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Sandbox experiments on basin inversion: testing the influence of basin orientation and basin fill

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Abstract

Analogue modelling experiments using brittle materials are performed to study the inversion of extensional structures. Asymmetric grabens of two different orientations are first created during a phase of extension and progressively filled. They are subsequently shortened in the same direction. The aim of our experiments is to determine factors affecting the style of deformation during inversion. We specifically investigate variations in thickness and distribution of strong and weak layers constituting the graben fill and in initial basin orientation. The main advantage of our experimental set-up is that we have a complete control on graben location, width, infill and orientation before inversion. The experiments show that shortening results only in limited reactivation of pre-existing normal faults. In general, forward thrusts and backthrusts cut across normal faults into the footwall of the graben. The forward thrusts either propagate parallel to the enveloping surface of faulted blocks or they cut across basin-limiting normal faults at various angles. The graben fill is mechanically extruded by displacement along forward thrusts that accommodate most of the shortening. Both pre-existing faults and weak graben fill act as zones of weakness during inversion and determine the orientation and location of both backthrusts and forward thrusts. The results of our experiments conform well to natural examples of inverted graben structures.

Keywords: Basin inversion; Asymmetric graben; Basin orientation; Basin fill

1. Introduction

Analogue modelling has been used since the nineteenth century to simulate natural geological structures with the aim of understanding the mechanisms controlling their geometry and kinematics. In this study, we focus on analogue models of basin inversion. Many previous analogue experiments on basin inversion have investigated hanging wall deformation using rigid footwalls. The footwall blocks usually represent a structural basement with faults of varied geometries, e.g. listric, planar or ramp/flat listric. The deformable hanging-wall made of sand, clay, or sand and clay mixtures is first extended and then contracted (McClay, 1989, 1995; Buchanan and McClay, 1991; McClay and Buchanan, 1992; Keller and McClay, 1995; Yamada and McClay, 2003). In these experiments, inversion results in both the reactivation of the main detachment and the initiation of new thrust faults. Inversion has also been achieved by uplift and rotation of a single rigid 'basement' block (Koopman et al., 1987) or by a series of rigid metal plates simulating rigid domino fault blocks (Buchanan and McClay, 1992; McClay and Buchanan, 1992; Mitra, 1993; Vially et al., 1994; Roure and Colletta, 1996). Reactivation of the normal faults is in this case again strongly influenced by the movement of the rigid blocks. A disadvantage of these models is the formation of rigid footwalls, basement blocks and metal plates that are unable to deform.

Other analogue experiments have allowed both footwall and hanging wall to deform freely. A graben-bounding master fault is initiated by a velocity discontinuity localised at the base of the model. This velocity discontinuity is created by the displacement of two overlapping basal plates. One of the basal plates is fixed to the mobile wall whereas

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the other is attached to the stationary wall. This particular set-up was used to study the geometry and kinematic evolution of structures in both extension and inversion models. In the experiments of Cloos (1968) and McClay and Ellis (1987) extension resulted in the formation of an asymmetric graben. In the inversion experiments of Eisenstadt and Withjack (1995) using wet clay, early shortening was accommodated by reverse displacement along the main normal faults. During further shortening, these reactivated normal faults are cut by low-angle thrust faults. No reactivation was observed in the clay models of Mitra and Islam (1994). Instead, initial shortening resulted in the uplift of the graben boundaries and in footwall deformation. Using the same experimental set-up, but with brittle and viscous analogue materials, Brun and Nalpas (1996) assessed the effects of obliquity between the direction of shortening and the graben axis. They showed that this obliquity had to be less than 45° to allow graben inversion and fault reactivation.

Our study is based on basin inversion experiments in which both the footwall and hanging wall are free to deform. These experiments use only granular materials as analogues for upper crustal rocks. Using a velocity discontinuity at the base, models are first extended and then shortened in the same direction. The extensional phase leads to the formation of an asymmetric graben that is progressively filled using materials of different strengths. Based on the fact that sedimentary deposits in basins are generally less competent than adjacent basement rocks, part of the graben fill consists of granular materials that are weaker than the surrounding material.

