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Fault reactivation control on normal fault growth: an experimental study

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Abstract

Field studies frequently emphasize how fault reactivation is involved in the deformation of the upper crust. However, this phenomenon is generally neglected (except in inversion models) in analogue and numerical models performed to study fault network growth. Using sand/silicon analogue models, we show how pre-existing discontinuities can control the geometry and evolution of a younger fault network. The models show that the reactivation of pre-existing discontinuities and their orientation control: (i) the evolution of the main fault orientation distribution through time, (ii) the geometry of relay fault zones, (iii) the geometry of small scale faulting, and (iv) the geometry and location of fault-controlled basins and depocenters. These results are in good agreement with natural fault networks observed in both the Gulf of Suez and Lake Tanganyika. They demonstrate that heterogeneities such as pre-existing faults should be included in models designed to understand the behavior and the tectonic evolution of sedimentary basins.

Keywords: Normal faults; Reactivation; Relay faults; Extension; Rift; Gulf of Suez; Lake Tanganyika

1. Introduction

Fault propagation has been studied through field observation, analogue and numerical modeling. These methods have been used to define a growth sequence at the scale of an isolated fault and at the scale of the whole fault network: this growth sequence explains the evolution of throw and length by two main mechanisms, radial propagation and segment connection (Cartwright et al., 1995; Cowie and Scholz, 1992; Marchal et al., 1998; Peacock and Sanderson, 1991). The parameters emphasized to capture the characteristics of fault networks are mainly the characteristics of the homogeneous brittle layer such as the thickness and the mechanical behavior (Cowie and Scholz, 1992; Lavier et al., 1999; Vendeville et al., 1987). However, other controlling parameters such as fault reactivation are known to be important, as shown by several pieces of field evidence (see Morley, (1999) for a review). For example, in both the Gulf of Suez and the Lake Tanganyika rifts (East African rifts), geological evidence shows that earlier fault networks were reactivated during rifting (see below for references).

Despite these pieces of evidence, fault reactivation and the presence of pre-existing structural heterogeneities are generally neglected in analogue and numerical models of crustal extension. Analytical studies on reactivation (Ranalli and Yin, 1990; Yin and Ranalli, 1992) highlighted the importance of pre-existing fault orientation in the stress field. They do not take into account the entire fault population and cannot predict the features associated with reactivation, and for example the geometry of the small scale faulting around the reactivated faults. Experiments of oblique rifting on velocity discontinuity show the influence of an underlying oblique pre-existing zone of weakness (Clifton et al., 2000; McClay and White, 1995; Tron and Brun, 1991), especially on the fault orientation distribution. As underlined by Morley (1999), such studies neglect the effect of pre-existing zones of weakness inside the brittle layer. Only a few analogue and numerical models have included the pre-existing faults in a brittle layer. These models deal with basin inversion, thrust tectonics (Sassi et al., 1993), post-compression extension (Faccenna et al.,

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1995), and successive phases of extension (Bonini et al., 1997; Dubois et al., 2002) but not with reactivation of normal faults in extension. These studies show that reactivation depends not only on dip and strike of the pre-existing faults, but also on the spatial organization on the structural heterogeneities.

The aim of the experiments described in this paper is to define the influence of a pre-existing fault network on the geometry of the resulting normal fault network. We characterize its influence on fault orientation distribution, small faults, and depocenters.

2. Experimental procedure

The analogue models are made of sand representing brittle layers (2 cm thick) and silicone putty representing ductile layers (1 cm thick) (Fig. 1). They are deformed in a box with initial dimensions of $40\times50\times10\ \mathrm{cm}^3$. The dry sand obeys the Coulomb failure criterion, with a very low cohesion (30 Pa) and a friction angle of 35° (Dubois et al., 2002; Krantz, 1991). The silicon putty is a Newtonian fluid with a viscosity of 5×10^4 Pa s at room temperatures and strain rates of the experiments (Weijermars, 1986). These materials have been repeatedly used for modeling the brittle and ductile deformation of the crust and the scaling relations (see Hubbert, 1937; Davy and Cobbold, 1991) indicate that the length factor is about 10^{-5} (1 cm in the model represents 1 km) and the time factor is about 10^{-10} (1 h represents 1 Ma).

