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Plutonic-squishy lid and beyond: implications of intrusive magmatism and characterization of a new global-tectonic regime 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. [2016] by taking into account intrusive magmatism, and systematically investigate the effect of plutonism, in conjugation with eruptive volcanism. 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 three common convection regimes are usually reached in simulations when using a visco-plastic rheology: stagnant-lid regime (a one-plate planet), episodic lid (where the lithosphere is unstable and frequently overturns into the mantle), and mobile-lid regime (similar to plate tectonics). At high intrusion efficiencies, we observe and characterise a new additional regime called here “plutonic-squishy lid”. This regime is characterised by a set of strong plates separated by warm and weak regions due to 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. The location of plate boundaries is strongly time-dependent and mainly occurs in magma intrusion regions. This regime is also distinctive because it generates a thin lithosphere, which results in high conductive heat fluxes and lower internal temperatures when compared to a stagnant lid. The plutonic-squishy-lid regime has the potential to be applicable to the Archean Earth and Venus, as it combines elements of both protoplate tectonic and vertical tectonic models, such as horizontal plate motion and reprocessing of the lithosphere for the former, and lithospheric diapirism, volcanism, and basal delamination for the later.