3D Thermo-mechanical numerical modelling of continental rifting via plume-lithosphere interaction in presence of far-field forces

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Abstract:

The role of mantle–lithosphere interactions in rifting processes has long been debated. Identification of mantle contribution to rift topography and structure is difficult, especially in the continents. At the same time, the volcanic activity, which is commonly considered a prime signature of mantle upwellings, is not systematically detected in the areas of presumed active rifting. It can be argued therefore that complex brittle-ductile rheology and stratification of the continental lithosphere result in screening and deviation of mantle upwellings as well as in short-wavelength modulation and localization of surface deformation induced by mantle flow. This deformation should also be affected by far-field stresses and, hence, interplays with the "tectonic" topography. Testing these ideas requires fully-coupled high-resolution "tectonic grade" 3D numerical modelling of mantle-lithosphere interactions, which is so far has not been possible due to the conceptual and technical limitations of earlier approaches.
Here we present fully-coupled high resolution 3D thermo-mechanical numerical models to investigate the impact of the laterally heterogeneous structure and rheological stratification of the continental lithosphere on the plume activated rifting and continental break-up processes in presence of preexisting far-field tectonic stresses. In our experiments, the "plumes" represent short-lived diapiric upwellings that have no continuous feeding from the depth. Such upwellings may be associated with "true" plumes but also with various instabilities in the convective mantle. The models demonstrate that the prerequisite of strongly anisotropic strain localization during plume-lithosphere interaction (linear rift structures instead of axisymmetric radial faulting) refers to simultaneous presence of a mantle upwelling and of (even extremely weak) directional stress field produced by far-field tectonic forces (i.e. ultra-slow far field extension at < 3 mm/y). Although in all experiments the new-formed spreading centers have similar orientations perpendicular to the direction of the main far-field axis, the models with homogeneous lithosphere show that their number and spatial location is different for various extension rates and thermo-rheological structures

of the lithosphere: relatively slow extension (3 mm/year) and colder isotherm (600-700C at Moho depth) at the crustal bottom lead to the development of single rifts, whereas "faster" external velocities (6 mm/year) and "hotter" crustal geotherm (800C at Moho depth) result in dual (sometimes asymmetric) rift evolution. On the contrary, the models with heterogeneous lithosphere (thick cratonic block with cold and thick depleted mantle embedded into «normal» lithosphere) and the plume centered below the craton, systematically show similar behaviors: two symmetrical and coeval rifting zones embrace the cratonic micro-plate along its long sides.

The experiments where the initial plume position has been laterally shifted with respect to the craton center, demonstrate a fundamentally different development, since in this case the upwelling plume is deflected by the cratonic keel and preferentially channeled along one of its sides, leading to formation of a large rift zone, characterized by important magmatic activity with substantial amounts of melts derived from mantle plume material. The assumption of rheologically weak vertical interface (inherited suture zone) along other side of the craton or the presence of a second smaller plume initially shifted in opposite direction permit us to reproduce the first-order features observed in dual asymmetric (amagmatic western versus magmatic eastern branch) Central East-African rift system. Moreover, this contrasted double rifting and asymmetric distribution of the hot material on either side of the craton may be also a result of unequal splitting of relatively big plume which initial position is slightly shifted to the eastern side of the craton (in this case, neither a particular weakness of the interface between the craton and the embedding lithosphere nor a presence of second small plume is required).

The series of models with more geologically consistent structure of «normal» lithosphere (thickness is different for western and eastern segments: 200 km and 150 km, respectively) provide the best fit with the observations, further increasing rift asymmetry, favoring intensive magmatism at the eastern border of the Tanzania craton.

Our results reconcile the active (plume-activated) and passive (far-field tectonic stresses) rift concepts demonstrating that both magmatic and a-magmatic rifts may develop in identical geotectonic environments.

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