THE FATE OF WATER WITHIN EARTH-LIKE PLANETS AND IMPLICATIONS FOR THE ONSET OF PLATE TECTONICS.

S. M. Tikoo[1] (sonia.tikoo@rutgers.edu), L. T. Elkins-Tanton[2]. [1]Department of Earth & Planetary Sciences, Rutgers University, Piscataway Township, New Jersey 08854, USA [2]School of Earth and Space Exploration, Arizona State University, Tempe, Arizona 85287, USA.

Introduction: Water is thought to be vital for the development of plate tectonics because it lowers viscosities in the asthenosphere and enables subduction. However, the following issue persists: if water is necessary for plate tectonics, but subduction itself hydrates the upper mantle, how is the upper mantle initially hydrated? Here we present models demonstrating that processes associated with magma ocean solidification and overturn may segregate sufficient quantities of water within the Earth's upper mantle to induce partial melting, produce a damp asthenosphere, and thereby facilitate a rapid onset for plate tectonics.

Model framework: Geochemical studies suggest that the Earth likely accreted from chondritic planetesimals (see review in [1]) that may have contained up to 20 wt. % water as evidenced from meteorites [2]. It is likely that volatiles were partially retained through planet formation and therefore that the majority of Earth's water was acquired during accretion. In addition to delivering water, the giant impacts of late accretion created magma lakes and oceans [3], which degassed during solidification to produce a heavy atmosphere [4]. However, some water would have remained in the mantle, trapped within crystallographic defects in nominally anhydrous minerals.

Magma oceans on Earth-sized planets are thought to solidify from the bottom-up because the solidus and adiabat would intersect at depth [3]. Because the magnesium ion is smaller than that of iron, magnesium is preferentially incorporated into mantle silicate minerals during the initial stages of magma ocean solidification. The remaining magma ocean liquid is increasingly enriched with dense iron and incompatible elements, yielding an unstable mantle profile with density radially increasing as solidification progresses from the bottom up. As a result, the solid mantle overturns until it reaches a gravitationally stable configuration [3].

As solidification proceeds from the bottom-up, water is preferentially incorporated up to saturation into late-crystallizing, dense cumulates that are gravitationally unstable. During overturn, these relatively water-rich cumulates sink into the lower mantle (**Fig. 1**). Because lower mantle minerals such as perovskite and magnesiowüstite have water saturation limits 10-100 times lower than upper mantle phases such as olivine and pyroxene, sinking cumulates must undergo dewatering as they enter the lower mantle.

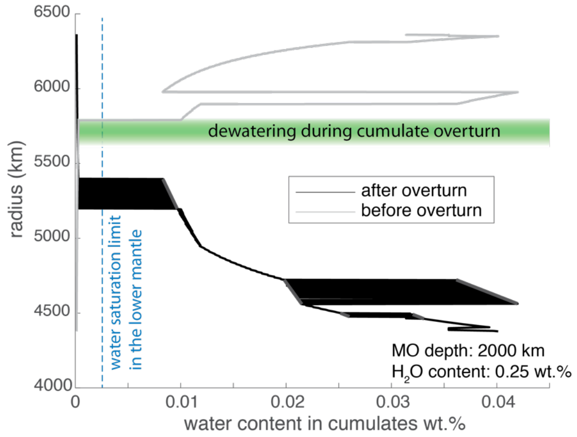

Figure 1: Cumulate mantle density before and after overturn for a 2000-km deep terrestrial magma ocean with an initial water content of 0.25 wt. % at solidus temperatures and a reference pressure of 1 atm. The green highlighted area denotes the lower mantle boundary (i.e., the top of the perovskite stability zone) where dewatering occurs.

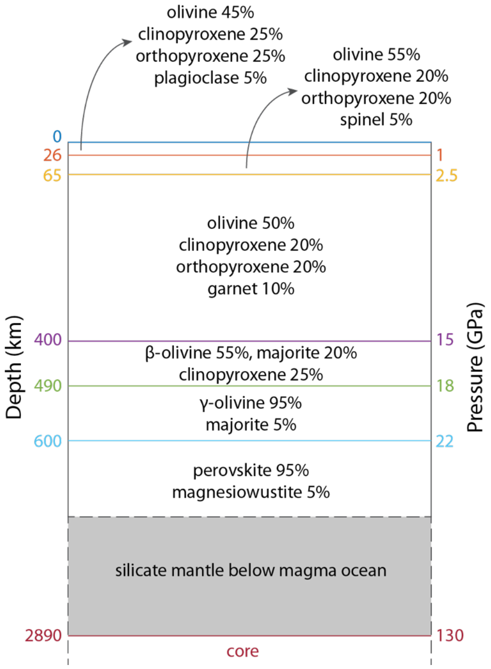

Figure 2: Mineral assemblages and relative abundances assumed to solidify from a terrestrial magma ocean.

We modeled scenarios for terrestrial magma ocean solidification and overturn using initial water contents spanning from 0.001 wt. % to 5 wt. % and magma ocean depths ranging between 250 km and 2800 km using the same code as [4,5]. We assumed that the mantle solidified via fractional crystallization according to specified mineral assemblages (**Fig. 2**) and that water partitioned into nominally anhydrous minerals according to their solid-melt partition coefficients up to saturation (see [6] for details). Our models variably assumed that magma ocean cumulates retained either 0% or 1% interstitial liquids.

