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Is there a speed limit for the thermal steady-state assumption in continental rifts?

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Data-driven thermostructural modelling of the lithosphere is a key approach to deduce the subsurface temperature field and rheological state of crust and mantle by integrating gravity, seismic, seismological, and lithological data sets. Such predictive models are mostly based on the assumption that the lithospheric temperature field resides in a thermal steady-state which is well-justified within non-deforming plate interiors. However, the validity of this assumption must be limited when considering active plate boundaries where the temperature field is affected by the advection of heat during lithosphere deformation, a process that we hypothesize to exert more control at higher deformation rates.

Here we test this hypothesis by focusing on continental rift dynamics using the finite element geodynamic code ASPECT. In order to account for a range of narrow and wide rift configurations, we model the dynamic rift evolution of setups with 4 crustal thicknesses (20, 30, 40, and 50 km), each of them extended at 11 different rift velocities (0.5-10 mm/yr). Our model setups account for four layers (sublithospheric mantle, lithospheric mantle, lower crust, upper crust) that deform in a visco-plastic manner. After a total extension of 50 km and 100 km, we extract the current lithospheric configuration and compute the purely conductive thermal steady-state. These steady-state subsurface temperatures are calculated based on individual layer thicknesses and their thermal properties, while thermal inheritance from the rifting process is neglected. By comparing key observables of these steady-state snapshots (i.e. the depth of the 100, 200, 300, and 400°C isotherms and the depth of the deepest brittle-ductile-transition) to those of the transient thermomechanical models, we finally assess the suitability of steady-state modelling approaches in continental rift settings.

We find that wide rifts, where local advection rates are much slower than in narrow rifts, reside in a thermal steady-state for all tested rift velocities. In narrow rift configurations, however, our hypothesis of a speed limit for the thermal steady-state assumption can be clearly verified for all observables. Assuming vertical uncertainties of +/- 5 km for all our observables (isotherms and brittle-ductile transition), we deduce that at a total extension of 50 km the steady-state approach in narrow rift settings is suitable for extension velocities smaller than ∼2-3 mm/yr. At 100 km of extension, the rift velocity can be as fast as ∼2-5 mm/yr depending on the observable and crustal thickness. We conclude that slow rifts like the Kenya Rift, Rhine Graben, and Rio Grande Rift as well as wide rifts like the Basin and Range Province lie within the steady-state limits. Contrastingly, narrow and relatively fast rifts like the Afar rift segments, the Red Sea, and the Gulf of Corinth must be expected to feature a pronounced transient component in the temperature field and therefore to violate the thermal steady-state assumption.