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Normal fault inversion by orthogonal compression: Sandbox experiments with weak faults

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ABSTRACT

Linear frictional failure criteria predict that normal faults form dipping around 60°, and reverse faults around 30°, depending on dry rock properties. Therefore, it is unlikely that normal faults be reactivated as reverse faults, unless the stress conditions are favourable, or the intrinsic properties of the intact rock or of the precursor fault (PF) are modified. In the present study, we focused on friction (strength) of the PF. We used sandbox experiments with an initially embedded weak PF dipping 60° or 70°, filled with a thin film of silicone putty that lubricated the (weak) fault, to investigate inversion of high angle PF by orthogonal compression. The results show that: (1) the PF can be inverted if it is weak during compression, even if the angle of dip is as great as 70°; (2) after inversion initiation, the reverse movement on the PF can last for as much as 30% model shortening, leading to great amounts of reverse displacement along the PF before the formation of a thrust ahead; (3) in models with more than one PF, the weakness of the reactivated fault closer to piston was not enough to prevent reactivation of the PF further ahead, after an amount of shortening that depended on distance between PFs.

The viscous material used to weaken the fault is scalable to salt in nature. However, the great decrease in friction due to lubrication with a viscous material can simulate many other weakening mechanisms observed in nature.

1. Introduction

The inversion of grabens has received great attention in the past two to three decades, because (1) of the important economic role played by inverted structures in petroleum generation and trapping; (2) most deformation in the brittle upper crust is accommodated by the reactivation of existing faults rather than by the creation of new faults; and (3) of the mechanical problem raised by inversion of high angle precursor faults (PF). Sibson (1985) showed that in nature, for typical rock friction coefficients, it is unlikely that high angle normal faults be reactivated as high angle reverse faults, unless the effective least principal stress is tensile and/or the friction coefficient is abnormally low. Brun and Nalpas (1996) showed experimentally that normal fault inversion occurs only when the angle of inversion is less than 45°. Despite these results, many authors have tried to simulate normal fault inversion by orthogonal compression using sandbox experiments. However, they have been, with no exception, unsuccessful. Even Sassi et al. (1993) and Panien et al. (2005), who made the normal faults weaker prior to shortening, did not succeed in producing significant reverse movement (if any) in the PFs. Therefore, we start by analyzing why.

The most intuitive way to do this is by using the Mohr diagram (Fig. 1). Dry quartz sand has negligible cohesion (e.g. Hubbert, 1951; Schellart, 2000), hence the fracture line for intact sand goes through the origin of the coordinate system. Despite the many determinations of the angle of internal friction (ϕ) of sand, we use a very commonly used $\phi = 35°$ (e.g. Hubbert, 1951). With such a construction, it is clear that normal faults cannot be reactivated by orthogonal compression when pure dry quartz sand is used. Increase of σ_1 during compression at constant σ_3 (dashed half circles in Fig. 1) makes the Mohr circle touch the fracture line for intact sand much before the point corresponding to the precursor normal fault does. Then a great deal of the Mohr circle will be inside the instability field (stresses greater than needed to form a fault). Therefore, less differential stress is required to form a new, low angle reverse fault (thrust), than to reactivate the PF. Even if one argues that a PF is weaker than intact sand because of dilation, the difference is not that significant (e.g. Sassi et al., 1993). The angle ϕ for the PF would be only slightly less than 35°, and hence much less work would be necessary to create a new thrust. Therefore, to invert precursor normal faults in a sandbox (or in nature), changes must

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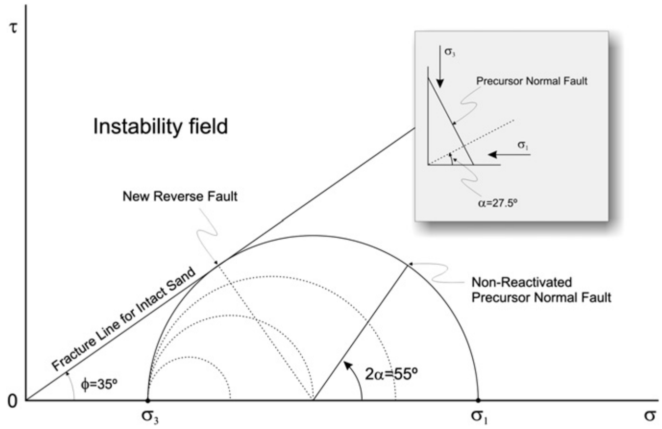

Fig. 1. Mohr diagram for sand. Increase of σ_1 during compression at constant σ_3 (dashed half circles) makes the Mohr circle touch the fracture line for intact sand much before the point corresponding to the precursor normal fault. Therefore, a low angle reverse fault forms instead of reactivation of the precursor high angle fault.

occur in σ_3 and/or in the intrinsic properties of the fault as indicated by Sibson (1985).

