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The role of buoyancy-driven flow at the lithosphere-asthenosphere boundary: from mid-ocean ridge to old sub-lithosphere models

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The classic definition of plate tectonics suggests that mid-ocean ridges (MORs) are places of passive mantle upwelling driven by plate divergence, and that the oceanic lithosphere forms by conductive cooling away from the ridge. This model predicts the symmetry of the partially-molten region beneath the ridge axis, and the lithosphere thickening with age (i.e., half-space cooling model). New and classic observations show some inconsistency with these predictions. Here we present dynamic, two-phase flow numerical models of MORs that reconcile theory and observations by incorporating buoyancy-driven flow associated with temperature, composition and porosity.

First, geophysical observations at various MOR segments indicate strong asymmetry in melt production, upwelling and seamount distribution across the axis at fast spreading centers such as the MELT region (Melt Seismic Team, 1998), intermediate-spreading centers such as Juan de Fuca Ridge (Bell et al., 2016) and the Mid-Atlantic Ridge (Wang et al., 2020), and slow-spreading centers such as the Mohns Ridge (Johansen et al., 2019). Passive flow models cannot explain this asymmetry, as they require unrealistically large forcing (Toomey et al., 2002).

Second, both seismic and electromagnetic studies have inferred variations in the lithosphere-asthenosphere boundary (LAB) and plate thickness that do not monotonically increase with age (e.g., Rychert et al., 2020). Sublithospheric small-scale convection (SSC) is generally the preferred explanation of these oscillations (e.g., Parsons and McKenzie, 1978, Likerman et al., 2021). However, seismic anomalies cannot be explained using solely solid-state thermal variations. While other mechanisms have been proposed to match the sharp discontinuities in seismic data, small amounts of melt (1-5.5%) could be the most straightforward explanation (Rychert et al., 2021). Sub-plate partial melt could also explain the cause of intraplate volcanism or petit-spot volcanoes observed on the outer rise in some subduction centers (Hirano et al., 2006).

We show that melting-induced buoyancy effects may provide an explanation for both the asymmetric distribution of melt beneath the axis and LAB variations. Here, we extend our 2D mid-ocean ridge calculations to incorporate chemical (residue depletion) and thermal buoyancy, in order to investigate how the dynamics of melt generation and migration may influence small-scale convection at the LAB.

We run two types of models: closer to the ridge axis, where melt is generated over an extended region, and further away from the axis, where active flow may induce small amounts of partial-melting. Results show that MOR models with both chemical and porous buoyancy are sensitive to background forcing and can readily induce asymmetry and small-scale, time-dependent convection beneath the axis. Melting and crystallization of enriched material leads to a dynamic LAB closer to the ridge axis. Models of older oceanic LAB are more susceptible to the influence of thermal instabilities, which can erode the lithosphere and limit the base of the ocean lithosphere from cooling.

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