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On the origin of plate tectonics: Thinking outside of the convective box

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From the observational point of view, there is no evidence of plate tectonics on other planets in the Solar System. Remote sensing methods for detecting plate tectonics on exoplanets are yet to be developed and are unlikely to be as robust as the surface observations that were conducted for Venus, Mars, and Mercury. The observational constraints on the tectonics of the early Earth are probably the most important clues to the plate tectonics origin and yet, their interpretations remain ambiguous. Some researchers see a very early start of plate tectonics in the data while others do not exclude a relatively late start. From the theoretical point of view, the absence of plate tectonics is easy to explain and can be considered as a normal state of any rocky or icy body. Two decades ago, both the observational data and theoretical studies led to the reversal of the question “why do other planets not have plate tectonics” to “why does the Earth have plate tectonics”. Since then various theories and numerical models focused on the latter question and investigated how plate tectonics began and what conditions are required for plate tectonics to occur on a planet. In most models the starting state of a planet is a non-plate tectonics regime (e.g. stagnant lid convection) which then transitions to plate tectonics. The forces responsible for the transition can be caused by convective motions below the lithosphere and with thermal (e.g. lithospheric relief) and compositional density variations (e.g. continents) near the surface. The role of the factors involved can be complicated. For example, the crust can both hinder and help plate tectonics. The transition to plate tectonics can also be caused by external factors, such as impacts and tidal forces. Similar to the previous, internal factors, these external factors can also either help or hinder plate tectonics initiation. For example, even though impacts are sometimes considered as a possible cause of plate tectonics, they can create conditions that would hinder plate tectonics initiation later on or stop it in case if plate tectonics was previously initiated by other mechanisms. Plate tectonics could also have emerged from a magma ocean, bypassing the stagnant lid regime. In this scenario plate tectonics is a continuation of convection in the magma ocean. As the magma ocean crystallizes, the surface boundary layer, which has little difficulty to recycle in the liquid magma, eventually transforms into tectonic plates as the crystallizing magma ocean undergoes a transition from turbulent convection controlled by melt viscosity to laminar convection predominantly controlled by solid-state creep. Regardless of the origin of the first episode of plate tectonics, the question of how plate tectonics survived and evolved into a relatively stable regime is a challenge for any of these models and may require a combination of many factors such as asthenosphere, surface oceans and volatile cycling.

Keywords: Plate tectonics, Stagnant lid convection, Giant impacts, Magma oceans, Exoplanets