

EVIDENCE FOR MULTIPLE GIANT IMPACTS AND MAGMA OCEANS FROM MANTLE NOBLE GASES. J. M. Tucker¹ and S. Mukhopadhyay¹, ¹Harvard University Department of Earth and Planetary Sciences, Cambridge, MA. jtucker@fas.harvard.edu.

Introduction: Global magma oceans are theorized to result from giant impacts during Earth's accretion. However geochemical evidence requiring a terrestrial magma ocean is scarce [1]. A terrestrial magma ocean is expected to fractionate the noble gases, as the differences in noble gas solubilities are quite large. Equilibration between a magma ocean and proto-atmosphere may therefore leave a detectable signature in the mantle. High $^3\text{He}/^{22}\text{Ne}$ ratios in the mantle have previously been attributed to magma ocean outgassing or ingassing [2-4]. Here, we examine this hypothesis with new noble gas measurements from equatorial Atlantic mid-ocean ridge basalts (MORBs) [5]. We find that the $^3\text{He}/^{22}\text{Ne}$ ratio of the ocean island basalt (OIB) source can be explained by equilibrium ingassing of a primary nebular atmosphere to a magma ocean, and the depleted MORB source was subject to multiple giant impact-induced magma ocean and atmospheric loss episodes.

He/Ne in the MORB source: The equatorial Mid-Atlantic Ridge is characterized by some of the most depleted and enriched MORBs in the entire ocean ridge system in close geographical proximity. Lithophile isotopes were previously characterized [6] and noble gas measurements presented in [5]. Because recent magmatic degassing can fractionate He and Ne, measured $^3\text{He}/^{22}\text{Ne}$ ratios must be corrected for magmatic degassing. We corrected for this through the mantle $^4\text{He}/^{21}\text{Ne}$ production ratio [e.g., 2] and the corrected $^3\text{He}/^{22}\text{Ne}$ ratio reflects the value in the undegassed melt. Given the incompatible nature of He and Ne [e.g., 7,8], at melt fractions corresponding to MORB generation (~8%), partial melting will not fractionate He and Ne. Therefore, the $^3\text{He}/^{22}\text{Ne}$ ratio in the undegassed melt should reflect the mantle source value.

The $^3\text{He}/^{22}\text{Ne}$ ratios in the undegassed equatorial Atlantic MORBs range from ~6 to ≥ 9.7 , which we take as the range in the mantle source value in this region. The most depleted MORBs have the highest $^3\text{He}/^{22}\text{Ne}$ ratios (Figure 1), more extreme than the average MORB value 7.0, recalculated from [2] to $^{20}\text{Ne}/^{22}\text{Ne} = 12.5$. Additionally, primitive plumes have $^3\text{He}/^{22}\text{Ne} \leq 3$ [9,10]. We conclude that the present day mantle has a range of $^3\text{He}/^{22}\text{Ne}$ ratios.

Origin of high $^3\text{He}/^{22}\text{Ne}$: The primordial $^3\text{He}/^{22}\text{Ne}$ incorporated into Earth during accretion is at most 1.5, the solar nebula value. Therefore, some processes must have increased the MORB source $^3\text{He}/^{22}\text{Ne}$ ratio from the primordial value by at least a factor of 6.5. Mechanisms associated with the present style of plate tecton-

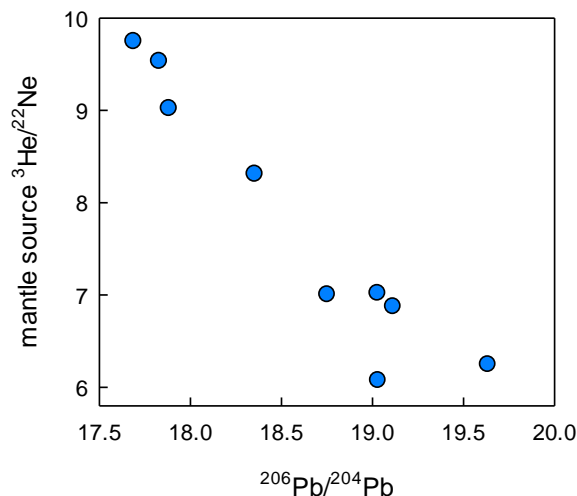


Figure 1 Mantle source $^3\text{He}/^{22}\text{Ne}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ for 9 samples from the equatorial Mid-Atlantic Ridge. The correlation indicates that $^3\text{He}/^{22}\text{Ne}$ variability in MORBs is due to recent mixing between components with variable $^3\text{He}/^{22}\text{Ne}$. The most depleted MORBs have the highest $^3\text{He}/^{22}\text{Ne}$.

ics that can change the mantle $^3\text{He}/^{22}\text{Ne}$ ratio include diffusion, partial melting, and recycling of plates.

Diffusive fractionation between ^3He and ^{22}Ne is not likely to generate the correlation between $^3\text{He}/^{22}\text{Ne}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ (Figure 1) or similar correlations with $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{21}\text{Ne}/^{22}\text{Ne}$. Rather the correlation seen in Figure 1 suggests mixing of two sources, a depleted component with high $^3\text{He}/^{22}\text{Ne}$ (≥ 9.7) and a more enriched component with low $^3\text{He}/^{22}\text{Ne}$ (≤ 3.0).