The discontinuities (Fig. 1) are created by the introduction of 0.5-mm-thick and 10-cm-wide pieces of cardboard through the sand layer down to the top of the silicone layer. Their dip is 60° and their strike is at 45 or 70° to the direction of extension. The introduction and removal of the cardboard create a zone of dilation as a result of grain re-arrangements. This zone acts as a zone of weakness and obeys a Coulomb's frictional slip criterion. The coefficient of friction (0.4) (Sassi et al., 1993) of this zone is lower than the internal friction (0.6) of the undisturbed sand (Sassi et al., 1993). The density of the discontinuities is about 50

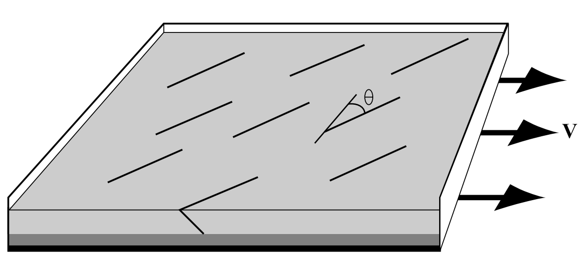

Fig. 1. Experimental setup. The models are composed of two layers, one sand layer representing brittle layers and one silicone layer that represents a viscous layer. The discontinuities are introduced by the introduction of a 10-cm-long piece of cardboard, with a dip around 60°. The extension is transmitted through the base of the model and the stretching of a basal rubber sheet.

faults per meter square. This density was mainly decided by practical reasons: spacing should not be too small to avoid perturbing a discontinuity when creating another one, spacing should not be too high to observe some fault interactions. The spacing of pre-existing faults in nature is difficult to estimate. Thus, we did not really try to simulate a particular natural spacing. In this study, a basal rubber sheet transmits the extension to the overlying materials and induces a quite homogeneous extension. The models have been chosen for their similarity with the conditions inside a rift, while at the scale of the whole rift, the basal conditions are often considered as a velocity discontinuity (Allemand and Brun, 1991; Brun, 1999; Michon and Merle, 2000). Furthermore, the models allow the intrinsic role of discontinuities inside the brittle layer to be examined without the influence of underlying discontinuities. The experiments are analyzed using photographs and time lapse topography of the models (laser acquisition with a resolution of $0.25\times0.25\times0.25$ mm). The topographic information is used to compute fault throw at the surface.

3. Results

The four experiments described below have been selected from a set of 20 experiments to highlight the role of the pre-existing discontinuity orientation and the consequences of fault reactivation at the scale of the complete fault network.

3.1. Experiment 1: reference experiment

The first experiment (Fig. 2) is an experiment without discontinuities (the layers are homogeneous). This experiment is briefly described and considered as a reference experiment. This experiment is a classical one, where sand and silicone are subjected to a basal extension. In this experiment, faults grow as detailed in many previous studies (Cartwright et al., 1995; Cowie and Scholz, 1992; Marchal et al., 1998; Peacock and Sanderson, 1991; Bellahsen et al., 2003). The fault segment connection occurs after interaction between two segments: one (or both) curves to connect to the other or secondary faulting occurs in the relay ramp (Fig. 2). In each case, the young relay segment fault has a throw smaller than the two older segments, which produces irregular throw profiles after connection. The throw minima can be about 50% of the maximum throw and are located at the linkage point (Childs et al., 1995; Peacock and Sanderson, 1991; Trudgill and Cartwright, 1994; Willemse et al., 1996).

The fault segments are counted as a function of their orientation. A fault segment is defined by its propagation mechanism (growth of a fault by lateral tip propagation) and its orientation. In experiment 1, the distribution of the fault segment orientation is unimodal, perpendicular to the extension direction, as shown in several previous studies (Clifton et al., 2000; Tron and Brun, 1991). During the