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Exploring Tectonic Behaviour in Sub- and Super-Earths: A Study of Magmatism and Planetary Mass

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Hidden among the stars, the discovery of exoplanets has broadened our understanding of planetary formation and evolution. The extraordinary diversity of these celestial bodies has revealed just how dramatically they differ from the planets in our Solar System. They exhibit a wide range of characteristics, including variations in mass, host star types, orbital distances, and other physical conditions. Numerous rocky exoplanets have been detected, with super-Earths—planets up to ten times the mass of Earth—being among the most commonly observed. These planets are often considered analogues to Earth, and studying them may offer valuable insights into the nature and evolution of our planet.

Notably, Earth is the only known planet to exhibit plate tectonics, in contrast to other rocky planets in our Solar System, which typically operate under a stagnant lid regime. This unique feature has long intrigued scientists, raising the question of why plate tectonics appears to be exclusive to Earth. By observing and modelling the interior processes of rocky exoplanets of various sizes, we may gain deeper insights into the conditions necessary for plate tectonics and assess their potential presence on other worlds.

Advances in numerical modelling have significantly improved our understanding of tectonic regimes, including the tectonically active "mobile lid" and the inactive "stagnant lid" modes. In addition, other potential regimes, such as the episodic lid, plutonic-squishy lid, and sluggish lid, have been proposed, though they remain unconfirmed by direct observation. The recognition of these diverse tectonic behaviours has sparked interest in exploring how factors like planetary mass influence the likelihood of plate tectonics, or whether alternative regimes become more probable. Although this topic has been previously investigated, findings have often been inconsistent. Furthermore, many existing studies overlook factors such as mantle melting, crustal production, and the role of intrusive magmatism.

In this study, we employ the mantle convection code StagYY to model generic sub-Earth and super-Earth planets using a 2D spherical annulus geometry. Building on previous work, we incorporate magmatic processes, allowing for crustal formation through both intrusive and extrusive mechanisms. The model includes a simplified treatment of magmatism, with the ratio of intrusion to extrusion adjustable from Earth-like values to more extreme scenarios. The primary aim is to assess the likelihood of plate tectonics as a function of planetary mass and to investigate alternative tectonic regimes that may arise on rocky planets such as sub-Earths and super-Earths. Key parameters explored include planetary mass (ranging from 0.5 to 2 Earth masses), surface yield stress, and the intrusion-to-extrusion magmatism ratio.

Our models indicate that the tendency for a planet to enter the mobile lid regime at low surface yield stresses is only weakly dependent on planetary mass. In contrast, variations in the proportion of melt that is intruded versus extruded play a significant role at higher surface yield stresses. Specifically, the plutonic-squishy lid regime emerges under conditions of high intrusion efficiency combined with high yield stress, while the stagnant lid regime occurs at high extrusion efficiency and high yield stress. A particularly noteworthy outcome is the emergence of an episodic-squishy lid regime at intermediate yield stresses, characterised by periodic transitions between a mobile lid and a plutonic-squishy lid state.

Future research will involve implementing an alternative approach to model intrusive magmatism within the code, as well as exploring the impact of surface temperature on both surface and interior processes. This work not only aims to advance our understanding of planetary geodynamics but also holds significant relevance for assessing the tectonic and thermal evolution of rocky exoplanets.