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The Conditions for Plate Tectonics on Super-Earths: Inferences From Convection Models With Damage

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Within the last decade astronomers detected the first terrestrial exoplanets, allowing the study of super-Earths, rocky exoplanets that are approximately 1-10 Earth masses. Currently, with data from the Kepler mission, nearly 300 super-Earth's have been discovered. One of the most important questions concerning these planets is whether they have plate tectonics, because plate tectonics is thought to be necessary for maintaining a stable climate capable of supporting life. Recent studies using a pseudoplastic rheology reached different conclusions about the propensity for super-Earths to have plate tectonics; one study found that larger planets would be significantly more likely to have plate tectonics, and concludes that super-Earths would be in a plate-tectonic regime [1]; a later study concludes that larger planets would be less likely to have plate tectonics, and predicts stagnant lid convection on super-Earths [2]; still another study finds that the presence of liquid water is the necessary for plate tectonics regardless of planet size, and thus super-Earths will have plate tectonics if they have liquid water [3]. To clarify this debate, we present a comprehensive first-principles analysis of the factors that determine the tectonic regime of a planet using a damage-grainsize feedback mechanism (grain-damage) as opposed to the pseudoplastic rheology. In addition to allowing for weakening due to stresses, grain-damage allows for dormant weak zones and for the dependence of healing on thermal conditions, both effects that the pseudoplastic rheology does not treat.

We use numerical simulations of mantle convection with grain-damage to develop scaling laws for predicting conditions at which super-Earths would have plate tectonics. In particular, the numerical simulations are used to determine how large a viscosity ratio between pristine lithosphere and mantle (μ_l/μ_m) damage can offset to allow mobile (or plate-like) convection. Regime diagrams of μ_l/μ_m versus the damage number (D) show that the transition from stagnant lid to mobile convection occurs for higher μ_l/μ_m as D increases; a similar trend occurs for increasing Rayleigh number. We hypothesize a new criterion for the onset of plate tectonics on terrestrial planets: that damage must reduce the viscosity of shear zones in the lithosphere to a critical value equivalent to the underlying mantle viscosity; a scaling law based on this hypothesis reproduces the numerical results. For the Earth, damage is efficient in the lithosphere and provides a viable mechanism for the operation of plate tectonics. We scale our theory to super-Earths and map out the transition between plate-like and stagnant-lid convection with a "planetary plate-tectonic phase" diagram in planet size-surface temperature space. We find that both size and surface conditions are important, with plate tectonics being favored for larger, cooler planets. This gives a natural explanation for Earth, Venus, and Mars, and implies that plate tectonics on exoplanets should correlate with size, incident solar radiation, and atmospheric composition.

References

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