Following solidification, each modeled cumulate layer has a unique composition and water content that is tracked by the code. During overturn, we assume that cumulates which sink into the perovskite-magnesiowüstite stability zone will release all water in excess of a defined lower mantle water saturation limit of 2.58×10^{-3} wt. %. We obtained this lower mantle water saturation limit by assuming a lower mantle mineral assemblage of 64% Mg-perovskite, 8% Fe-perovskite, 8% Ca-perovskite, and 20% magnesiowüstite with corresponding water saturation limits for these minerals.

Results and Discussion: We found that magma ocean overturn and the dewatering processes are potentially capable of enriching the upper mantle with up to ~0.1-1 wt. % water, depending on model parameters (**Fig. 3**). Inclusion of interstitial liquids increases the amount of dewatering by a factor of <2. This water would remain in the upper mantle and potentially lower mantle viscosities, induce partial melting, and create a damp asthenosphere. Our results thus predict that the presence of a perovskite-magnesiowüstite stability zone may facilitate an early onset for plate tectonics on >~1 M_E Earth-like planets and super-Earths rather than the development of a stagnant lid regime (which would form on small <0.2 M_E bodies as exemplified by the Moon, Mars, and Mercury). However, it is possible that subsequent events may cause plate tectonic activity to cease, as in the case of Venus where it is possible that impact devolatilization [7], hydrodynamic escape from a runaway greenhouse [8], or planet-wide desiccation from forming too close to the sun [9] may have dehydrated the mantle.

References: [1] Drake M. J., Righter, K. *Nature* 416, p. 39-44. [2] Wood J. A., in: Krot A, Scott E, Reipurth B, editors. Chondrites and the Protoplanetary Disk; Kaua'i, Hawai'i: ASP Conference Series, p. 953-71 (2005). [3] Solomatov, V. S., in: Origin of the Earth and Moon, p. 555 (2000). [4] Elkins-Tanton L. T. *Earth Planet. Sci. Lett.* 271(1-4), p. 181-191 (2008). [5] Brown S., Elkins-Tanton, L. T., Walker, R. *Earth Planet. Sci. Lett.* 408, p. 313-330 (2014). [6] Tikoo S. M., Elkins-Tanton L. T., *Phil. Trans. R. Soc. A* (2017, in press). [7] Davies J. H. *Earth Planet. Sci. Lett.* 268, p. 376-383 (2008). [8] Kasting J. F., Pollack J. B. *Icarus* 53, p. 479-508 (1983). [9] Hamano K., Abe Y., Genda H. *Nature* 497, p.607-610 (2013). [10] Scheinberg A. L., Elkins-Tanton L. T., Zhong S. J. *J. Geophys. Res. Planets* 119, p. 454-67 (2014). [11] Breuer D., Spohn T. *J. Geophys. Res.* 108(E7):5072 (2003).

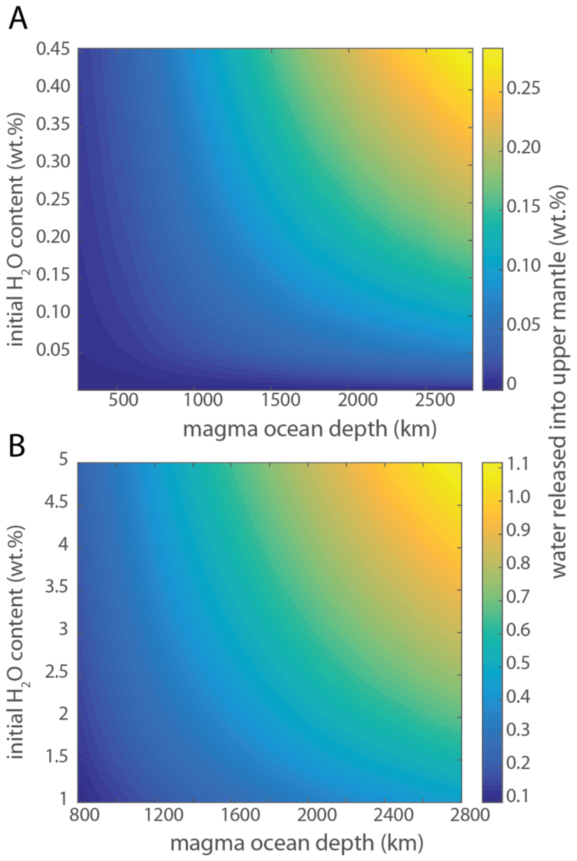

Figure 3: Amount of water released into the upper mantle as a result of the dewatering process for magma oceans ranging in depth between 250 and 2800 km, excluding contributions from interstitial liquids. (A) Calculated water release for initial water contents ranging between 0.001 wt. % and 0.45 wt. % and (B) initial water contents ranging between 1 wt. % and 5 wt. %. Depicted results assumed that cumulates in the top (near-surface) 1% by volume of the magma ocean simulations participated in magma ocean overturn, although solidification and overturn is not directly modeled for this fraction due to its unknown mineral assemblage compositions. The evolution of this top layer is uncertain but possible outcomes are discussed in [10,11]. Therefore, these results represent upper limits on the amount of dewatering produced by magma ocean overturn.