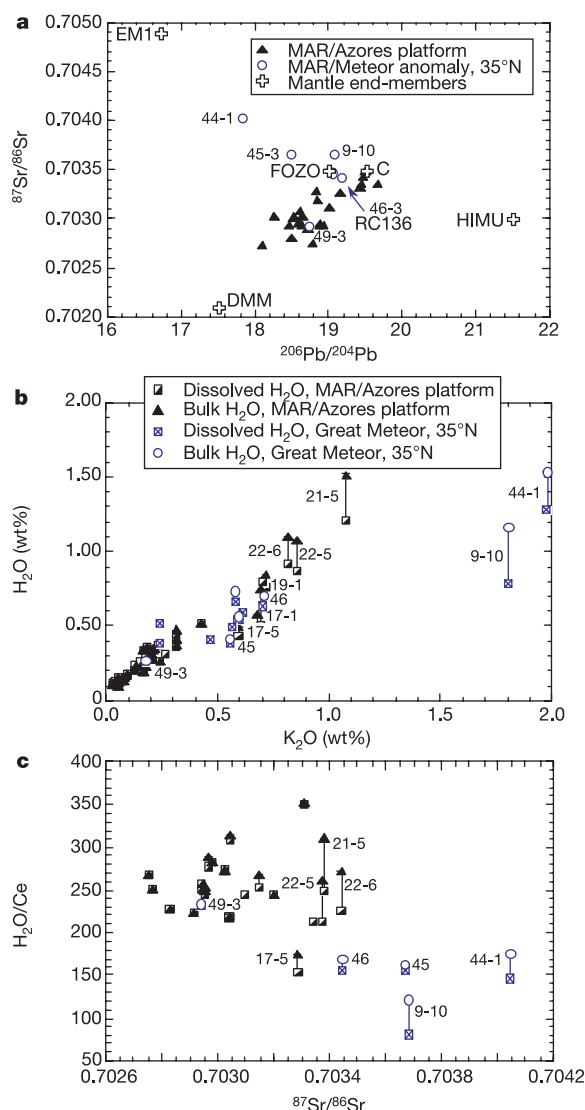
The north Mid-Atlantic Ridge samples were dredged by the RV *Atlantis II* (FAZAR expedition<sup>40</sup>) between  $33.2^\circ$  and  $40.5^\circ\text{N}$  with depths varying between 926 and 3,900 m (see Supplementary Table S2). Two distinct geochemical anomalies occur within this region, including the long-wavelength anomaly associated with the intersection of the Azores archipelago with the Mid-Atlantic Ridge at  $\sim 38\text{--}39^\circ\text{N}$  (Azores platform) and a short-wavelength anomaly centred at  $35^\circ\text{N}$  (the Great Meteor anomaly<sup>41</sup>, used here, or the 'north of Oceanographer fracture zone anomaly'<sup>42</sup>). Sr and Pb isotopic data<sup>43</sup> (Fig. 2a) show that Azores platform basalts form a linear mixing array between DMM and FOZO. In contrast, basalts from the Great Meteor anomaly form a mixing array between FOZO and an EM component, with samples 9-10, 45-3 and 44-1 having the highest  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios. An exception is 49-3, which falls within the Azores platform array.

Because of the high vesicularity of many of the Azores platform and Great Meteor samples, loss of water into vesicles may have been significant. Both measured dissolved and calculated bulk water concentrations (see Supplementary Information) are shown in Fig. 2b and c. Samples from dredges 17, 19, 21 and 22 from the summit of the Azores platform (926–1,950 m) are highly vesicular (25–60 vol.%) and have lost about 10–30% of their initial water into vesicles. Dissolved water concentrations in the less vesicular Azores platform samples correlate positively with  $\text{K}_2\text{O}$  and have  $\text{H}_2\text{O}/\text{Ce}$  ratios ( $253 \pm 33$ ) consistent with previously reported values for the North Atlantic<sup>28</sup>. Estimated bulk  $\text{H}_2\text{O}/\text{Ce}$  for the highly vesicular samples ( $247 \pm 54$ ) are similar to values for nonvesicular samples for all but the shallowest dredge (17), which may have suffered some gas loss (open-system degassing).

