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On the fate of water in the formation of rocky planets

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Rocky planets go through at least one and likely multiple magma ocean stages, produced by the giant impacts of accretion. Planetary data and models show that giant impacts do not dehydrate either the mantle or the atmosphere of their target planets. The magma ocean liquid consists of melted target material and melted impactor, and so will be dominated by silicate melt, and also contain dissolved volatiles including water, carbon, and sulfur compounds.

As the magma ocean cools and solidifies, water and other volatiles will be incorporated into the nominally anhydrous mantle phases up to their saturation limits, and will otherwise be enriched in the remaining, evolving magma ocean liquids. The water content of the resulting cumulate mantle is therefore the sum of the traces in the mineral grains, and any water in trapped interstitial liquids. That trapped liquid fraction may in fact be by far the largest contributor to the cumulate water budget.

The water and other dissolved volatiles in the evolving liquids may quickly reach the saturation limit of magmas near the surface, where pressure is low, but degassing the magma ocean is likely more difficult than has been assumed in some of our models. To degas into the atmosphere, the gases must exsolve from the liquid and form bubbles, and those bubbles must be able to rise quickly enough to avoid being dragged down by convection and re-dissolved at higher pressures. If bubbles are buoyant enough (that is, large enough) to decouple from flow and rise, then they are also dynamically unstable and liable to be torn into smaller bubbles and re-entrained. This conundrum led to the hypothesis that volatiles do not significantly degas until a high level of supersaturation is reached, and the bubbles form a buoyant layer and rise in diapirs in a continuum dynamics sense. This late degassing would have the twin effects of increasing the water content of the cumulates, and of speeding up cooling and solidification of the planet.

Once the mantle is solidified, the timeclock until the start of plate tectonics begins. Modern plate tectonics is thought to rely on water to lower the viscosity of the asthenosphere, but plate tectonics is also thought to be the process by which water is brought into the mantle. Magma ocean solidification, however, offers two relevant processes. First, following solidification the cumulate mantle is gravitationally unstable and overturns to stability, carrying water-bearing minerals from the upper mantle through the transition zone and into the lower mantle. Upon converting to lower-mantle phases, these minerals will release their excess water, since lower mantle phases have lower saturation limits, thus fluxing the upper mantle with water. Second, the mantle will be near its solidus temperature still, and thus its viscosity will be naturally low. When fluxed with excess water, the upper mantle would be expected to form a low degree melt, which if voluminous enough with rise to help form the earliest crust, and if of very low degree, will further reduce the viscosity of the asthenosphere.