EARLY PLANETARY EVOLUTION: THE CRUST AND MANTLE BEFORE PLATE TECTONICS. L. T. Elkins-Tanton, Massachusetts Institute of Technology, Dept. Earth, Atmospheric, and Planetary Sciences, Cambridge, MA, USA, ltelkins@mit.edu.

Introduction: The Moon-forming impact and other giant accretionary impacts likely formed magma oceans of some depth in the young terrestrial planets. The magma ocean stage forms a clean initial condition for modeling planetary evolution, where we can apply existing knowledge of the physics and chemistry of silicate freezing.

Models that incorporate water in small amounts predict a novel and potentially important redistribution of mantle water content, a "water catastrophe," soon after magma ocean solidification. This event introduces fluid water into the upper mantle and may play a role in the onset of plate tectonics.

Magma ocean solidification: Magma ocean solidification proceeds from the bottom up [1, 2] because pressure effects cause the solidus to first intersect the adiabat at depth. Water is partitioned into the solidifying nominally anhydrous minerals in small quantities (as described by experimental data) and is thus progressively enriched in magma ocean liquids. Water is simultaneously degassed into a growing primordial atmosphere in equilibrium with the saturation limit in the magma ocean liquids [3].

A critical outcome of magma ocean solidification is the development of a density gradient in which density increases with radius. In the nominally anhydrous minerals solidifying out of the magma ocean, most have a crystal site that receives either magnesium or iron. Magnesium is incorporated preferentially, which enriches the remaining magma ocean liquids with iron. Gradually, solidifying minerals are forced to accept more and more iron, producing heavier and heavier solid cumulates as solidification nears the surface.

The gravitationally unstable cumulate mantle will flow via Rayleigh-Taylor instabilities to gravitational stability (Fig. 1). The resulting cumulate mantle has a stable density gradient and is non-convectng for some period of time, but is heterogeneous in composition. Magma ocean processes produce significant silicate differentiation, an aspect of early planetary evolution often overlooked. The time of overturn depends upon a competition between the rate of solidification and the time of onset of gravitational overturn. Overturn time is dependent upon the reciprocal of layer thickness squared, which does not approach the time to solidification until the mantle is almost completely solidified.

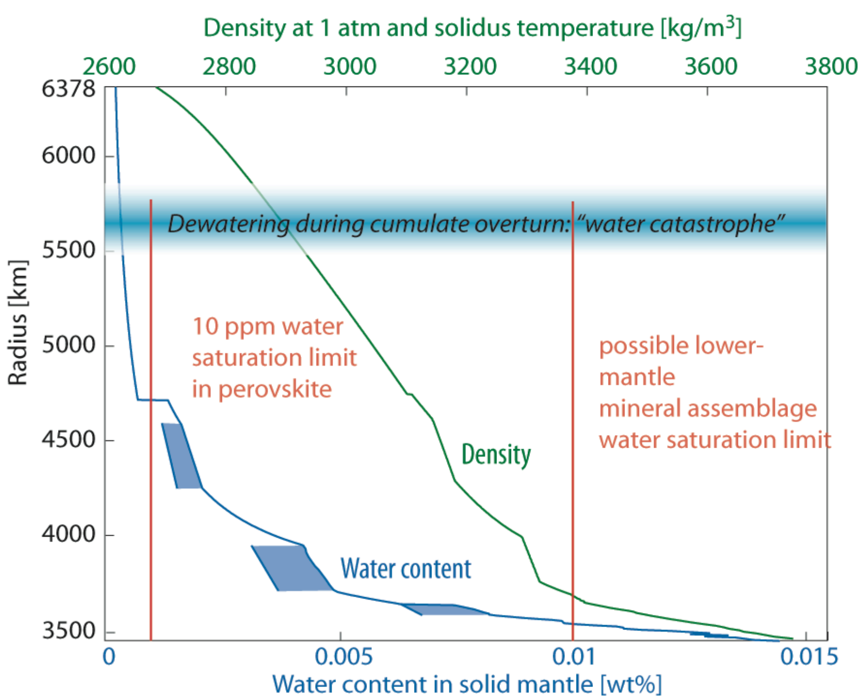


Fig. 1: Density and water content of mantle cumulates following solidification and overturn to stability. As shallow, water-rich cumulates sink into the perovskite stability zone, they may dewater and thus flux the upper mantle with fluids.

The importance of mineralogy: On planets larger than Mars the lower mantle is assumed to consist of perovskite with a small amount of magnesiowüstite, while the upper mantle consists of an expected range of lower-pressure minerals including olivine, pyroxenes, garnet, spinel, or plagioclase; ringwoodite, wadseyite, and majorite (Fig. 2).

