

TRIPLE OXYGEN ISOTOPE CONSTRAINS ON INTERACTIONS BETWEEN PLANETARY INTERIOR AND SURFACE. Xiaobin Cao^{1*}, Huiming Bao¹, Caihong Gao², Yun Liu², Fang Huang³, Yongbo Peng¹, and Yining Zhang², ¹Department of Geology & Geophysics, Louisiana State University, Baton Rouge, LA 70803, USA (*: xcao@lsu.edu), ²State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China, ³CAS Key Laboratory of Crust-Mantle Materials and Environments, School of Earth and Space Sciences, USTC, Hefei 230026, China.

Introduction: Deep mantle is one of the least understood regions of the solid Earth. Ocean island basalts (OIBs) have provided a crucial window to deep mantle's composition, evolution, and interaction between the mantle and the surface layers. Currently, a prevalent model for OIB's formation is the mantle plume hypothesis, in which subducted oceanic crust is evoked to explain observed large compositional variation in OIBs [1]. However, the observed variations may alternatively be explained by variations of oceanic lithosphere thickness and/or fractionation in subduction, partial melting, and fractional crystallization processes [2]. Although sulfur mass-independent fractionation (S-MIF) found in OIBs show that oceanic sediments can survive in subducted oceanic crusts, S-MIF signature is only useful for subducted oceanic crusts at or before the great oxidation event at ~2.3 Ga [3] and cannot be used to determine the exact fraction of subducted oceanic crusts in OIB's mantle source owing to large variations of sulfur isotope compositions in subducted oceanic crust [3].

Here, we propose that triple oxygen isotope compositions ($\Delta^{17}\text{O}$) of olivine are exempted from these uncertainties and can serve as an effective tool in resolving OIB's origin. Our working hypothesis is that high-temperature processes (e.g. >1000°C) cannot shift olivine's $\Delta^{17}\text{O}$ away from that of primitive mantle, but the addition of subducted oceanic crusts to OIB's mantle source will because subducted oceanic sediments and hydrothermally altered oceanic crusts have negative and positive $\Delta^{17}\text{O}$ values, respectively, relative to that of the primitive mantle, due to their interaction with ocean water [4]. We will test this hypothesis by 1) theoretically calculating triple oxygen isotope relationships for related olivine-mineral pairs (i.e. the θ values), with a special interest in high temperatures relevant to olivine formation; and 2) examining published $\Delta^{17}\text{O}$ values in OIB's olivine sampled worldwide.

Methods: Density functional theory was employed to estimate the equilibrium θ values [5]. The $\Delta^{17}\text{O}$ data presented by Greenwood et al. [6] was recalibrated to the primitive mantle, and olivine samples with high $^3\text{He}/^4\text{He}$ ratio from Ofu Island were chosen as the representative of the $\Delta^{17}\text{O}$ in primitive mantle.

Results and discussion: Our calculated results show that the values of equilibrium θ for the related

mineral pairs range from 0.5300 to 0.5303 at temperature ranging from 1000°C to 1300°C (Fig. 1). Given the limited ^{18}O isotope fractionation between olivine and its surroundings (i.e. < 1‰) at these temperatures [7], this range of θ values can only contribute to a change in the $\Delta^{17}\text{O}$ in less than 0.5 ppm or per mag. Therefore, the partial melting and fractional crystallization processes cannot shift the $\Delta^{17}\text{O}$ measurably.

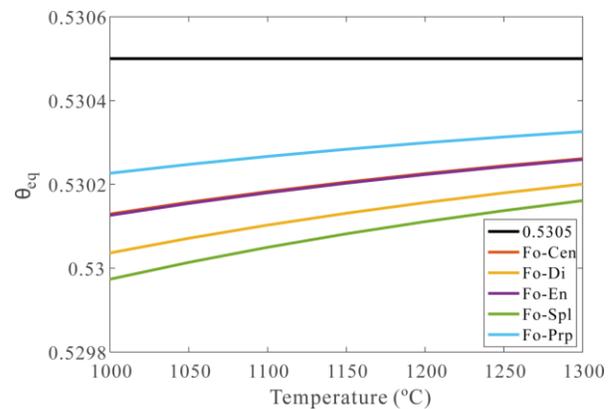


Fig. 1. Calculated equilibrium triple oxygen isotope relationships θ_{eq} for different olivine-mineral pairs at different temperatures above 1000°C. The 0.5305 line is our reference line. Fo, Cen, Di, En, Spl, and Prp refer to Forsterite, Clinoenstatite, Diopside, Enstatite, Spinel, and Pyrope, respectively.

The recalibrated $\Delta^{17}\text{O}_{\text{PM}}$ values for published olivine data range from -13.8 ppm to 15.0 ppm (Fig. 2). The correlation of $\Delta^{17}\text{O}_{\text{PM}}$ values and $^3\text{He}/^4\text{He}$ ratios in olivine samples from the same location (Fig. 2) indicates that the observed small variations of $\Delta^{17}\text{O}_{\text{PM}}$ values are real, even though most of them are smaller than their one standard deviation.

Several mechanisms can cause the small $\Delta^{17}\text{O}_{\text{PM}}$ variation among olivine samples. Olivine samples with high $^3\text{He}/^4\text{He}$ ratios tend to have zero $\Delta^{17}\text{O}_{\text{PM}}$ values (Fig. 2), which indicates that these small $\Delta^{17}\text{O}_{\text{PM}}$ variations are not likely resulted from mantle heterogeneity.