Great Meteor anomaly samples are also highly vesicular (5–60 vol.%), with vesicularity correlating roughly inversely with depth (5 vol.% at 3,900 m to 60 vol.% at 1,657 m). Samples with the largest EM component have dissolved and bulk water concentrations at a given  $\text{K}_2\text{O}$  (Fig. 2b) that are significantly lower than undegassed samples from the Azores platform.  $\text{H}_2\text{O}/\text{Ce}$  is also 30% lower than the mean for the Azores platform samples ( $168 \pm 29$  versus  $253 \pm 33$ ). Though the correlation is rough, extrapolation from FOZO through the Great Meteor data yields  $\text{H}_2\text{O}/\text{Ce} < 100$  at  $^{87}\text{Sr}/^{86}\text{Sr} > 0.705$ . Thus, like the Discovery samples, EM components in the North Atlantic are depleted in water relative to FOZO.

### Discussion

In each setting described above, there are two distinct mantle plume components: one close to FOZO (common mantle plume component), and the other enriched in recycled material of continental derivation (EM). In each case, the ratio of water to other similarly incompatible elements is lower in the EM component than in FOZO. Our data show that basalts influenced by EM mantle



**Figure 2** Comparison of radiogenic isotopic compositions,  $\text{H}_2\text{O}$ ,  $\text{K}_2\text{O}$  and  $\text{H}_2\text{O}/\text{Ce}$  in basaltic glasses from the North Atlantic. **a**,  $^{87}\text{Sr}/^{86}\text{Sr}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$ . Azores platform basalts<sup>43</sup> (black filled triangles) are consistent with mixing between DMM and C-type mantle components. Great Meteor anomaly basalts (blue open circles) are consistent mixing between EM-type and FOZO-type mantle components. **b**,  $\text{H}_2\text{O}$  versus  $\text{K}_2\text{O}$ .  $\text{K}_2\text{O}$  data from ref. 40. Measured dissolved  $\text{H}_2\text{O}$  concentrations are shown as black half-filled squares (Azores platform) and blue crossed squares (Great Meteor). Calculated bulk  $\text{H}_2\text{O}$  concentrations (see Supplementary Tables S1 and S2) are shown as black filled triangles (Azores platform) and blue open circles (Great Meteor). Lines connect dissolved and bulk water concentrations for individual samples. Calculated bulk  $\text{H}_2\text{O}$  concentrations for dredge 17 from the summit of the Azores platform are probably low owing to open-system degassing (J.E.D., manuscript in preparation). EM-type basalts have less water at a given  $\text{K}_2\text{O}$  content than FOZO-type basalts from the North Atlantic. **c**,  $\text{H}_2\text{O}/\text{Ce}$  versus  $^{87}\text{Sr}/^{86}\text{Sr}$  for the North Atlantic. EM-type basalts have lower  $\text{H}_2\text{O}/\text{Ce}$  than FOZO-type basalts and depleted MORB. Symbols as in **b**.



components are depleted in water ('damp' plumes) relative to those influenced by FOZO ('wet' plumes).

# What is FOZO?

We have shown that FOZO plumes are 'wetter' than EM plumes, but we still need to address the origin of H<sub>2</sub>O in these mantle components. Though the origin of FOZO is an area of active debate, the following characteristics are generally accepted. First, FOZO is not pristine primitive mantle. Paradoxically, Sr- and Nd-isotopic compositions require moderate time-integrated depletion in incompatible elements (Rb/Sr lower and Sm/Nd higher than primitive mantle), whereas the present-day source is enriched in incompatible elements<sup>6,44</sup>. In addition, Pb-, Os- and O-isotopic compositions and trace-element ratios (Nb/U, Nb/Th and Ce/Pb) suggest involvement of a HIMU component<sup>6,10,21–25,44</sup>. Second, high concentrations of Ni, Cr and heavy rare-earth elements in FOZO require melting of a peridotitic source, and are inconsistent with melting of a purely eclogitic (HIMU) source<sup>44,45</sup>. Third, FOZO typically has elevated <sup>3</sup>He/<sup>4</sup>He, indicating involvement of mantle that is less degassed and more primitive than MORB mantle, probably located deeper than the MORB source<sup>17,18</sup>. High <sup>3</sup>He/<sup>4</sup>He also rules out generation of FOZO by mixing between DMM and HIMU components<sup>45</sup>. Lastly, the globally widespread occurrence of FOZO in ocean island basalts and carbonatites makes it unlikely that FOZO is the product of melting heterogeneous recycled crustal materials that make up only 4–10% of mantle volume<sup>18,45</sup>. Similar to a recent model by Donnelly *et al.*<sup>44</sup>, we suggest that FOZO represents dominantly primitive or slightly depleted peridotitic mantle (~97–99%), metasomatized by a small amount (1–3%) of a small extent melt (2–6%) of a HIMU component. If the lower mantle is composed of peridotite with 'streaks' of recycled eclogitized oceanic crust (HIMU), then this metasomatism could occur during ascent of plumes, a process recently proposed to explain major-element heterogeneity in picrites and komatiites<sup>46</sup>. In such a mixture, concentrations of noble gases and compatible elements (Ni, Cr and heavy rare-earth elements) in the FOZO source come almost completely from the peridotitic mantle, whereas roughly half to two-thirds of the highly incompatible elements are supplied by the metasomatic HIMU-melt. Thus, water in FOZO plumes is a combination of primitive and recycled water.

