Are complex rift patterns the result of interacting crustal and mantle weaknesses, or of multiphase rifting? An analogue modelling study

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During extension of the continental lithosphere, deformation often localizes along pre-existing weaknesses originating from previous tectonic phases. When simulating such structures with analogue or numerical methods, modellers often focus on either crustal or mantle heterogeneities. By contrast, here we present results from 3D analogue models to test the combined effect and relative impact of (differently oriented) mantle and crustal weaknesses on rift systems.

Our model set-up involves a rigid base plate fixed to a mobile sidewall. When this sidewall moves outward, the edge of the base plate induces a “velocity discontinuity” (VD) that acts as an upper mantle fault/shear zone in a strong upper mantle. The VD is either parallel to the model axis, or 30° oblique. On top of this base plate, we apply a viscous layer representing the ductile lower crust, followed by a sand cover that simulates the brittle upper crust. Crustal weaknesses were either imposed by implementing “seeds” (i.e. ridges of viscous material at the base of the sand layer), or by pre-cutting the sand. Similar to the basal plate edge, we apply different crustal weakness orientations as well.

Without weaknesses in the model crust, an axis-parallel VD forms an axis-parallel rift basin above along the VD. When adding oblique seeds, they strongly localize deformation, creating a series of obliquely oriented graben. Yet the VD still induces faulting along the model axis, leading to the development of offset axial graben as well. Pre-cut faults also localize deformation but are less dominant than the seeds. As a result, the VD has more control and the axial rift structures are much more pronounced. In the oblique VD case, the reference model develops a series of en echelon graben along the VD. Axis-parallel seeds strongly localize faulting, to such a degree that the effect of the VD is very much overruled. Pre-cut faults allow more influence from the VD, but still dominate the system. Doubling the extension rate increases the strength of the viscous layer, enhancing coupling between the VD and sand cover, so that a series of en echelon graben crosscutting the seed-induced structures develop.

We find that the orientation and relative weakness of inherited weaknesses in the mantle and crust, as well as extension rates control subsequent rift structures. These structures and their
relative evolution can be complex due to the interplay of the above factors, and importantly, all
develop under the same pure shear extensional boundary condition. Our results show that very
differently oriented rift structures can form during one phase of extension without the need to
invoke multiple rift phases. Furthermore, coupling can change over time due to changes in
extension velocity or gradual thinning of the lower crust, thus affecting rift evolution. These
findings provide a strong incentive to reassess the tectonic history of various natural examples.