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Numerical experiments of volcanic dominated rifts and passive margins

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Continental rifting is driven by plate tectonic forces (passive rifting), thermal thinning of the lithosphere over a hotspot (active rifting), or a combination of the two. Successful rifts develop into passive margins where pre-drift stretching is accompanied by normal faulting, clastic sedimentation, and various degrees of magmatism. The structure of volcanic passive margins (VPM) differs substantially from margins that are dominated by sedimentation. VPMs are typically narrow, with a lower continental crust that is intruded by magma and can flow as a low-viscosity layer. To investigate the role of the deep crust in the early development of VPMs, we have developed a suite of 2D thermomechanical numerical experiments (Underworld code) in which the density and viscosity of the deep crust and the density of the rift basin fill are systematically varied.

Our experiments show that, for a given rifting velocity, the viscosity of the deep crust and the density of the rift basin fill exert primary controls on early VPM development. The viscosity of the deep crust controls the degree to which the shallow crust undergoes localised faulting or distributed thinning. A weak deep crust localises rifting and is efficiently exhumed to the near-surface, whereas a strong deep crust distributes shallow crust extension and remains buried. A high density rift basin fill results in gravitational loading and increased subsidence rate in cases in which the viscosity of the deep crust is sufficiently low to allow that layer to be displaced by the sinking basin fill. At the limit, a low viscosity deep crust overlain by a thick basalt-dominated fill generates a gravitational instability, with a drip of cool basalt that sinks and ponds at the Moho. Experiment results indicate that the deep crust plays a critical role in the dynamic development of volcanic dominated rifts and passive margins. During rifting, the deep continental crust is heated and readily responds to solicitations of the shallow crust (rooting of normal faults, exhumation of the deep crust in normal fault footwalls).

Gravitational instabilities caused by high density rift infill similar to those observed in our numerical experiments may be present in the Mesoproterozoic (∼1100 Ma) North American Midcontinent Rift System (MRS). The MRS is a failed rift that is filled with >20 km of dominantly basaltic volcanic deposits, and therefore represents an end member VPM (high density basin fill) where the initial structure of a pre-drift VPM is preserved. Magmatism occurred in two pulses over <15 Ma involving deep mantle melting first (>150 km), then shallow melting (40-70 km). Post-rift subsidence accumulated up to 10 km of clastic sediments in the center of the basin. Evidence of cool, dense rocks sinking into a low-viscosity deep crust as predicted in our numerical experiments may be present in the western arm of the MRS, where crustal density analyses suggest the presence of dense bodies (eclogite) at the base of the crust.