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Thin viscous middle-crust and evolving fault distribution during continental rifting: Insights from analog modeling experiments

R. Keppler [a],*, F.M. Rosas [b,c], T.J. Nagel [d]

[a] Christian-Albrechts Universität zu Kiel, Institut für Geowissenschaften, Otto-Hahn-Platz 4, D-24118 Kiel, Germany
[b] Instituto Dom Luiz, Campo Grande, Ed. C1, Piso 2, 1749-016 Lisboa, Portugal
[c] Universidade de Lisboa, Faculdade de Ciências, Departamento de Geologia, Campo Grande, Ed. C6, Piso 4, 1749-016 Lisboa, Portugal
[d] University of Bonn, Steinmann-Institut, Poppelsdorfer Schloss, D-53115 Bonn, Germany

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ABSTRACT

Analog modeling of continental rifting, assuming a crustal scale "jelly sandwich"-like rheology, was carried out to test the mechanical effect of varying the absolute thickness of a weak (viscous) middle crust (silicone layer), interbedded between a brittle upper crust (sand layer) and a strong lower crust.

Results consistently show a delocalization of the brittle deformation (i.e. a uniform scattering of the faults) throughout the upper brittle layer. This effect is interpreted to be associated with pressure driven flow in the viscous layer, caused by the tectonic collapse of upper brittle fault blocks into the viscous substratum. A reduction of the overall viscous layer thickness increases its resistance to accommodate internal thickness variations, which promotes delocalization of the fault pattern in the upper brittle layer.

Our results contribute to the understanding of the mechanics of the so-called "upper plate paradox", a large-scale structure often recognized at non-volcanic rifted margins. A thin viscous middle crust provides means of decoupling the deformation affecting upper and lower crust during rifting. On one hand this promotes a uniform scattering of faults throughout the upper brittle crust, on the other hand it allows for a strong localization of the deformation in lower crust and upper mantle expressed by the lithospheric necking in the rift center.

1. Introduction

In continental rifts, normal faulting in the upper crust displays very different degrees of localization. Extension may be either concentrated along single faults accommodating very large offsets and eventually exhuming middle or lower crust (detachment faults bounding metamorphic core complexes, e.g. Brun et al., 1994; Chéry, 2001; Hill et al., 1992; Malavieille and Taboada, 1991), or distributed over wide areas represented by a large number of brittle normal faults with individual limited slip. The pattern of active faults in a rift system can also change through time, during different successive extensional phases, from strongly localized to distributed (e.g. Basin and Range Province of the southwestern United States, Dickinson, 1991, 2006).

The mechanical processes controlling such brittle fault patterns and associated wide or narrow rifting have been investigated through many experimental and theoretical studies over the past decades (e.g. Bellahsen et al., 2003; Benes and Davy, 1996; Brun et al., 1994; Buck, 1991; England, 1983; England and McKenzie, 1982; Sonder and England, 1989; Tirel et al., 2006) and are excellently summarized in Buck et al. (1999). Generally, strain weakening and strain hardening processes promote localization and delocalization of deformation, respectively. Strain weakening processes (e.g. loss of cohesion/friction along a fault zone, and progressive necking of strong brittle crust) cause the deformation to stay where it is, whereas strain hardening processes (e.g. the formation of topography caused by fault offset, and consequent buildup of elastic stresses due to the resulting regional isostatic response) make deformation shift to adjacent unstrained areas, spreading and delocalizing.

The vertical rheological stratification of the continental lithosphere, comprising soft and strong layers, is of critical importance in addressing the mechanics of rifting. Many studies assume that the continental crust has a relatively thin, weak and viscous layer in the middle crust (Gueydan et al., 2003; Lavier and Manatschal, 2006; Nagel and Buck, 2004, 2007; Ord and Hobbs, 1989) or an altogether weak lower crust (Brun and Beslier, 1996; Brun et al., 1994; Wijns et al., 2005). The soft layer separates and decouples two relatively strong domains from each other: the overlying brittle upper crust, from the lower crust, or from the upper mantle lithosphere, respectively (e.g. Brace and Kohlstedt, 1980; Brun et al., 1994; Burov and Diament, 1995). The viscosity and thickness of this middle weak/soft layer exert a significant control on the distribution of brittle faulting in the upper crust, although both parameters depend on the compositional and thermal structure of

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* Corresponding author. Tel.: +49 4316002323.
E-mail address: rkeppler@geomar.de (R. Keppler).

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the crust as a whole, and thus, can vary for different rifting scenarios (Ord and Hobbs, 1989; Ranalli, 1995).

In the present work we performed a series of physical (analog) modeling experiments, in which a soft/weak layer of varying thickness, accounting for the middle crust, is interbedded between an upper brittle layer (upper crust) and a basal rigid one corresponding to a strong lower crust (mechanically coupled with the underlying lithospheric mantle). We investigate the influence of different thicknesses of the soft/weak middle crust on the development of localized versus delocalized brittle fault patterns in the upper crust. Furthermore, we compare our results with natural examples of typical non-volcanic rifted margins, and explore their implications for the interpretation of the evolution and final configuration of such margins.

