Geophysical Research Abstracts
Vol. 16, EGU2014-12455, 2014
EGU General Assembly 2014

The effect of plumes and a free surface on mantle dynamics with continents and self-consistent plate tectonics

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Rolf et al. (EPSL, 2012) and Coltice et al. (Science, 2012) investigated the thermal and dynamical influences of continents on plate tectonics and the thermal state of Earth's mantle, but they did not explicitly consider the influence of mantle plumes. When present, strong mantle plumes arising from the deep mantle can impose additional stresses on the continents, thereby facilitating continental rifting (Storey, Nature 1995; Santosh et al., Gondwana Research 2009) and disrupting the supercontinent cycle (Philips and Bunge, Geology 2007). In recent years, several studies have characterized the relation between the location of the plumes and the continents, but with contradicting observations. While Heron and Lowman (GRL, 2010; Tectonophysics, 2011) propose regions where downwelling has ceased (irrespective of overlying plate) as the preferred location for plumes, O'Neill et al. (Gondwana Research, 2009) show an anti-correlation between the average positions of subducting slabs at continental margins, and mantle plumes at continental/oceanic interiors.

Continental motion is attributed to the viscous stresses imparted by the convecting mantle and the extent of this motion depends on the heat budget of the mantle. Core-mantle boundary (CMB) heat flux, internal heating from decay of radioactive elements, and mantle cooling contribute to this heat budget. Out of these sources, CMB heat flux is not well defined; however, the recent determination that the core's thermal conductivity is much higher than previously thought requires a CMB heat flow of at least 12 TW (de Koker et al., PNAS 2012; Pozzo et al., Nature 2012; Gomi et al., PEPI 2013), much higher than early estimates of 3-4 TW (Lay et al., Nature 2008). Thus, it is necessary to characterize the effect of increased CMB heat flux on mantle dynamics.

In almost all mantle convection simulations, the top boundary is treated as a free-slip surface whereas Earth's surface is a deformable free surface. With a free-slip boundary condition, the uppermost part of the model is not allowed to move vertically. In contrast, a free surface boundary condition allows for the development of topography and leads to realistic single-sided (asymmetric) subduction (Crameri et al., GJI 2012; Crameri et al., GRL 2012). A free-slip surface may also create incorrect stresses in the model continents, forcing them to spread horizontally along the boundary to minimize the gravitational potential. This is something we aim to test here.

Here, we test (i) the impact of increased basal heating on mantle dynamics with continents and self-consistent plate tectonics, including whether plumes prefer to develop under continents; (ii) the influence of a free surface on continents in the context of self-consistent plate tectonics. The existing model from Rolf et al. (EPSL 2012) is developed further but with weaker continents. A 'sticky-air' approach is used, in which a low density and a small viscosity fluid layer is added to the top of the model. We study these using StagYY code (Tackley, PEPI 2008), which uses a finite-volume discretization, a multigrid solver to obtain a velocity-pressure solution at each timestep on a staggered grid and tracers to track composition.