# H<sub>2</sub>O in mantle sources of FOZO and HIMU plumes

On the basis of eclogite measurements<sup>47</sup>, subducted oceanic crust

(HIMU source) is low in water, with ~600 p.p.m. H<sub>2</sub>O, ~6 p.p.m. Ce, and H<sub>2</sub>O/Ce = ~100. These data suggest that subducted oceanic crust is efficiently (~97%) dehydrated during subduction (Table 1). In contrast, mantle sources of FOZO plumes have ~750 p.p.m. H<sub>2</sub>O and H<sub>2</sub>O/Ce of ~210 in the Pacific and South Atlantic and ~250 in the North Atlantic (ref. 25, and P. Asimow, C.L. and J.E.D., manuscript in preparation). The high H<sub>2</sub>O/Ce in FOZO plumes cannot be derived from recycled oceanic crust; a significant amount of water must be juvenile, left over from planetary accretion. We believe that it is the presence of this juvenile water that makes FOZO plumes 'wet'.

# Water in EM components

We have shown that recycled oceanic crust is efficiently dehydrated during the subduction process. The lower H<sub>2</sub>O/Ce of EM plumes relative to FOZO plumes indicates that recycled continentally derived components are also efficiently dehydrated. For example, an estimate of globally subducted sediment<sup>48</sup> contains 57 p.p.m. Ce and ~7.3 wt% H<sub>2</sub>O (H<sub>2</sub>O/Ce = 1,280). Reduction of the H<sub>2</sub>O/Ce to <100, lower than the ambient upper mantle of >150, requires >92% dehydration of the water from sediments (Table 1). These dehydrated sediments are still fairly hydrous (<0.57 wt% H<sub>2</sub>O), but addition of only a few per cent sediments to HIMU will only increase the water concentration by 50 to 150 p.p.m. Thus our data suggest that dehydration is efficient for all recycled materials. These estimates of dehydration are consistent with other approaches that have considered mass balance at the subduction zone itself<sup>49</sup>.

Discovery of dense hydrous magnesian silicate phases in laboratory experiments is generally considered consistent with a scheme whereby water may be efficiently transported into the deep mantle during subduction<sup>50</sup>. However, laboratory generation of phases capable of holding significant amounts of water does not constitute evidence that these phases in fact carry significant water to the deep mantle. Our data suggest that much of the recycled material that has passed through the subduction 'factory' has H<sub>2</sub>O/Ce < 100. Thus, as is the case for Pb (refs 21–23), the subduction process effectively partitions water into the exosphere (mantle wedge, crust, ocean and atmosphere), resulting in time-integrated depletion of water relative to other incompatible elements in the recycled lithosphere and accompanying continental-derived materials. Thus, like a well-squeezed sponge, the residual slab and EM plume components are not 'wet', but 'damp'. □

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Table 1 Dehydration efficiency

Rock	Ce (p.p.m.)‡	H <sub>2</sub> O/Ce	H <sub>2</sub> O (wt%)	Dehydration (%)
Crustal components: Pre-subduction				
Atlantic MORB*	12	250	0.3	
Pacific MORB*	14	150	0.2	
Mature oceanic crust*	~6	2,500–5,000	2–3	
Global subducted sediment†	57	1,280	7.3	
Crustal components: Post-subduction				
Mature oceanic crust	~6	~100	0.06§	97
Global subducted sediment	57	<100	<0.57	>92
Mantle components				
DMM*	0.5	200	0.010	
Atlantic FOZO	3	250	0.075	
Pacific FOZO	3.8	200	0.075	
EM#	4	<100	<0.04	

\* GERM (Geochemical Earth Reference Model) database (<http://earthref.org/databases/GERMRD/main.htm>).

† GLOSS (Global Subducting Sediment)<sup>48</sup>.

‡ Represents conservative estimate—some rare-earth elements are lost from subducting lithosphere during subduction.

§ Bulk water concentration in eclogite<sup>47</sup>.

|| Asimow, P., C.L. and J.E.D., manuscript in preparation.

¶ From refs 27 and 30.

# EM sources have Ce contents similar to HIMU sources<sup>6</sup> and slightly greater than FOZO-type sources. EM mantle sources have roughly half as much water as FOZO-type sources (this study).

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