Possible solutions are the use of fluid overpressure and/or weak faults, as a first approximation, to significantly change the intrinsic properties of pure dry quartz sand or of PFs. The effects of overpressure have been studied with sandbox experiments by, e.g., Cobbold and Castro (1999) and Mourgues and Cobbold (2003). In the present study, we investigate the effects of fault weakening on the inversion of high angle PFs by orthogonal compression, by lubricating the fault surface (much lower coefficient of friction). In order to weaken the fault, we insert a thin layer of silicone putty on the fault, which substantially decreases the friction on the fault surface and can simulate widespread weakening mechanisms and be compared directly with salt injection in natural faults. It is not the aim of the present study to discuss weakening mechanisms; we just take as premise that they exist and can be simulated with a weak analogue material.

We used sandbox modelling to investigate the: (1) effects of fault weakening on inversion of high angle PFs during shortening; (2) amount of dip slip displacement during inversion; and (3) inversion in a model with more than one PF. We did not carry out a first phase of extension of the model to make the normal faults (similar to Sassi et al., 1993); for practical and strategic reasons, we used models with initially embedded weak faults whose angle of dip is typical for normal faults that form in nature and in sandbox experiments, which is between 50° and 70°.

2. Experimental method

2.1. Scaling

We chose a length ratio (model over nature) $l_r = l_m/l_n = 5.0 \times 10^{-6}$, so that a brittle crust 10 km thick scales down to a model layer ca. 50 mm thickness. Our models were 400 mm long, 100 mm wide and 50 mm deep (Fig. 2), thus representing 80 km × 20 km × 10 km in nature. We chose a strain rate ratio $(v_m/l_m)/(v_n/l_n) \approx 10^9$, so that a prototype velocity (v) of about 0.44 cm yr^{-1} (ca. 1.4×10^{-8} m s^{-1}) scales down to ca. 7.0×10^{-5} m s^{-1} in the models.

For the convenience of PDMS as geological model material, in particular as analogue of rock salt, we rely on the detailed analyses of Weijermars (1986) and Weijermars et al. (1993).

2.2. Model materials

To model the brittle upper crust, we used a Coulomb material, natural quartz sand from Fontainebleau, with grain size of ca. 300 μm, density of ca. 1.3×10^3 kg m^{-3}, very low cohesion and an angle of internal friction between 30° and 40°, as in brittle rock (e.g. Hubbert, 1951). For better definition of faults, Galland et al. (2006) and Coelho et al. (2006) used silica powder. For the present experiments, normal sand seemed appropriate. However, ongoing work on fault reactivation by our group will use silica powder. For the viscous filling of the PF (in some experiments also at the base of the sand pack), we used polydimethylsiloxane (PDMS – Dow Corning SGM36), which, at room temperature, has a density of ca. 0.965×10^3 kg m^{-3}, is Newtonian (at the applied strain rate) and has a viscosity of about 5×10^4 Pa s.

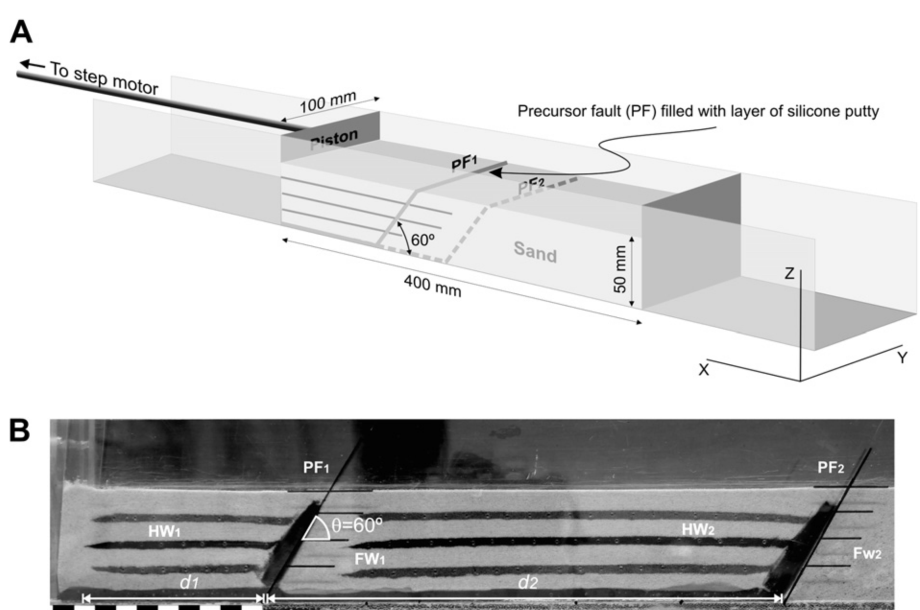

Fig. 2. (A) Sketch of geometry and layer distribution in the experimental models. (B) Side view of initial stage. PF_1 and PF_2 are precursor faults closest to and furthest from piston. HW_1 and HW_2 are hanging walls to PF_1 and PF_2, respectively.