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Polyphase evolution of continental rifting over active mantle upwelling: Spatial and temporal aspects of transition between wide and narrow rifts

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The extension of continental lithosphere is usually classified into three modes: narrow rift, wide rift, and core complex. According to previous numerical and analogue experiments, a high-strength lithospheric mantle causes localized brittle deformation and the formation of a narrow rift whereas a ductile sub-Moho mantle was supposed to be favorable for wide rifting or core complex modes of extension. Here we use high-resolution 3D thermo-mechanical numerical modeling in order to show that the extension of a continental lithosphere with a high-strength uppermost mantle can initially result in both wide rift and core complex crustal deformation modes. We find that, irrespective of the rheological stratification, a plume-induced rifting process always occurs in two stages: an early crustal rifting stage and a late lithospheric necking (breakup) stage. Ultra-slow far-field extension applied to a homogenous lithosphere does not appear to be sufficient for propagation of large faults into the lithospheric mantle. As a result, during initial stage of extension, deformation concentrates in the crust with diffuse brittle strain in both upper and lower crust (wide rift mode) or localized brittle deformation in the upper crust underlain by lower crust subjected to ductile flow (core complex mode). In the latter case, series of sub-parallel normal faults merge into a localized, linear rift, which crosses the entire model domain in the direction perpendicular to the far-field extension, with considerable narrowing in its central part above the center of mantle upwelling. Further extension and/or localized ascent of hot plume material results in concentrated deformation that eventually crosscuts the whole lithosphere and marks the transition to narrow rifting.
The Main Ethiopian Rift, the Basin and Range province, and the East Shetland Basin may be natural examples of regions that have passed through these two stages of extension. The evolution of "passive" margin magmatism where pre-break-up volcanism over a large area predates syn-breakup magmatic activity concentrated at the continent-ocean boundary, is also consistent with this two-stage development.
Previous models assumed considerably larger far-field forcing (compared to the ultra-slow extension applied here, consistent with geodetic observations of present-day rifting) and/or pre-imposed lithospheric weaknesses. As a result, they lead to fast strain localization in the brittle sub-Moho mantle so that the initial stage of crustal extension observed here is absent. In contrast, our experiments predict a long (up to ∼100 Myr) stage of extensional deformation in the crust, either in wide rift or core complex mode, before strain localization into a narrow rift. These models permit to reproduce self-consistent polyphase evolution of complex rift systems observed in nature without appealing to inherited crustal and/or lithospheric heterogeneities and/or change in kinematics at the boundary of the system. The delay between plume impact and final lithospheric necking produces the diversity of structures that pre-structure the final rift at the stage of breakup.