1.1. Previous experimental work

Many physical and numerical studies have previously explored lithospheric or crustal scale normal faulting in vertically stratified systems to establish fundamental mechanical relations, to study particular extensional structures such as core complexes, or to reproduce the entire rifting and breakup processes (Bahroudi et al., 2003; Bellahsen et al., 2003; Benes and Davy, 1996; Brun, 1999; Brun et al., 1994; Buck, 1991; Buck et al., 1999; Buiter et al., 2008; Koyi and Skelton, 2001; Nagel and Buck, 2004, 2006, 2007; Tirel et al., 2006; Wijns et al., 2005).

In classical analog modeling, two- or four-layered sand silicone cakes have been used to account for crustal or lithospheric strength profiles (Fig. 1). These models typically use sand as a brittle material

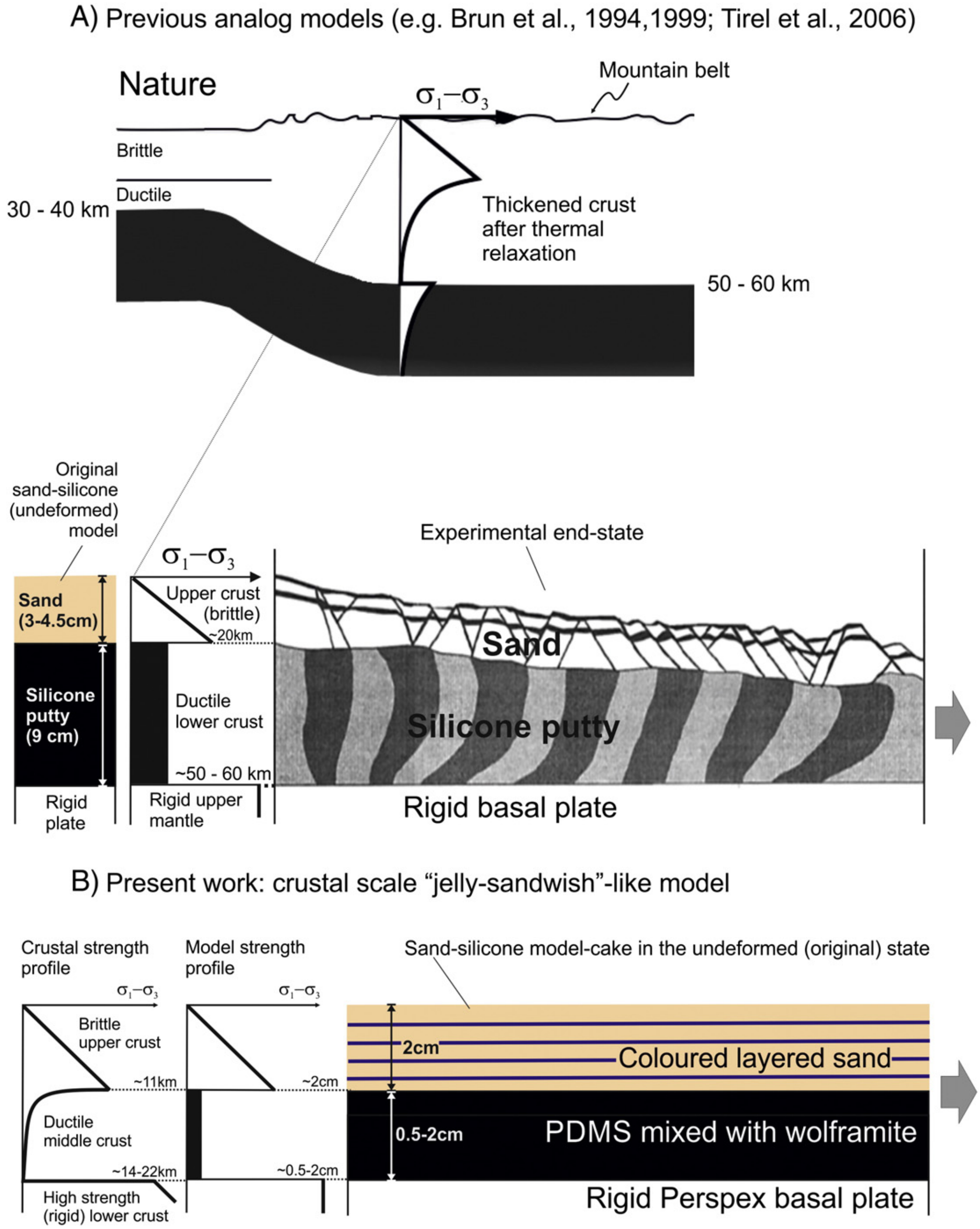

Fig. 1. (A) Previous analog models (e.g. Brun et al., 1994; Brun, 1999; Tirel et al., 2006); (B) present work “jelly-sandwich”-like models. Note that the PDMS thickness varies between 0.5 and 2 cm for different experiments. Schematic representations of model and nature strength-depth profiles are also included for the two cases.