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Plutonic-squishy lid: a new global tectonic regime generated by intrusive magmatism on Earth-like planets

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It is now well established that compositional variations in the lithosphere can alter the stress state and greatly influence the likelihood of plate tectonics. Mechanisms that have been found to facilitate plate tectonics include: water circulation [Regenauer-Lieb et al., Science 2001; Dymkova and Gerya, GRL 2013], presence of continents [Rolf and Tackley, GRL 2011], and melting [Korenaga, GJI 2009; Armann and Tackley, JGR 2012]. In a recent work by Lourenço et al. [EPSL 2016], it has been shown that Earth-like plate tectonics is more likely to occur in planets that can produce a crust of variable thickness and density through melt extraction from the mantle. The authors employed a first-order approximation by assuming that all magmatism was extrusive. However, volumes of intruded magmas are observed to be around 4− 9 times more present on Earth than erupted magmas [Crisp, J. Volcanol. Geotherm. Res. 1984]. Therefore, intrusive magmatism is thought to play a role in the dynamics of the lithosphere on Earth [Cawood et al., Geol. Soc. Am. Bull. 2013] and other Earth-like planets.

We extend the work of Lourenço et al. [EPSL 2016] by taking into account intrusive magmatism, and systematically investigate the effect of plutonism, in conjuction with eruptive volcanism, i.e. we study the effect of intruding hot magma at the base of the crust, in conjunction with erupting it to the surface where it cools down quickly and piles up on top of previously erupted material. We present a set of 2D spherical annulus simulations of thermo-compositional global mantle convection using StagYY [Tackley, PEPI 2008], which uses a finite-volume discretization of the governing compressible anelastic Stokes equations. Tracers are used to track composition and to allow for the treatment of partial melting and crustal formation. A direct solver is employed to obtain a solution of the Stokes and continuity equations, using the PETSc toolkit. The heat equation is solved in two steps: advection is performed using the MPDATA scheme and diffusion is then solved implicitly using a PETSc solver.

Results show that for high intrusion efficiencies (i.e. dominance of intrusion versus extrusion) a new tectonic regime, named “plutonic-squishy lid”, exists. This regime is characterized by a set of strong plates separated by warm and weak regions generated by plutonism. Eclogitic drippings and lithospheric delaminations often occur around these weak regions. These processes lead to significant surface velocities, even if subduction is not active. Furthermore, we show that intrusive magmatism has a first-order effect on mantle cooling for planets with no subduction in their history: it can cool the mantle more efficiently than volcanic eruptions, especially if the partition of heat-producing isotopes into the melt phase is less efficient. These two studies demonstrate that the evolution and internal state of a planet are not only conditioned by rheology and boundary conditions, but also depend strongly on plutonic and eruptive processes associated with melting, and the relative importance of them.