The aim of our experiments is to identify factors affecting the style of deformation and contributing to reactivation of the graben-bounding normal faults during inversion. We investigate the thickness and distribution of strong and weak layers constituting the graben fill and the pre-inversion basin orientation. In our experimental set-up we have complete control of graben location, width, infill and orientation before inversion. The experimental results are compared with other model studies and with natural examples.

2. Scaling and modelling materials

Deformation structures in analogue models generally are smaller, develop in a much shorter time, and require less force than structures in nature. Analogue models, therefore, must be scaled in such a way that similarity between the model and a natural example is as close as possible. The theory of mechanical scale models was applied to geological structures by Hubbert (1937, 1951) and Ramberg (1981), who derived a set of scale ratios between the mechanical properties of the model and the corresponding properties of the natural object. Dynamic similarity of the surface forces must be maintained for proper scaling and requires that both analogue material and natural (rock) material must have similar mechanical properties (cf. Weijermars and Schmeling, 1986). In general, upper crustal rocks are assumed to deform according to the Coulomb failure criterion, which implies a time-independent rheological behaviour and can be described by:

$$\tau = C_0 + \sigma\mu \quad \text{where} \quad \mu = \tan\phi$$

where C_0 = cohesion, σ = normal stress, τ = shear stress, μ = coefficient of internal friction, and ϕ = angle of internal friction.

As ratios of length and time are independent ratios, we can then choose ratios suitable for our experiment.

In our experiments, quartz sand, corundum sand and microbeads are used as analogue materials. The size of the grains varies between 80 and 200 µm for quartz sand, between 88 and 125 µm for corundum sand and between 70 and 110 µm for microbeads. We determined the mechanical properties of each of these granular materials using a ring shear tester (Schulze, 1994). Several authors have shown that the standard assumption that granular materials are ideal cohesionless Coulomb-materials with constant frictional properties is inadequate (Lohrmann et al., 2003; Panien 2004). In our ring-shear tests, friction was determined for three different states: at the onset of failure (first peak strength), at the moment of fault reactivation (second peak strength) and once a fault is formed or reactivated (dynamic-stable strength) (Table 1 and Fig. 1). The cohesion values are difficult to estimate for the low normal stresses found in our models. Repeated ring-shear tests on the same analogue material revealed widely varying cohesion values. According to shear tests made by Schellart (2000), granular materials have negligible cohesion at very low normal stresses (<400 Pa).

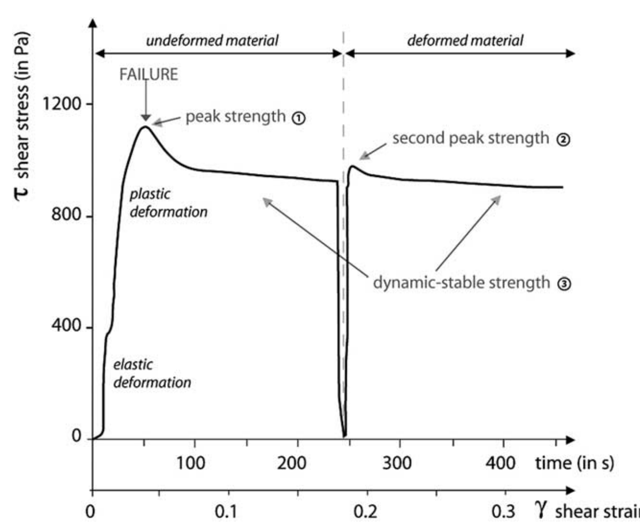

Fig. 1. Shear stresses (τ) variations plotted as a function of shear strain (γ) and time obtained with a ring-shear tester for corundum sand using a normal load of 3 kg. The numbers (1, 2 and 3) correspond to the numbers of Table 1.