DYNAMICS OF THE INWARD MIGRATION OF TECTONIC ACTIVITY DURING CONTINENTAL RIFTING: INFERENCES FROM LITHOPSHERIC-SCALE ANALOGUE MODELLING

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Summary

Lithospheric-scale analogue models are used to analyse the parameters controlling the inward migration of tectonic activity during the evolution of continental rifts. The models reproduce the extending continental lithosphere (crust + thinned lithospheric mantle) floating above a low-viscosity asthenosphere and are deformed in a centrifuge. The experiments consider a central zone of weakness, generated by a local increase in thickness of the crust; this weakness is orthogonal or oblique to the stretching vector, thus simulating conditions of orthogonal and oblique rifting, respectively. Model results reproduce the typical evolution of a narrow continental rift. This is characterized by an early activation of large boundary faults defining the main rift depression, followed by an inward shift of the tectonic activity leading to the activation of internal faults close to the rift centre and the subsequent abandonment/reduction of the tectonic activity along the boundary faults. The experiments testify that the evolution of deformation, in particular the amount of bulk extension (and the timing) needed for the inward migration of the tectonic activity, is strongly dependent on the rheology of the lithosphere (thickness of the brittle and ductile layers), the kinematics of extension (obliquity angle α, defined as the angle between the normal to the rift trend and the extension direction) and the syn-rift sediment accumulation. The experimental results suggest that the inward migration of faulting during extension of continental lithosphere results from the interplay between the ductile stresses acting at the base of the brittle upper crust and the total strength of this layer.

Introduction

Continental rifting represents one of the most important geodynamic processes affecting the lithosphere-asthenosphere system. The process (e.g. Ebinger, 2005; Corti, 2009) is usually defined by a two-phase evolution, with an early stage characterized by the activation of large boundary faults defining a subsiding undeformed basin, followed by the progressive focusing of volcano-tectonic activity in the axial rift valley. The process eventually may lead to continental break-up and the transition of the central narrow deforming region into an oceanic spreading centre (e.g. Ziegler and Cloetingh, 2004; Ebinger, 2005; Corti, 2009).

Comparison of natural examples worldwide suggests that the time and the amount of bulk extension needed for the inward migration of deformation is highly variable, reflecting the different rheological characteristics of the continental lithosphere affected by the extension: lateral variations in strength and thickness may strongly affects the entire process. In this work we focus on the parameters controlling the inward shift of tectonic deformation during narrow continental rifting by reviewing and integrating the results of analogue modelling presented in two previous papers (Agostini et al., 2009; Corti et al., 2010). Model results indicate that the timing of the inward migration of the tectonic activity may be strongly affected by the kinematic conditions (i.e. the direction of extension with respect to the rift trend; Agostini et al., 2009), the rheological layering of the analogue lithosphere (Corti et al., 2010), and the amount of syn-rift sediment accumulation (Corti et al., 2010).

Model setup and experimental series

The model setup is similar to that used in Corti (2008). The experiments were performed in an artificial gravity field of maximum acceleration of ~18g using the large-capacity centrifuge at the Tectonic Modelling Laboratory of CNR-IGG, Department of Earth Sciences, University of Florence. Complex multilayer models reproduce the extending continental lithosphere (crust + thinned lithospheric mantle) floating above a low-viscosity asthenosphere (Fig. 1a). They were built inside a transparent rectangular Plexiglas box and confined by two moveable sidewalls; removal of rectangular blocks (spacers) at the sides of these moving walls allowed vertical thinning and lateral expansion of the models in response to the centrifugal forces to fill the empty space (Fig. 1a). The brittle upper crust UC was simulated by a K-feldspar powder, which shows a linear increase in strength with depth (Fig. 1b). The ductile lower crust LC was made by three different layers (a mixture of plasticine and silicone) (Fig. 1b), with constant density but decreasing viscosity to simulate the decrease in strength with depth typical of the continental lower crust (see, e.g. Ranalli, 1995). Similarly, the lithospheric mantle was made by two layers with constant density but different viscosity (Fig.1b): the strongest upper mantle (UM1) was made by a mixture of plasticine and silicone, and the weaker underlying layer (UM2) was made by a mixture of silicone, corundum sand and oleic acid. The models were deformed at a constant extension rate.

