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Review Article

Evolution and characteristics of continental rifting: Analog modeling-inspired view and comparison with examples from the East African Rift System

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ABSTRACT

The evolution and characteristics of narrow continental rifting are illustrated in this paper through a review of recent lithospheric-scale analog models of continental extension compared with selected examples from the East African Rift System.

Rift location is controlled by reactivation of lithospheric-scale pre-existing weaknesses; in these areas, the initial phases of rifting correspond to the activation of few, large-offset boundary faults that accommodate basin subsidence, which can be at places strongly asymmetric. The plan-view geometry of rift faults is primarily related to the relative orientation of the lithospheric weakness with respect to the extension direction: orthogonal rifting gives rise to long, extension-orthogonal boundary faults with associated pronounced subsidence, whereas oblique rifting results in a general en-echelon arrangement of faults and basins with less subsidence. Inherited fabrics having variable orientation with respect to the rift trend may control rift architecture at both regional and local scales. In these initial phases, widespread magmatism may encompass the rift, with volcanic activity localized along major boundary faults, transfer zones and limited portions of the rift shoulders (off-axis volcanism).

Progressive extension leads to a change in deformation style from the few, large-offset boundary faults at the rift margins to dense fault swarms – with limited vertical motions – affecting the rift floor where the magmatic activity is concentrated. In these areas of focused tectono-magmatic activity (the so-called magmatic segments) the thinned lithosphere is strongly modified and weakened by the extensive magma intrusion, and extension is facilitated and accommodated by a combination of magmatic intrusion, dyking and faulting. The feedback between strain localization, magma injection and lithospheric weakening is self-reinforcing, facilitating the rupture of the continental lithosphere. At this stage, magmatic segments (as for instance in the Northern Main Ethiopian Rift) act as incipient slow-spreading mid-ocean ridges, developing within a lithosphere that is transitional between continental and oceanic.

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1. Introduction

In the last years our understanding of the process of rifting and rupture of continental plates has greatly improved. Geological–geophysical studies of both volcanic (e.g., North Atlantic continental margins) and non-volcanic (e.g., Iberia-Newfoundland) passive margins and continental rifts (e.g., Main Ethiopian Rift, Baikal Rift System) have provided a clearer picture of their structure and evolution (e.g., Péron-Pinvidic et al., 2009 and references therein), increasingly highlighting the complexity of the rifting process (e.g., Armitage et al., 2010), which may involve large differences in deformation style and magmatism across short lateral distances (Lizarralde et al., 2007), and elucidating the role of important – previously overlooked – parameters, such as magma, on extension and break-up (e.g., Thybo and Nielsen, 2009, White et al., 2008; Yirgu et al., 2006). Geological–geophysical monitoring at unprecedented detailed scale of the ongoing magmato-tectonic event at a nascent oceanic center in Afar (e.g., Ebinger et al., 2010) has illustrated the interaction and partitioning of tectonic and magmatic events that occur during the final stages of continental break-up.

Apart from the indications derived from analysis of passive margins, most of our observational record of rifting processes comes from analysis of active continental rifts (e.g., East African Rift System, Baikal Rift, Cenozoic European Rift System). Among these, the East African Rift System is of special interest: it is the place where, in 1894, John Gregory first introduced the term rift valley to indicate the typical physiographic expression characterized by fault-bounded elongated basins; since then, this rift has provided basic information for developing the concepts of continental rifting (see Chorowicz, 2005). Indeed, the East African Rift records along its length all the different stages of rift evolution from rift initiation to break-up, and it is thus an ideal place to analyze the evolution of continental extension, the rupture of lithospheric plates and the dynamics by which distributed continental deformation is progressively focused at oceanic spreading centers (e.g., Ebinger, 2005). Given these ideal conditions, this rift system has recently catalyzed the attention of many different research groups that – mostly owing to multidisciplinary international projects, such as the Ethiopia-Afar Geoscientific Lithospheric Experiment, EAGLE (Maguire et al., 2003) – have led to an increasingly detailed knowledge of the crustal/lithospheric structure during the different stages of continental rifting and the main parameters controlling rift evolution and break-up (e.g., Ebinger, 2005).

