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Inward migration of faulting during continental rifting: Effects of pre-existing lithospheric structure and extension rate

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ABSTRACT

Lithospheric-scale analogue models are used to analyse the parameters controlling the typical evolution of deformation during continental narrow rifting, characterized by early activation of large boundary faults and basin subsidence, followed by localization of tectonic activity in internal faults at the rift axis. Integration of current and previous experiments shows that the evolution of deformation, in particular the amount of extension needed for the abandonment of boundary faults and migration of deformation to in-rift faults, is dependent on at least five boundary conditions: (i) thickness of brittle layers (including syn-rift sediments); (ii) thickness of ductile layers; (iii) extension rate; (iv) width of the weak zone localizing extension; and (v) rift obliquity with respect to the extension direction. An increase in the amount of extension corresponding to the inward migration of faulting (i.e., a longer phase of slip on boundary faults) is observed for (a) an increase in the thickness of both brittle and ductile crustal layers and syn-rift sediment accumulation, (b) a decrease in extension rate and width of the weak zone, and (c) a decrease in rift obliquity. A unified account of these correlations is presented, based on the hypothesis that fault migration occurs when boundary faults can no longer accommodate the imposed bulk extension, leading to time–space variations of internal strain and strain rate (and consequently stress) in the ductile layers which overcome the total resistance of brittle layers to thoroughgoing faulting.

1. Introduction

The process by which continental plates are separated and new oceanic basins are formed is a fundamental feature of global tectonics. Several lithospheric-scale analogue models have been used to gain insights into different aspects of the rifting process (e.g., Corti, 2012), including: the pattern and evolution of deformation and its dependence on rift kinematics (e.g., Agostini et al., 2009; Autin et al., 2010; Corti, 2008; Mart and Dauteuil, 2000); the role of the pre-existing lithospheric rheological structure on rift architecture, distribution of deformation and modes of extension and their relations with parameters such as lithospheric strength and/or strain rate (e.g., Brun, 1999; Corti et al., 2003; Michon and Merle, 2003); the influence of magma injection on extensional deformation (e.g., Corti et al., 2003); and the boundary conditions of displacement (Mulugeta and Ghebreab, 2001). Yet, many aspects of these complex thermo-mechanical processes are still not completely understood.

Evidence from passive margins and active rifts in the stage of incipient break-up, such as the Main Ethiopian Rift in East Africa, suggests that the typical evolution of continental rifts is characterized by a progressive narrowing of the tectonic activity in time, with early activation of large boundary faults and basin subsidence followed by later activation of internal faults leading to a localization of deformation in a narrow region within the floor of the rift and deactivation of large boundary faults (e.g., Ebinger, 2005). Although this evolution represents a major aspect of the rifting process, the parameters controlling it and its timing (e.g., the duration of the rifting process prior to fault migration and break-up) remain unclear. Data from continental rifts and passive margins worldwide (e.g., Ziegler and Cloetingh, 2004) suggest a high variability of the process in terms of rift duration and boundary conditions, making it difficult to obtain conclusive insights on the controlling parameters from the geological record alone. Similarly, previous analogue modelling studies (e.g., Agostini et al., 2009; Brun, 1999; Brun and Beslier, 1996; Corti, 2008; McClay et al., 2002) have illustrated a progressive narrowing of the tectonic activity during extension, but have not analysed this process and its controlling parameters in detail.

In a previous paper (Corti et al., 2010), we have presented analogue models of the evolution of narrow rifting, reproducing the evolution from boundary faulting to in-rift deformation. These models have shown that the rate of rift evolution (in terms of time and

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amount of extension needed for the transition from boundary faults activity to focused deformation) is dependent on the initial thickness of both brittle and ductile layers, as well as on the amount of syn-rift sedimentation. In parallel, analogue models of oblique rifting by Agostini et al. (2009) have shown that rift kinematics is another key parameter in controlling rift evolution. However, in these previous papers, important parameters such as extension rate and width of the deforming zone were not considered. In this paper, we expand the previous results and present new models that investigate the influence of these latter parameters on the amount of finite extension needed for deformation to start migrating inwards from the rift borders. We also use new models with internal markers to monitor the internal deformation of the brittle–ductile system at different stages during model evolution. The new results, integrated with those of the previous work, are used to present a tentative analysis of the dynamics of fault migration in terms of the time–space variation of internal strain in the models as a function of the thinning and deformation rates (and therefore stresses) in the ductile layers, rift subsidence, and the total resistance of brittle layers to thoroughgoing faulting.

2. Experimental set-up and materials

The experimental set-up is the same as in Corti et al. (2010). For the sake of completeness, a brief account is given here.

2.1. Set-up and boundary conditions

The models were performed in an artificial gravity field of ~18 *g* using the large capacity centrifuge at the Tectonic Modelling Laboratory of the Institute of Geosciences and Earth Resources (National Research Council of Italy) at the Earth Sciences Department of the University of Florence. The models simulate extension of thinned continental lithosphere (crust + lithospheric mantle) floating above a low-viscosity material representing the asthenosphere (Fig. 1). The models extend during centrifuge runs in response to the centrifugal body forces, reproducing steady rifting with a constant displacement rate at the lateral boundaries that is controlled by sequential removal of rectangular spacers (Fig. 1a, b). A central lithospheric weak zone localizes deformation during extension (e.g., Corti, 2008; van Wijk, 2005). This is a realistic approximation for continental rifting, where extensional stresses are applied to a pre-deformed, heterogeneous lithosphere and deformation typically tends to follow pre-existing large-scale weaknesses (e.g., Corti, 2009; Dunbar and Sawyer, 1989; Keranen et al., 2009; Morley, 1999; Sokoutis et al., 2007; Tommasi and Vauchez, 2001; Versfelt and Rosendahl, 1989; Ziegler and Cloetingh, 2004), although in some specific cases inherited weak fabrics have been suggested to have played a minor role (e.g., Gulf of Aden; Autin et al., 2010), or their role may have varied along strike (e.g., Gulf of Corinth; Mattioni et al., 2006).

