INFLUENCE OF VISCOUS CHANNEL THICKNESS ON THE DEVELOPMENT OF OVERLYING BRITTLE DEFORMATION PATTERNS UNDER EXTENSION: NEW INSIGHTS FROM ANALOGUE MODELING

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Summary

In two-layer sand-silicone experiments we studied the influence of the varying thickness of a mid-crustal ductile layer on the extensional fault pattern in the overlying brittle crust. Experiments with four distinct ratios for the thickness of the layers have been compared at different amounts of stretching. Our results show that thinning of the lower ductile layer is an effective way of delocalizing the brittle deformation. A thinner ductile layer results in a shorter wavelength of failure in the brittle layer and causes a higher number of faults. This study provides new insights on the deformation pattern formed during continental rifting, showing that the thickness of a weak mid-crustal ductile layer can have a major influence on the structural configuration of a rifted basin.

I - Introduction

1.1. Previous work

The geometry of continental extension is controlled by different factors, such as the rheological stratigraphy of the crust and the thickness of its layers. In continental crust, the influence of a low viscosity – ductile - mid-crustal layer in the extensional deformation pattern of the overlying brittle crust has been examined in both numerical (Buck 1991, Benes et al. 1996, Nagel et al. 2004, Huismans et al., 2005, Buiter et al. 2008) and analogue (Brun et al. 1994, Bellahsen et al., 2003, Tirel et al. 2006) experiments. These previous studies focus on the influence of the varying viscosity of the ductile layer, the strain rate and the amount of extension. The analogue models of Bellahsen et al. (2003) and the numerical models of Huismans et al. (2005) and Buiter et al. (2008) showed that a higher viscosity of the ductile layer promotes a delocalization of the extensional fault pattern in the overlying brittle one. In their numerical models Nagel and Buck (2006) showed that the thinning of the ductile (mid-crustal) layer is an alternative way to delocalize upper layer brittle deformation. Adding to this, the same authors also pointed out that widely distributed (i.e. delocalized) parallel dipping normal faults in the upper crust can be formed through the thinning of the underlying ductile layer, since viscosity increase favors extensional horst and graben formation.

1.2. Present work

So far, the influence of the varying thickness of a mid-crustal ductile layer has only been investigated numerically. As a consequence, in their (symmetrical and asymmetrical) extension experiments, the authors cited above assumed ideal perfect free-slip, or perfect stick-slip, boundary conditions. In this work, we present the results of physical (analogue) modeling, in which boundary conditions were set to simulate a diachronic change along margin propagation of extension, instead of instantaneous propagation of the whole margin-length, as in previous numerical models. The objective is thus to test the previous numerical modeling assumptions, regarding the influence of mid-crustal ductile layer thinning in the mechanics of fault delocalization in the upper brittle crust, during rifting of a continental margin.
II-Experimental approach

2.1. Deformation box

The experiments were performed in the Perspex deformation box depicted in figure 1.

![Deformation box](image)

Figure 1: Deformation box

2.2. Experiment set-up

Inside the deformation box we constructed a two-layer sand-silicone model: a lower PDMS layer of varying thickness, and an overlying 2 cm thick dry quartz (sand) layer. The sand has a grain size < 0.25mm, very low cohesion and a friction angle of about 30°. The PDMS has a viscosity of $2.5 \times 10^4$ MPa/s and behaves as a Newtonian fluid under laboratory conditions. The sand works as a mechanical analogue of the upper crust and the silicone simulates the mid crustal ductile layer. Colored sub-layers in the sand were used as markers, enhancing the recognition of the fault offsets.

The floor beneath the PDMS is lubricated with neutral soap to simulate a low shear stress lower boundary condition. However the right end of the PDMS layer is non-lubricated and sticks to a small portion of mylar sheet and to the moving right wall to which this is fixed (see Fig.1). The mylar sheet has a length of 2 cm to assure that there is a surface of PDMS of at least 2 cm attached to the right wall for any thickness of the lower layer.

2.3. Experimental procedure

In our experiments we stretched the 2-layer sand-silicone cake by moving the right wall to the right with a velocity of 3.76 cm/hr. This velocity corresponds to an extension rate of 1.58 cm/yr in nature and was scaled accordingly (Hubbert, 1937).