Fresh olivine can hardly survive once it interacts with water due to serpentinization. Therefore, fluid-rock interaction is also not a plausible mechanism for the observed $\Delta^{17}\text{O}_{\text{PM}}$ variations among olivine samples.

If the observed variations of $\Delta^{17}\text{O}_{\text{PM}}$ in olivine samples are caused by mixing between subducted oceanic crusts and primitive mantle, negative and positive $\Delta^{17}\text{O}_{\text{PM}}$ values in olivine samples from Pitcairn Island and from Mauna Loa and Iceland should result from subducted oceanic sediments and hydrothermally altered oceanic crusts, respectively. These interpretations are consistent with previous studies on these OIBs.

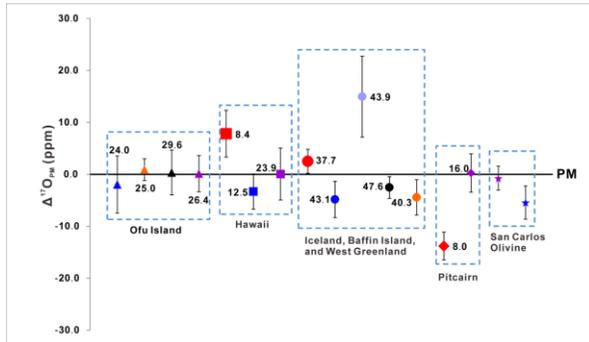


Fig. 2. Paired, recalibrated $\Delta^{17}\text{O}_{\text{PM}}$ value and its corresponding $^3\text{He}/^4\text{He}$ ratio (number close to the data symbol) for individual olivine samples separated from basalts from different locations. All $^3\text{He}/^4\text{He}$ ratios are reported relative to the atmospheric one (i.e. R/R_a). The error bar is given by $1\times\text{SEM}$ (i.e. one standard error of the mean).

Furthermore, the fractions of subducted oceanic crust in the mantle sources of Pitcairn, Mauna Loa, and Iceland lavas are estimated to be $10.4\pm 2.0\%$, $22.3\pm 12.9\%$, and $7.1\pm 6.6\%$, respectively (Fig. 3). The determined fractions of hydrothermally altered oceanic crust for Mauna Loa and Iceland lavas are close to those previous estimates using trace elements.

In addition to these non-zero $\Delta^{17}\text{O}_{\text{PM}}$ values, the olivine samples from Hawaii and Pitcairn plumes can also have zero $\Delta^{17}\text{O}_{\text{PM}}$ values (Fig. 2). There are three possible mechanisms to interpret these zero $\Delta^{17}\text{O}_{\text{PM}}$ values: 1) the subducted oceanic crusts exist locally and do not affect their entire mantle sources; 2) subducted oceanic crusts do exist in their mantle sources but these crusts barely experience hydrothermal alterations; and 3) the $\Delta^{17}\text{O}_{\text{PM}}$ value of part of the subducted oceanic crust is altered to be zero during subduction process. If the latter two cases were true, the $^3\text{He}/^4\text{He}$ values in these olivine samples should have been low, which does not agree with the observation (Fig. 2). Therefore, the first mechanism is the most likely scenario for the zero $\Delta^{17}\text{O}_{\text{PM}}$ values in these olivine samples. In other words, subducted oceanic crust only exists locally in the mantle plume, and is not always sampled by the OIBs. Considering the observed S-MIF in

Pitcairn [8], we conclude that the $\Delta^{17}\text{O}$ heterogeneity generated by subducted oceanic crust can be preserved locally in deep mantle for billions of years.

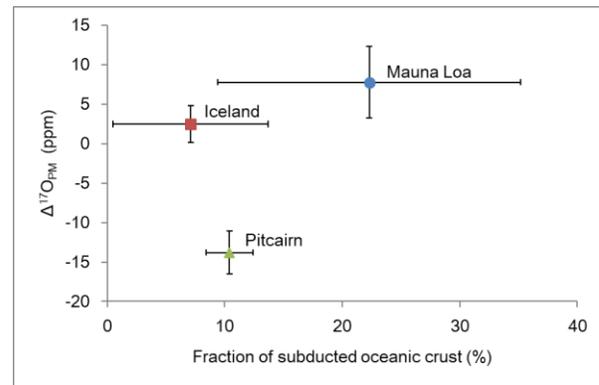


Fig. 3. Estimated fractions of subducted oceanic crust in OIB's mantle source of three different cases. Errors were $1\times\text{SEM}$ value of the $\Delta^{17}\text{O}_{\text{PM}}$.

Implications: Our analysis of the $\Delta^{17}\text{O}_{\text{PM}}$ of olivine from different locations suggests that there had existed a $\Delta^{17}\text{O}$ -homogeneous deep mantle, but the recycling of oceanic crusts has since generated $\Delta^{17}\text{O}$ heterogeneity in mantle. Those $\Delta^{17}\text{O}$ -heterogeneous regions are likely spatially limited. With the addition of $\Delta^{17}\text{O}_{\text{PM}}$ values of olivine, partition of trace elements, stable isotope fractionation, and variation of radiogenic isotopes can be better quantified. This study calls for an effort to improve high-precision $\Delta^{17}\text{O}$ analysis of terrestrial minerals.

Similar approach can be employed to study the mantle and crust interaction beyond Earth, e.g. the Moon and Mars. Although plate tectonics was not developed on these planets, but if crustal assimilation or delamination had occurred during early history, the $\Delta^{17}\text{O}$ will be able to tell.

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