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RESEARCH FOCUS

Forces within continental and oceanic rifts: Numerical modeling elucidates the impact of asthenospheric flow on surface stress

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Rift dynamics are controlled by a combination of local and far-field forces. These forces interact with the thermo-rheological rift configuration and thereby generate the characteristic normal faults, graben structures, and transfer zones documented in rifts and rifted margins worldwide (Ebinger and Scholz, 2012; Buck, 2015).

Classically, a fundamental distinction was made between active rifts caused by thermal upwelling of the sublithospheric mantle, and passive rifts generated in response to far-field tectonic forces (Sengör and Burke, 1978). However, this distinction appeared to be not as clear-cut as originally thought (Ziegler and Cloetingh, 2004) and it was even shown that there may be a temporal transition from passive to active rifting within a single rift system (Huismans et al., 2001). The numerical modeling study by Mondy and colleagues (2018, p. 103 in this issue of *Geology*) now illustrates that this transition also involves an important three-dimensional component. Hence, active and passive rift types must be considered end-member concepts of a continuous spectrum resulting from the evolution of several main rift forces.

FORCES IN RIFTS

Major forces and their orientation within a rift are displayed in Figure 1. Far-field forces are transmitted through the plates and may combine the classical plate driving forces of slab pull, slab suction, basal drag, and ridge push (Forsyth and Uyeda, 1975). Rift suction is a local force arising from the thinning of the lithosphere, which generates a relative pressure gradient at depth that causes subvertical inflow of asthenospheric mantle. The thermal buoyancy of these upwelling hot mantle rocks constitutes another local force within the rift (Huismans et al., 2001) that may impact the entire region if a mantle plume exists, such as under East Africa (Bagley and Nyblade, 2013). Flow dynamics of the sublithospheric mantle have a twofold impact on rifting: (1) the upward flow component generates dynamic topography, which increases the gravitational potential energy and hence produces a tensional body force (Bott and Kusznir, 1979; Lithgow-Bertelloni and Silver, 1998); and (2) the divergent mantle flow component viscously couples to the lithosphere, generating shear stresses. Lithospheric cooling plays a major role during slow rifting (van Wijk and Cloetingh, 2002) and in the post-rift phase (Petersen et al., 2015) by imposing a downward-directed body force via negative thermal buoyancy. This may ultimately lead to Rayleigh-Taylor instabilities where parts of the lithosphere are removed (Göğüş, 2015). Isostatic adjustment is the major control on topography, where thinning crust generates characteristic depressions within the rift. Surface processes distribute material, and thus generate negative or positive vertical loads in erosional areas and depocenters, respectively (Burov and Poliakov, 2001; Clift et al., 2015).

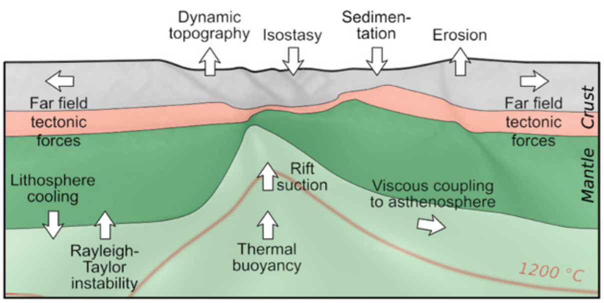

Figure 1. Forces and processes during rifting. Arrows designate direction of acting force. Sketch based on numerical model (Brune et al., 2017).

GEODYNAMIC RIFT MODELING

Rift forces evolve through time, they superpose each other, and they act at depth, which makes them difficult to quantify using observational techniques. Therefore, analog, analytical, and numerical modeling approaches (e.g., Brune, 2016) are commonly used to investigate the relative importance of driving forces, the controlling parameters, and rift processes.

In this issue of *Geology*, Mondy et al. contribute a numerical study addressing the stress field evolution during rotational rifting. Their setup features a 1000-km-long and 500-km-wide crust/mantle segment with a typical horizontally layered initial configuration. They account for the rotational rift aspect by imposing an extension rate that varies along strike by an order of magnitude. Despite the simple and transparent setup, the model exhibits a surprisingly complex stress field evolution with distinct phases of prevailing tensional, transcurrent, and compressional surface stress. The complexity results from along-strike changes in local forces: gradients in rift suction and thermal buoyancy generate along-strike flow of the asthenosphere toward the pole of opening. The model also suggests a diachronous transition from passive to active rifting where one region of the rift might already experience active rifting while a domain closer to the opening pole still develops in passive rift mode.