Four different ratios of the brittle/ductile layer thickness were tested (Table 1). The sand layer had a constant thickness of 2 cm corresponding to an 11 km thick upper crust. The thickness of the silicone varied between 2.0 (ratio 1), 1.0 (ratio 2), 0.7 (ratio 3) and 0.5 cm (ratio 4) corresponding to middle crust thicknesses of 11, 5.5, 3.85 and 2.75 km. The amounts of stretching were 2.73 cm, 5.45 cm and 6.72 cm, corresponding to approximately 15, 30 and 40 km in nature. Side-view photographs were taken at regular time intervals.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>1st exp.</th>
<th>2nd exp.</th>
<th>3rd exp.</th>
<th>4th exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand layer thickness (Brittle upper crust)</td>
<td>2 cm (11 km)</td>
<td>1 cm (5.5 km)</td>
<td>0.7 cm (3.9 km)</td>
<td>0.5 cm (2.8 km)</td>
</tr>
<tr>
<td>Silicone layer thickness (ductile middle crust)</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand/silicone thickness ratio</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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</tbody>
</table>

Table 1 - Summary of the procedure parameters adopted for each of the 3 sets of experiments that were carried out for 2.73 cm, 5.45cm and 6.72 cm of stretching (15km, 30km and 40km respectively).
III - Experimental results

At the final stage of all the experiments the mean distance between successive necking zones in the brittle layer was systematically measured. Ridges, similar to folds in the top PDMS surface, mark these necking zones (see Fig. 2). Likewise, the number of faults was also counted.

![Figure 2: Photo and interpretation of the final stage of SS ratio = 3 after 5.45 cm of extension](image)

3.1 Mean necking distance (MND)

In all the experiments, the MND decreases as sand-silicone (SS) ratio increases (see graph of Fig. 3a), i.e. as a function of the successively thinner PDMS ductile layers. Marked reductions in MND measurements were observed to preferentially occur both between ratios SS=1 and SS=2, and between ratios SS=3 and SS=4, although a consistent decrease in measured MND was always found with increasing SS ratio.

3.2 Number of faults

Generally, in experiments with higher SS ratios (thinner silicone layer thickness), a higher number of faults was observed to form, although some exceptions to this did occur (see graph of Fig. 3b). In some experiments, ratios 2, 3 and 4 induce the same number of faults, while in others there is a constant rise in the number of faults with increasing SS ratios.

![Figure 3: Different lines denote sets of experiments with different amounts of extension. A: MND in cm vs. SS ratio. B: Number of faults vs. SS ratio](image)
3.3. Fault pattern

The final fault pattern observed in most of the experiments is characterized by horst and graben-like structures and right-dipping single faults. However, close inspection of the grabens always revealed a systematically larger offset on the left-hand faults than on the right-hand ones (fig. 4a). Also, in experiments with higher SS ratios several minor faults form in one necking area.

IV - Discussion

Our experiments show that the diachronic propagation of extension along a two-layered brittle-ductile model of continental crust is influenced by the thickness of the lower ductile layer accordingly with the theoretical predictions of Nagel and Buck (2006). According to these authors, thinning of the ductile layer causes a higher viscous work rate. This is confirmed by our low SS ratio experiments, in which it is easy for the ductile material to be pulled up into the necking areas. In experiments with higher ratios this becomes increasingly more difficult, which results in a shorter wavelength of failure in the brittle layer.

In most experiments higher SS ratios cause a higher number of necking zones and a higher number of faults to form. So generally, high SS-ratios lead to a more distributed deformation pattern. In experiments with high SS ratios (thin ductile layers), clustering of minor faults and ridges in the same main necking areas is common. During extension, the accumulation of minor faults in necking zones is favored over the formation of new necks or main faults. This shows that the delocalization of deformation as a consequence of ductile layer thinning manifests itself, predominantly (although not exclusively), at the expense of the diminishing wavelength of necks and main faults, without necessarily causing a wider rifted area.

Finally, obtained fault patterns are seemingly characterized by “geometric” horst and grabens. However, a careful inspection of these reveals that they formed mechanically as parallel right-dipping faults, which are later, cut by left-dipping minor faults that accommodate late extensional pulses in the necking area, clustering in these weaker zones (see fig. 4b). This parallel dipping predominance also concurs with previous numerical modeling predictions (Nagel and Buck, 2006).

Our experiments support models of continental rift break of, which assume collapse of brittle upper crust over a thin weak middle crust into the rift center (Nagel & Buck 2004, Lavier & Manataschal 2006).

REFERENCES


• Lavier L.L., G. Manatschal; 2006: A mechanism to thin the continental lithosphere at magma-poor margins. Nature 440, 324-328