In parallel, both analog and numerical modeling have recently greatly advanced, benefiting from improvements in analytical and numerical techniques and the development of new laboratory procedures to perform experiments and monitor model results. In particular, analogmodeling of continental rifting has improved in recent years and, since the pioneeristic clay models by Cloos (1939), the early centrifuge experiments by Ramberg (1967) and the first multi-layer lithospheric-scale models at the Geosciences Rennes laboratory (e.g., review in Brun, 1999), a further increase in model complexity has allowed investigating an increasing number of parameters involved in the process. Recent lithospheric-scale analog models of continental rifting have consequently focused on different aspects of the rifting process, such as (1) the pattern and evolution of deformation and its dependence on rift kinematics (e.g., Agostini et al., 2009; Autin et al., 2010; Corti, 2008; Corti et al., in press; Mart and Dauteuil, 2000), (2) the role of the lithospheric rheological structure on rift architecture (e.g., Bonini et al., 2007; Corti et al., in press; Corti and Manetti, 2006; Sokoutis et al., 2007), (3) the mode of extension (e.g., symmetry/asymmetry of the extensional process; e.g., Michon and Merle, 2003), (4) the evolution of faulting during rifting and its relations with inherited structures (Agostini et al., 2009; Corti et al., 2010, in press), (5) the influence of magma injection on extensional deformation (e.g., Corti et al., 2003a, 2004, 2007a), or (6) the boundary conditions of displacement (i.e., episodic or steady rifting; Mulugeta and Ghebreab, 2001). These new modeling approaches and results have been applied to complex natural prototypes, allowing to successfully elucidate complex tectonic patterns and evolutions of natural rifts (e.g., Corti, 2008).

Given this increased knowledge of analog and natural continental rifts, the aim of this paper is to provide an up-to-date view of the evolution of narrow continental rifting from the early to the mature stages. The focus is on narrow continental rifts (sensu Buck, 1991), exemplified by the rift valley system of the East African Rift System, and on recent lithospheric-scale analog models of continental extension whose results, along with selected natural examples, provide a general picture of the different evolutionary stages of continental rifting and the main parameters controlling it. To this purpose, I first review the main insights into the large-scale response of the continental lithosphere to extension provided by previous lithospheric-scale analog models (Section 2). Specifically, after summarizing the typical experimental results and limitations (Section 2.1), I discuss the main experimental results (Section 2.2) and in particular the modeling suggestions on the localization of deformation during the initial stages of rifting (Section 2.2.1), on the patterns of plan-view deformation (Section 2.2.2), on the dynamics of evolution of the rifting process (Section 2.2.3), as well as on the geometry of lithospheric thinning (Section 2.2.4). Moreover, since many rifts and passive margins worldwide are associated with significant volumes of magmatic products emplaced during rifting, a process that has been recently and increasingly proven to have an important control on rifting, the analog modeling works investigating the role of magmatism on the evolution of deformation and the relations between structures and magma emplacement will be reviewed in detail (Section 2.2.5). Finally, in Section 3, the modeling results are compared and integrated with the deformation pattern and evolution of selected examples from the East African Rift System, to provide a comprehensive view of continental rift evolution (Sections 3.1–3.3).

Aspects of continental rifting that have not been reproduced and analyzed experimentally in recent years (e.g., driving mechanism for extension: active vs. passive rifting; modes of deformation: wide and narrow rifting, core complexes) are not treated in the current review: for them, the reader is referred to previous review papers such as Brun (1999) or Corti et al. (2003a).

2. Lithospheric-scale modeling of continental rifting

2.1. Set-ups and limitations

Analog models are performed using different apparati belonging to two different categories: natural-gravity models (performed under the Earth's gravity field) and centrifuge models (performed under an enhanced gravity field — up to 20,000 g). It is out of the scope of this