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Mantle dynamics and plate tectonics on super-Earths: Effect of rheology

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The discovery of extra-solar "super-Earth" planets with terrestrial composition and sizes up to twice that of Earth has prompted interest in their possible lithosphere and mantle dynamics and evolution. Plate tectonics is sometimes thought to be essential for the development of life on a planet. Simple scalings [1,2] demonstrate that other things being equal, super-Earths are equally likely or more likely than an equivalent Earth-sized planet to be undergoing plate tectonics. In Earth, viscosity and thermal conductivity increase with depth (pressure) while thermal expansivity decreases, resulting in lower convective vigour and large-scale features in the deep mantle. The pressure at the core-mantle boundary (CMB) of a ten Earth mass super-Earth is about ten times the pressure at Earth's CMB, so if these trends continued to higher pressure then a super-Earth's deep mantle would have a very low effective Rayleigh number and very sluggish or no convection. Two developments, however, suggest that the viscosity does not become as high as first expected. (i) The mantle of a super-Earth is made mostly of post-perovskite (PPv), which according to calculations using density functional theory (DFT) [3] has a 2-3 orders of magnitude lower viscosity that perovskite. We have extended these DFT calculations to pressures up to 1 TPa, finding that the activation volume for diffusion creep becomes very low at high pressure, although for the largest super-Earths the deep mantle viscosity can become very high. (ii) At very high pressures, deformation by intersticial diffusion may become more effective than by vacancy diffusion, possibly even causing in a decrease of viscosity with pressure along an adiabat [4]. Here we use plausible rheological parameters for PPv, either from DFT calculations or from scaling arguments [4] in numerical simulations of mantle and lithosphere dynamics planets with up to ten Earth masses. The models assume a compressible anelastic approximation that includes the depth-dependence of material parameters, and is solved using StagYY [5]. Plastic yielding at low pressures facilitates plate-like lithospheric behaviour. Initial results confirm the likelihood of plate tectonics on super-Earths and show some novel behaviours that will be discussed. Future models should also account for the influence of widespread deep-mantle melting that may persist for billions of years, similar to [6].

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