The experimental lithosphere contained a central weakness zone (generated by a local increase in crustal thickness (Fig. 1a,b) that localizes deformation during progressive extension (see van Wijk, 2005; Corti, 2008). The model weak zone represented the equivalent of a pre-existing lithospheric weakness inherited by previous deformation phase that in natural processes of continental rifting tends to concentrate the extensional deformation (e.g. Ziegler and Cloetingh, 2004; van Wijk, 2005). The orientation of this weak zone was either orthogonal or oblique to the stretching vector, in order to reproduce conditions of normal and oblique rifting, respectively (see below).

Experimental series	Obliquity α	Thickness Upper Crust (mm)	Thickness Lower Crust (mm)	Thickness Lith Mantle (mm)	Ductile Thickness (mm)	Total sedimentation (mm)	Fault migration (mm bulk extension)
Standard	0°	15	8	5	13	7	**18**
Variable obliquity (Serie 1)	15°	15	8	5	13	7	**14**
	30°	15	8	5	13	7	**12**
	45°	15	8	5	13	7	**10**
	60°	15	8	5	13	7	**4**
	75°	15	8	5	13	7	**0**
Variable LC (Series 2)	0°	15	2	5	7	7	**9**
	0°	15	5	5	10	7	**15**
	0°	15	14	5	19	7	**24**
Variable UC (Series 3)	0°	5	8	5	13	7	**9**
	0°	10	8	5	13	7	**12**
	0°	20	8	5	13	7	**24**
Variable sedim (Series 4)	0°	15	8	5	13	0	**12**
	0°	15	8	5	13	10	**18**

LC: lower crust; Lith: lithospheric; sedim: sedimentation; UC: upper crust.
The velocity of deformation (~5 10^{-5} ms^{-1}) is constant in all the different experiments.

Table 1: Characteristics of the different experimental series.

The standard experiment was characterised by α=0° (α is the angle between the normal to the rift trend and the direction of extension), UC thickness 15mm, LC thickness 8mm and 7mm of total sedimentation (Table 1). In Series 1, the obliquity angle α was varied in different experiments with respect to the standard experiment between 0° and 75° in increments of 15° (Fig. 1c and Table 1), while the thickness of the different rheological layers was kept constant. The other experimental series considered conditions of normal rifting (α=0°) and variable thickness of the brittle upper crust and ductile lower crust (Series 2-3; Table 1) or variable syn-rift sedimentation (Series 4) by comparing a model with no sediment accumulation and a model with increased total sedimentation with respect to the standard model (Table 1). Increased sedimentation was achieved by filling the model with K-feldspar powder up to 1 mm above the top of the boundary faults, thus burying the rift floor and shoulders. In each experiment series, the other boundary conditions (e.g., velocity of deformation, amount of bulk extension, etc.) were kept constant.

Model results

Models characterized by low to moderate obliquity (α≤45°) displayed a typical two-phase evolution of deformation (Fig. 1). The early phase of deformation was characterized by nucleation at the strong-weak lithosphere boundaries of major boundary fault systems bordering a subsiding rift depression, and by the development of minor antithetic normal faults giving rise to marginal grabens, delimiting a central horst (Fig. 1d). Increasing extension led to a change in deformation style (second phase), with development of internal normal faults which start to affect the still undeformed rift floor (Fig. 1e). During continuing extension, the amount of deformation accommodated by the internal faults increased with a progressive decrease of the amount of slip along boundary faults. The final structural pattern of the model displayed boundary escarpments and remnants of marginal grabens flanking a rift depression strongly affected by internal faults (Figs. 1f). The architecture of internal faults is strictly dependent on the obliquity angle α (see Agostini et al., 2009 for details).

