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Delivery of volatiles to terrestrial planets during accretion: Setting the stage for plate tectonics

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A persistent problem in planetary science is how and when plate tectonics can begin in planetary evolution. On Earth, plate tectonics is thought to be facilitated by the low-viscosity asthenosphere, which obtains its low viscosity partly through low pressure, and partly through a water content on the order of hundreds of parts per million, likely trapped in the crystal structure of nominally anhydrous silicate minerals. Subduction zones introduce water contents of that magnitude to the mantle that circulates above the sinking oceanic plate, and subduction zones are sometimes cited as the process that hydrates an originally dry planetary interior. Thus there is a chicken-and-egg problem: If a damp asthenosphere is needed for plate tectonics, but plate tectonics itself creates the damp asthenosphere, how does the process initiate?

Despite the existence of a metallic (reduced) core, both the compositions of meteorites and the certainty of radial mixing during accretion suggest that the Earth and other rocky planets accreted with some non-zero water content. Tracking water partitioning between magma ocean fluids and solidifying mantle minerals suggests that the planetary interior could begin with a non-zero water content.

Here we present models for the interior water content of the Earth following accretion, and hypothesize about a dynamic processes that may have sped the development of plate tectonics. On an Earth-sized planet a magma ocean would solidify to produce very dense near-surface solids that also contain the bulk of the water held in the solid state, and the bulk of the incompatible elements. During gravitationally-driven overturn shallow, dense, damp solids carry their water as they sink into the perovskite stability zone and transform the bulk of their mineralogy into perovskite. The last solids that form near the surface exceed the likely water saturation levels of perovskite and will be forced to dewater as they cross the boundary into the lower mantle, leaving water behind in a rapid flux as the dense material sinks.

This event will form a kind of "water catastrophe," and would have the potential to partially melt the upper mantle, to produce a damp asthenosphere, and indeed to encourage convection. 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.