2.2. Rheological layering and experimental materials

In the models, a vertical sequence of brittle and ductile materials reproduces the rheological multilayer of the extending continental lithosphere (Fig. 1c). A K-feldspar powder, characterized by a linear increase in strength with depth, simulates the brittle upper crust. Three different levels made of homogeneous ductile mixtures, with constant density but decreasing viscosity (strength) with depth (see detailed description in Agostini et al., 2009), simulate the ductile lower crust. This set-up allows approximating the temperature-related decrease in strength with depth in natural ductile layers (Fig. 1). These layers were made of a mixture of plasticine (Pongo modelling dough, distributed by FILA) and polydimethylsiloxane (silicone SGM36 distributed by Dow Corning, hereafter referred to as PDMS) (100:45% in weight) (Table 1). Plasticines with different

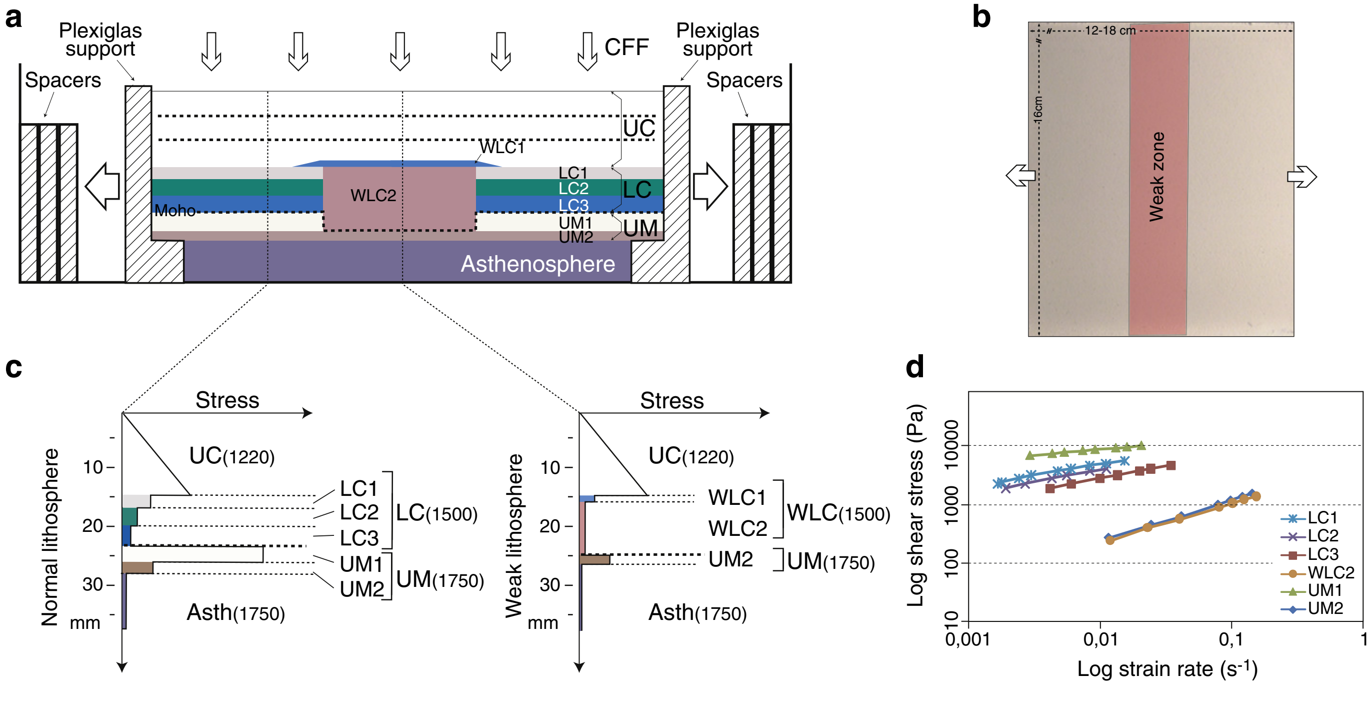

Fig. 1. Experimental set-up. a) Cross-section illustrating the model rheological layering and a schematic representation of the extension conditions in the centrifuge. The models were built inside a transparent Plexiglas box and confined by two moveable L-shaped side walls; removal of rectangular blocks (spacers) at the sides of these moving walls allowed vertical thinning and lateral extension of the models in response to the centrifugal forces (CFF) to fill the empty space. Sequential removal of these spacers during successive runs in the centrifuge was instrumental in controlling the amount and rate of extension. Model rheological layering (from top to bottom): UC, upper crust; LC1–3, lower crustal layers; UM1–2, lithospheric upper mantle layers; WLC1–2, weak lower crustal layers; Asth, asthenosphere. See Agostini et al. (2009) for details of experimental materials. b) Model top-view photo with illustrated the weak area in the centre. c) Strength profiles of the normal (left) and weak (right) model lithospheres. Symbols as above. Numbers denote the density of the different materials (kg m^{-3}).
Modified after Agostini et al. (2009).