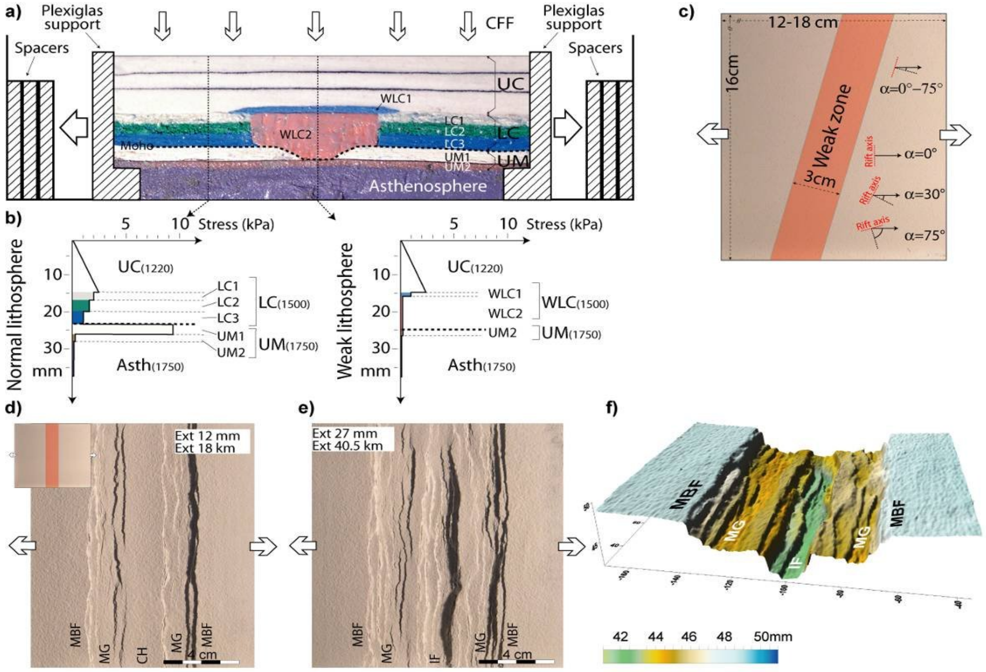

Fig. 1: a) Model cross-section illustrating the vertical rheological layering and schematic representation of the extension conditions in the experimental apparatus. CFF: centrifugal forces. LC1-3: lower crustal layers 1-3; UM1-2: upper mantle layers 1-2; WLC1-2: weak lower crustal layers 1-2. b) Strength profiles of the normal (left) and weak (right) model lithosphere. UC: upper crust; Asth: asthenosphere; other symbols as above. Numbers in brackets indicate the density of the different materials in kg m^{-3}. c) Top view photo of the models. d-e) two different stages of the evolution of the standard model illustrated as top-view. f) digital elevation model of the final model surface. MBF: main border fault; MG: marginal graben; CH: central horst; IF: internal faults. Modified from Agostini et al., 2009.

On the contrary, high obliquity models (α≥60°) did not display a two-phase evolution as no boundary faults form, and the extensional deformation affects the rift depression since early stages of extension.

The different experimental series documented a control of the obliquity and the thickness of both the ductile and brittle layers on the amount of bulk extension needed for the development of internal faults and thus for the change in deformation style. In term of varying obliquity, we observed that increasing the α angle with respect to the standard experiment (α=0°) the amount of extension needed for the development of the internal faults decreases (see Table 1 and Fig. 2). As an end-member behaviour, high obliquity did show a single-phase evolution, with faults affecting the whole rift depression since the beginning.