He and Ne could be fractionated in the mantle by recycling of slabs (comprising the oceanic crust and the residues of partial melting). Mixing the subducting slab could change the $^3\text{He}/^{22}\text{Ne}$ ratio of the mantle over time. We model this process assuming 5% batch melting, the range of partition coefficients of [8], and instantaneous mixing of slabs with the mantle [11]—the most favorable conditions for changing $^3\text{He}/^{22}\text{Ne}$. We also assume that the oceanic crust is degassed of ^3He and ^{22}Ne . We find that it is impossible to change the $^3\text{He}/^{22}\text{Ne}$ of the mantle either from the highest primordial value (1.5) to the OIB value (3) or from the OIB value to the depleted MORB value (Figure 2). Even after 20 mantle overturns, the $^3\text{He}/^{22}\text{Ne}$ increases by at most 7%.

It is conceivable that the oceanic crust is not completely degassed of primordial $^3\text{He}/^{22}\text{Ne}$. However, HIMU (high μ where μ is U/Pb) OIBs that are known

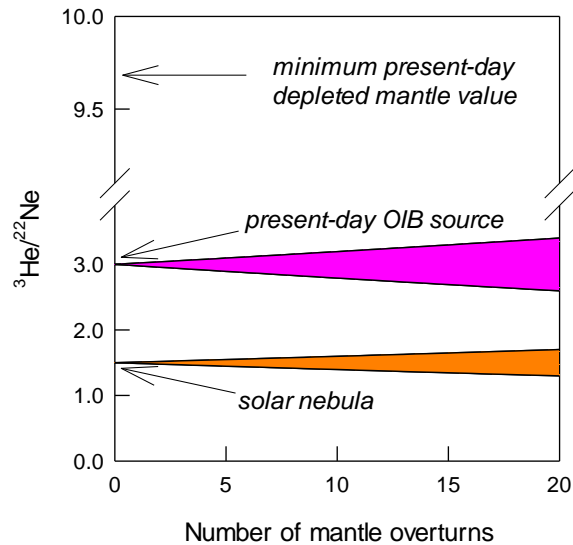


Figure 2 Evolution of the mantle $^3\text{He}/^{22}\text{Ne}$ as a function of recycling fractionated residues of partial melting. The ranges correspond to the 1- σ range of partition coefficients of [8]. Even under the most favorable conditions, the mantle $^3\text{He}/^{22}\text{Ne}$ cannot be significantly changed by this process.

to sample recycled oceanic crust have *low* $^3\text{He}/^{22}\text{Ne}$ ratios, such as 4.6 at the Cook-Austral islands [12]. Hence, recycling oceanic crust cannot increase the $^3\text{He}/^{22}\text{Ne}$ ratio to values of ≥ 9.7 observed for the depleted MORB source. Furthermore, recycling would likely lead to a decrease in mantle $^3\text{He}/^{22}\text{Ne}$ ratios as Ne should be recycled preferentially.

We therefore conclude that high $^3\text{He}/^{22}\text{Ne}$ in the depleted mantle compared to the plume source and the high $^3\text{He}/^{22}\text{Ne}$ of the plume source compared to primordial solar values cannot be due to processes associated with the long-term plate tectonic cycle.

A process that is expected to raise the mantle $^3\text{He}/^{22}\text{Ne}$ is solubility-controlled outgassing or ingassing of a magma ocean [2-4]. As He is more soluble in magmas than Ne, this process can raise the mantle $^3\text{He}/^{22}\text{Ne}$ and create reservoirs with significantly different $^3\text{He}/^{22}\text{Ne}$ ratios.

Magma oceans and high $^3\text{He}/^{22}\text{Ne}$: In equilibrium outgassing or ingassing of a magma ocean, the $^3\text{He}/^{22}\text{Ne}$ ratio of the mantle can increase by at most the ratio of He/Ne solubilities. Experimental determinations of noble gas solubilities in basaltic liquids at 1350–1400 °C yield a solubility ratio of ~ 2 [13,14]. An extrapolation of the ionic porosity model for noble gas solubility [15] to ultramafic liquids at ~ 1800 °C also yields solubility ratios ≤ 3 . OIBs with solar $^{20}\text{Ne}/^{22}\text{Ne}$ ratios have $^3\text{He}/^{22}\text{Ne}$ of ~ 3 [9,10], a factor of 2 higher than the nebular value. We therefore use a value of 2 for the He/Ne solubility ratio.

An equilibrium between a captured nebular atmosphere and magma ocean can account for the increase from the solar nebular $^3\text{He}/^{22}\text{Ne}$ ratio of 1.5 to the OIB source ratio of 3. This is consistent with solar $^{20}\text{Ne}/^{22}\text{Ne}$ ratios in OIB lavas [e.g., 4,10], which also imply a solar nebular ingassing source for OIB noble gases. However the depleted mantle is fractionated by at least $6.5\times$ primordial values, so a single episode of magma ocean ingassing/outgassing cannot account for the high values measured in depleted MORBs.

Raising the depleted mantle $^3\text{He}/^{22}\text{Ne}$ by more than a factor of the He/Ne solubility ratio requires an open system, specifically multiple magma ocean outgassing and atmospheric blow-off episodes. In this scenario, a giant impact must eject the existing atmosphere and create a new magma ocean. The magma ocean then degasses, forming a new atmosphere, and eventually solidifies. Residual noble gases in the magma ocean are fractionated by their solubility ratio. A later giant impact repeats this process. Each such episode raises the mantle $^3\text{He}/^{22}\text{Ne}$ ratio by a factor of 2, requiring a minimum of two or three such giant impacts, with the final episode the Moon-forming impact. We note that even starting with the OIB mantle value of 3 would require multiple magma oceans to generate $^3\text{He}/^{22}\text{Ne}$ ratios of ≥ 9.7 in the depleted MORB source. Modeling has shown that such giant impacts may not necessarily eject the existing atmosphere [16]. However if the Earth were spinning with a 2–3 hour day [17], complete atmospheric ejection through a giant impact may be achieved [18,19].

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