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Systematic numerical analysis of modes of deformation localisation during extension of continental lithosphere

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Rift basin formation and deep crustal flow are dynamically competing processes that strongly influence the mode of deformation localisation during extension of continental lithosphere. Both processes involve vertical mass transport that can accommodate space created during rifting, thereby affecting the strength profile of the lithosphere, the timing of rift-to-drift transition (crustal rupture), and the localisation of extension. We investigate the dynamic interaction between infilling of rift basins and flow of ductile crust via a suite of 2D numerical experiments under lithospheric extension (1-2 cm/yr̂1), where the thickness of the crust (40-km, 60-km), the viscosity of the deep crust (weak, intermediate, strong), and the density of rift infill (2620 – 2980 kg/m̂3) are systematically varied.

Experiments with a 40-km thick crust exhibit thinning/necking of the lithosphere. The mechanism by which the lithosphere is deformed varies between two end member modes: (1) experiments with a weak deep crust exhibit lateral and vertical flow of the deep crust, a maximum basin depth that is strongly correlated with the density of rift infill (denser = deeper), and crustal rupture at 40% extension; (2) experiments with a strong deep crust exhibit formation of a conjugate deformation zones that cross the entire lithosphere (i.e. graben structure), a triangular basin with a maximum depth that is weakly correlated with the density of rift infill, and crustal rupture at 33% extension. Experiments with a 60-km thick crust exhibit crustal rupture only after >55% extension. Experiments with a weak deep crust exhibit significant flow of low-viscosity crust that forms a metamorphic core complex, which suppresses significant sedimentation. However, high-density basin infill may result in a rapid gravitational instability, with dense basin fill sinking diapirically into the deep crust and resulting in a basin depth of <2 km to >20 km (low density to high density). In contrast, experiments with a strong deep crust exhibit a graben structure and a fault-bounded basin, similar to that observed in corresponding experiments with a 40-km crust. Experiments with an intermediate viscosity deep crust display mixed behaviour in which the localisation of strain along conjugate faults is offset by crustal flow, resulting in delayed rift-to-drift transition in experiments with both 40-km and 60-km crustal thickness.

Our results illustrate that the viscosity of the deep crust exerts a first-order control on the accommodation of extension in continental lithosphere and the timing of the rift-drift transition. The different modes of lithosphere extension provide a suite of predictable thermal structures and strain rate distributions that help understand shear zone patterns, crustal metamorphism, and mantle serpentinisation.