On the other hand, a reduction of the ductile lower crust thickness with respect to the standard experiment resulted in the earlier development of the central graben, and conversely, an increase in the ductile thickness resulted in a later development of internal faults (see Table 1 and Fig. 2). Similarly, a reduction in the brittle thickness led to an earlier development of internal faults (~12 mm and ~9 mm of bulk extension, respectively), whereas an increase in the upper crust thickness resulted in the later migration of faulting (see Table 1). Although less evident, a similar control on fault migration was observed for the syn-rift sedimentation (see Table 1 and Fig. 2). When sediment accumulation was absent faults migrated inwards earlier than in the reference model (in which the total sediment accumulation was of ~7 mm); however no difference was observed in the case of increased sediment accumulation probably because of resolution problems.

Discussion and conclusion

Experimental results suggest that the timing of the inward migration of deformation (and consequently the duration of the rifting process) may result from different kinematic conditions and

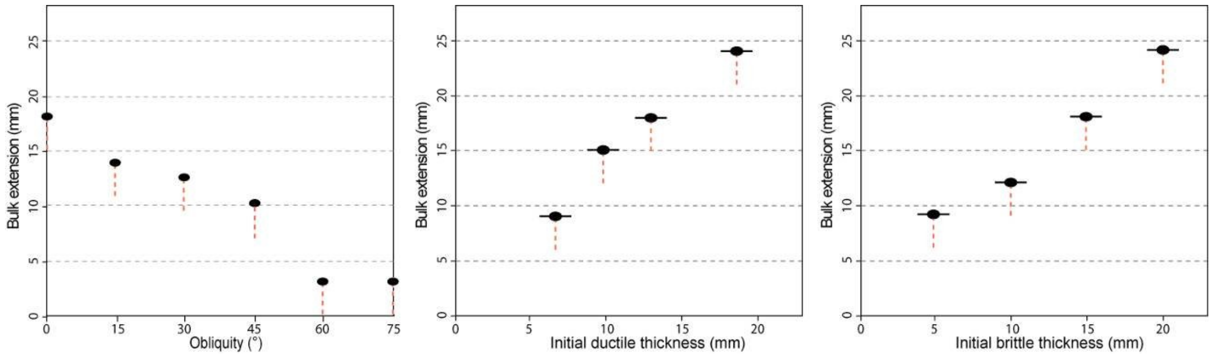

Fig. 2: Summary of experimental results illustrated as graphs plotting the amount of bulk extension needed for deformation to migrate within the rift depression as a function of obliquity (left panel), the thickness of the ductile layer (central panel) and the thickness of the brittle layer (right panel). The error bars in the x-direction indicate the variability in layer thickness introduced when building the model; the dashed red bars in the y-direction indicate the 3-mm deformation increment during which the intra-rift faults, observed at a given amount of bulk extension corresponding to the end the centrifuge run (indicated by the dot) could have formed. Modified from Corti et al., 2010.

pre-rift rheology of the continental lithosphere. Variations of these parameters could result in a faster abandonment of the border faults or in a prolonged slip along them. Moreover, while increased syn-rift sedimentation may favour a later development of internal faulting, decreased rate of sedimentation permits a rapid transition to in-rift fault development.

Analysis of Series 2-4 models suggests that fault migration is probably controlled by the interplay between the ductile stresses at the base of the brittle layer and the total resistance of the brittle layer itself: increases in both the thickness of the ductile layer (which reduce basal shear stresses) and the thickness of the brittle layer and/or sediment supply (which increase the total frictional resistance) tend to delay the abandonment of boundary faults and in-rift fault development.

Conversely, the increase in the strike-slip component of deformation (increasing rift obliquity) tends to produce high stresses at the base of the brittle crust from the early stages of deformation leading to internal faulting during rift initiation and no boundary faults activity (see Agostini et al., 2009 for details).

Further analysis is required to better define the mechanism governing the inward migration of tectonic deformation during narrow continental rifting. The controls exerted by the variations in strain rate, deformation zone width as well as its shape on the evolution of the rifting process, and the accurate mapping of strain localization processes are topics at present under investigation.

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