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Melting-induced crustal production helps plate tectonics on Earth-like planets

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Within our Solar System, Earth is the only planet to be in a mobile-lid regime. It is generally accepted that the other terrestrial planets are currently in a stagnant-lid regime, with the possible exception of Venus that may be in an episodic-lid regime (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 two. 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 of whether melting-induced crustal production changes the critical yield stress needed to obtain mobile-lid behaviour (plate tectonics).

Our results show that melting-induced crustal production strongly influences plate tectonics on Earth-like planets by strongly enhancing the mobility of the lid, replacing a stagnant lid with an episodic lid, or greatly extending the time in which a smoothly evolving mobile lid is present in a planet. Finally, we show that our results are consistent with analytically predicted critical yield stress obtained with boundary layer theory, whether melting-induced crustal production is considered or not.