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The role of small-scale convection on the formation of volcanic passive margins

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Volcanic passive margins (VPMs) are areas of continental rifting where the amount of newly formed igneous crust is larger than normal, in some areas up to 30 km. In comparison, magma-poor margins have initial oceanic crustal thicknesses of less than 7 km (Simon et al., 2009; Franke, 2012). The mechanism for the formation of these different types of margins is debated, and proposed mechanisms include: 1) variation in rifting speed (van Wijk et al., 2001), variation in rifting history (Armitage et al., 2010), enhanced melting from mantle plumes (e.g. White and McKenzie, 1989), and enhanced movement of mantle material through the melting zone by sublithospheric small-scale convection (SSC) driven by lithospheric detachments (Simon et al., 2009). Understanding the mechanism is important to constrain the petroleum potential of VPM.
In this study, we use a numerical modelling approach to further elaborate the effect of SSC on the rate of crust production during continental rifting. Conceptually, SSC results in patterns of upwelling (and downwelling) mantle material with a typical horizontal wavelength of a 100 to a few 100 km (van Hunen et al., 2005). If occurring shallowly enough, such upwellings lead to decompression melting (Raddick et al., 2002). Subsequent mantle depletion has multiple effects on buoyancy (from both latent heat consumption and compositional changes), which, in turn, can affect mantle dynamics under the MOR, and can potentially enhance SSC and melting further. We use two- and three-dimensional Cartesian flow models to examine the mantle dynamics associated with continental rifting, using a linear viscous rheology (in addition to a semi-brittle stress limiter to localize rifting) in which melting (parameterized using (Katz et al., 2003)) leads to mantle depletion and crust accumulation at the surface. The newly formed crust is advected away with the diverging plates.
A parameter sensitivity study of the effects of mantle viscosity, spreading rate, mantle temperature, and a range material parameters have indicated the following results. Decompression melting leads to a colder (from consumption of latent heat of melting) and therefore thermally denser, but compositionally more buoyant residue. The competition between thermal and compositional buoyancy determines the mantle dynamics after rifting initiation. For a mantle viscosity $> \sim 10^{22}$ Pa s, no SSC occurs, and a uniform 7-8 km-thick oceanic crust forms. For mantle viscosity $< \sim 10^{21}$ Pa s, SSC might be vigorous and can form passive margins with a crustal thickness > 10-20 km. If thermal density effects dominate, a convection inversion may occur for low mantle viscosities, and mantle downwellings underneath the rift/ridge area can result in a significant upwelling return flow that enhances further decompression melting, and can create VPMs. Such dynamics could also explain the continent-dipping normal faults that are commonly observed at VPMs. After the initial rifting phase, the crustal thickness reduces significantly, but not always to a uniformly thick 7-8 km, as would be appropriate for mature oceanic basins.