PRESENT-DAY ROTATIONAL RIFTS

The results of Mondy et al. elucidate observations from the Woodlark Rift east of Papua New Guinea, and the oceanic rift of the Galapagos Rise. Both rifts feature distinct regions of normal and strike-slip faulting that correspond to the modeled stress pattern. Another example of rotational opening is the Red Sea (Molnar et al., 2017). Here, periods of tectonic inversion during rifting have been documented at onshore normal faults (Schettino et al., 2016) suggesting a switch from tensional to compressional stress regime. In agreement with the numerical models, tectonic inversion occurs in the southern Red Sea; i.e., at the fast end of the rotationally opening rift.

The overall geotectonic setting of these three rift systems is plotted in Figure 2. Plate tectonic reconstructions of the past 10m.y. are used to deduce the Euler stage poles of rotational rifting and their temporal evolution. Interestingly, all cases exhibit past periods where the Euler pole was located extremely close to the rift, even closer than at present-day. This illustrates that the process described by Mondy et al. should play a major role during the entire history of these three rifts.

In this context, further research is required in order to elucidate the effect of an evidently changing Euler pole (Fig. 2) on surface stress patterns and rift structures. Considering the impact of rift strength loss on

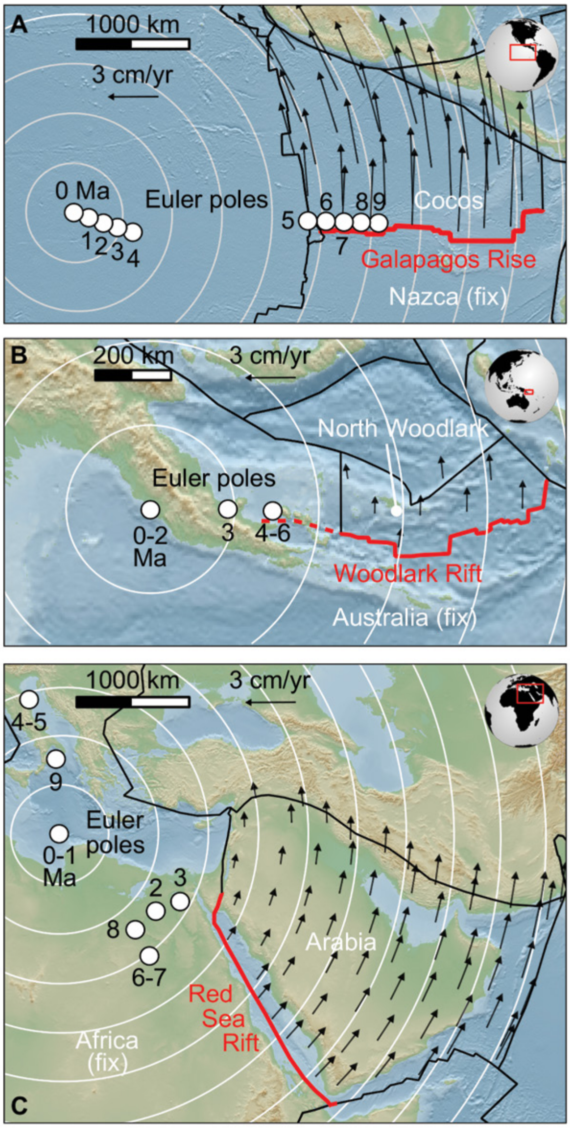

Figure 2. Present-day rotational rifts. A: Galapagos Rise. B: Woodlark Basin, east of Papua New Guinea. C: Red Sea Rift. White circles designate time-dependent Euler stage poles of relative plate motion with respect to the fixed plate. White lines are small circles of present-day plate motion. Arrows depict relative velocity field of relevant plate. Images generated with GPlates (www.gplates.org) using the global reconstruction of Müller et al. (2016).

plate motions (Brune et al., 2016), the evolving force balance within the rift may even provide key feedback on the location of the stage pole. Tectonic inversion during the rift-to-drift transition has also been documented at the eastern North American margin (Schlische et al., 2003; Withjack et al., 1998) that formed during Triassic-Jurassic rifting from present-day Africa. However, this period of compression along the southeastern United States margin is unlikely related to rotational rifting, since the corresponding Euler pole was located at a distance of >4000 km throughout the rift history. Further observational and modeling studies are needed to understand the force balance during rifting, the dynamics of mantle upwelling during the rift-to-drift transition, and its relation to the spatiotemporal evolution of magmatism in rifts and rifted margins.

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