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The effect of melting and crustal production on plate tectonics on terrestrial planets

Diogo L Lourenço and Paul J Tackley
ETH Zürich, Institute of Geophysics, Department of Earth Sciences, Zürich, Switzerland (diogo.lourenco@erdw.ethz.ch)

Within the Solar System, Earth is the only planet to be in a mobile-lid regime, whilst it is generally accepted that all the other terrestrial planets are currently in a stagnant-lid regime, showing little or no surface motion. A transitional regime between these two, showing episodic overturns of an unstable stagnant lid, is also possible and has been proposed for Venus (Armann and Tackley, JGR 2012).

Using plastic yielding to self-consistently generate plate tectonics on an Earth-like planet with strongly temperature-dependent viscosity is now well-established, but such models typically focus on purely thermal convection, whereas compositional variations in the lithosphere can alter the stress state and greatly influence the likelihood of plate tectonics. For example, Rolf and Tackley (GRL, 2011) showed that the addition of a continent can reduce the critical yield stress for mobile-lid behaviour by a factor of around 2. Moreover, it has been shown that the final tectonic state of the system can depend on the initial condition (Tackley, G3 2000 – part 2); Weller and Lenardic (GRL, 2012) found that the parameter range in which two solutions are obtained increases with viscosity contrast.

We can also say that partial melting has a major role in the long-term evolution of rocky planets: (1) partial melting causes differentiation in both major elements and trace elements, which are generally incompatible (Hofmann, Nature 1997). Trace elements may contain heat-producing isotopes, which contribute to the heat loss from the interior; (2) melting and volcanism are an important heat loss mechanism at early times that act as a strong thermostat, buffering mantle temperatures and preventing it from getting too hot (Xie and Tackley, JGR 2004b); (3) mantle melting dehydrates and hardens the shallow part of the mantle (Hirth and Kohlstedt, EPSL 1996) and introduces viscosity and compositional stratifications in the shallow mantle due to viscosity variations with the loss of hydrogen upon melting (Faul and Jackson, JGR 2007; Korenaga and Karato, JGR 2008).

We present a set of 2D spherical annulus simulations (Hernlund and Tackley, PEPI 2008) using StagYY (Tackley, PEPI 2008), which uses a finite-volume scheme for advection of temperature, a multigrid solver to obtain a velocity-pressure solution at each timestep, tracers to track composition, and a treatment of partial melting and crustal formation. We address the question whether melting-induced crustal production changes the critical yield stress needed to obtain mobile-lid behaviour as a function of governing parameters.

Our results show that melting and crustal production strongly influence plate tectonics on terrestrial planets. For the same parameters the use of a treatment for melting and crustal production facilitates breaking the stagnant-lid, replacing it with episodic-lid; however, a smoothly evolving mobile lid can also be replaced by episode-lid. Several factors can play a role on these, namely lateral heterogeneities, differences in the lid thickness and internal planetary temperatures induced by melting and crustal production.