On an Earth-sized planet the whole-mantle magma ocean would solidify to produce very dense near-surface cumulates that also contain the bulk of the water held in the solid state, and the bulk of the incompatible elements. In a magma ocean that began with 0.02 wt% water these dense near-surface cumulates contain up to about 150 ppm in this model.

During gravitationally-driven

overturn these densest and most water-rich cumulates sink to the core-mantle boundary.

The "water catastrophe" during overturn: As shallow, dense, wet cumulates begin to sink into the mantle during overturn, they carry with them their water content as they sink into the perovskite stability zone and transform the bulk of their mineralogy into perovskite. The saturation level of water in perovskite is the topic of ongoing research but is thought to lie between 10 and 100 ppm [4-6]. Upper mantle minerals, by contrast, are in some cases able to hold thousands of ppm or more (references in [3] and [4-10]).

Though none of the minerals reach saturation during solidification in magma ocean models that begin with fractions of a weight percent of water, the last cumulates that form near the surface exceed the likely water saturation lvels of perovskite. Thus even in this very low initial water content model, a large fraction of the sinking upper mantle material will be forced to dewater as it crosses the boundary into the lower mantle, leaving its water behind in a rapid flux as it sinks.

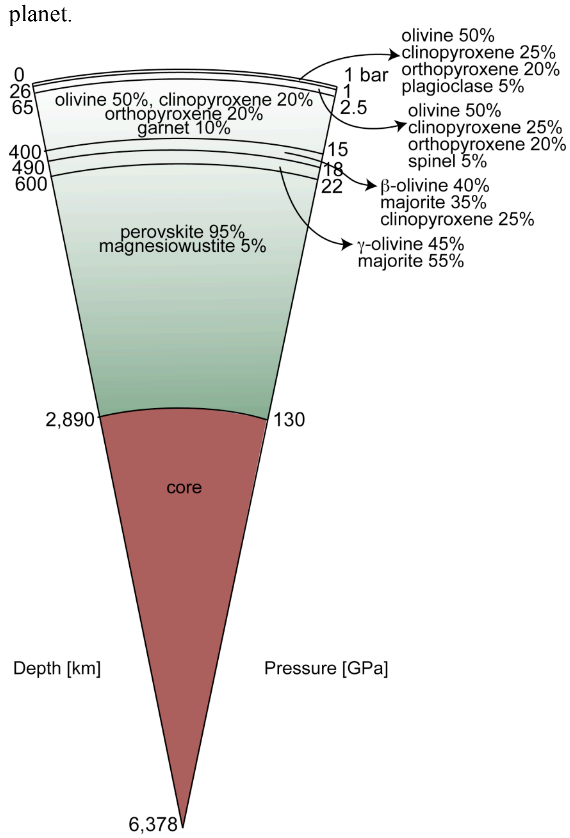
The region likely to initially receive this sudden flux of hydrous fluid during overturn is shown in the blue in Fig. 1; this event will form a kind of "water catastrophe," with potentially large effects on the composition and dynamics of the young terrestrial upper mantle. Movement of water in mantle minerals in the current Earth is being considered (for example, [11]), but this study attempts to track the first movements of water in the solidified planet.

In this low initial water model, the bulk water content of the initial magma ocean is about 2/3 of a present Earth ocean, or about 8×10^{20} kg of water. In this model the "water catastrophe" fluid release into the upper mantle during overturn would consist of between 3 and 5×10^{20} kg of water, depending upon the actual saturation limit of the lower mantle mineral assemblage. This is the equivalent of the addition of 350 to 450 ppm of water to the entire upper mantle, and represents the loss of 75 to 95% of the water originally held by cumulates formed above 600 km. The actual water saturation level of perovskite and the initial water content of the magma ocean will determine the extent of dewatering in each case.

Implications for planetary evolution: Following magma ocean solidification and overturn on planets that are Earth-sized or larger, the planet has formed its earliest basaltic crust through adiabatic melting during overturn, has formed what may be the future D" layer at the core-mantle boundary from compositionally dense cumulates, and in the absence of this water flux has a stably-stratified, non-convecting mantle.

This water catastrophe has the potential to partially melt the upper mantle, to produce an damp asthenosphere, and indeed to encourage convection in an otherwise stably-stratified and non-convecting post-magma ocean mantle. These results imply that planets in which perovskite is stable, that is, planets that are larger than Mars, are perhaps more likely to have an early initiation of plate tectonics, and that larger planets may have more violent and near-surface mantle volatile releases during any overturn event. This water addition, if it initiates or speeds convection, may prevent cooling to form a thick one-plate lithosphere, which would inhibit plate tectonics. Initial mantle convection may therefore be layered, and plate tectonics may begin within tens or hundreds of millions of years of the Moon-forming impact.

Fig. 2: Mineral assemblages in the mantle of an Earth-sized planet.



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