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The effects of pre-existing discontinuities on the surface expression of normal faults: Insights from wet-clay analog modeling

Lorenzo Bonini [a,*], Roberto Basili [b], Giovanni Toscani [c], Pierfrancesco Burrato [b], Silvio Seno [c], Gianluca Valensise [b]

[a] Dipartimento di Matematica e Geoscienze, Università di Trieste, Italy
[b] Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy
[c] Dipartimento di Scienze della Terra e dell'Ambiente, Università di Pavia, Pavia, Italy

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ABSTRACT

We use wet-clay analog models to investigate how pre-existing discontinuities (i.e. structures inherited from previous tectonic phases) affect the evolution of a normal fault at the Earth's surface. To this end we first perform a series of three reference experiments driven by a 45° dipping master fault unaffected by pre-existing discontinuities to generate a mechanically isotropic learning set of models. We then replicate the experiment six times introducing a 60°-dipping precut in the clay cake, each time with a different attitude and orientation with respect to an initially-blind, 45°-dipping, master normal fault. In all experiments the precut intersects the vertical projection of the master fault halfway between the center and the right-hand lateral tip. All other conditions are identical for all seven models. By comparing the results obtained from the mechanically isotropic experiments with results from experiments with precuts we find that the surface evolution of the normal fault varies depending on the precut orientation. In most cases the parameters of newly-forming faults are strongly influenced. The largest influence is exerted by synthetic and antithetic discontinuities trending respectively at 30° and 45° from the strike of the master fault, whereas a synthetic discontinuity at 60° and an antithetic discontinuity at 30° show moderate influence. Little influence is exerted by a synthetic discontinuity at 45° and an antithetic discontinuity at 60° from the strike of the master fault. We provide a ranking chart to assess fault-to-discontinuity interactions with respect to essential surface fault descriptors, such as segmentation, vertical-displacement profile, maximum displacement, and length, often used as proxies to infer fault properties at depth. Considering a single descriptor, the amount of deviation induced by different precuts varies from case to case in a rather unpredictable fashion. Multiple observables should be taken into consideration when analyzing normal faults evolving next to pre-existing discontinuities.

1. Introduction

Understanding how a normal fault evolves over time and how its geometry can be reconstructed from its surface evidence has been discussed at length in the literature. The most common way to describe a surface fault and to discuss its evolution is through three parameters: the maximum displacement (Dmax), the total length of the surface trace (L), and the displacement distribution along the fault trace. Relationships between these parameters and their variations over time and space have been extensively investigated (e.g., Schlische et al., 1996; Kim and Sanderson, 2005, and references therein; Torabi and Berg, 2011) and are often used to derive parameters that are unknown or cannot be directly measured. For instance, in active tectonics studies, Dmax, L, or displacement distribution profiles are often used to speculate about segmentation processes and then estimate the magnitude of either future or past earthquakes using empirical relationships (e.g., Wells and Coppersmith, 1994; Wesnousky, 2008; Leonard, 2014). It is well known, however, that 1) the degree of development of faults at the surface combined with 2) local geological conditions may complicate our understanding on the real geometry or behavior of faults at depth using empirical relationships or theoretical models (e.g. Cowie and Shipton, 1998; Bonini et al., 2014; Leonard, 2014). Concerning the first point, we know that faults evolve through different development stages. At immature stages a fault may be confined at depth; its surface evidence may consist of folds and secondary fractures associated with bending of the topographic surface (e.g. bending moment faults). At mature stages a fault is usually well expressed at the surface, its plane usually bounding a sedimentary basin (Gawthorpe and Leeder, 2000). As for the second point, the mechanical characteristics, the spatial distribution of different rock types and presence of pre-

* Corresponding author.
E-mail address: lbonini@units.it (L. Bonini).

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existing discontinuities (either faults or fractures) are first-order factors that alter the isotropy of host rocks which may subsequently affect fault development (e.g. Nicol et al., 1996; Tavarnelli et al., 2003).

The superposition of extensional fault systems derived by diachronic, non-coaxial, deformation phases is commonly observed in nature. This may happen in either of two cases: 1) regions that underwent multiple extensional phases, e.g. the North Sea (e.g., Whipp et al., 2014), Thailand (e.g., Morley et al., 2004), the East African rift system (e.g., Lezzar et al., 2002; Bonini et al., 2007; Corti et al., 2007), South Africa (Paton, 2006); or 2) regions where extensional phases are separated by a contractional phase (orogenic cycle), e.g. the Apennine (e.g., Hyppolite et al., 1994; Tavarnelli et al., 2001; Tavarnelli and Prosser, 2003), the Alps (e.g., Selverstone, 1988; Bonini et al., 2010; Decarlis et al., 2013), the Basin and Range in the western United States (e.g., Wernicke, 1981; Malavieille, 1993), and the Taiwan Orogen (e.g., Teng, 1996).

In this study we use analog models to investigate how pre-existing discontinuities, potentially formed under a different stress field or paleogeographic configuration, affect the surface expression of new normal faults. To this end we first carry out a series of mechanically isotropic experiments, aimed at building up an observation set for learning how an initially-blind normal fault develops before daylighting and beyond. Then, we repeat the experiments by introducing variously-oriented discontinuities and analyze their effect on the development of the surface fault properties.

2. Method

2.1. Modeling approach

Few materials are considered suitable to simulate extension in scaled physical models. Among them, dry granular materials (e.g. quartz sand) and wet clay are the most commonly used. How rheological differences between these two classes of materials affect modeling observations is a long-debated issue. Several investigators compared results obtained using wet and dry materials, concluding that both can be used (e.g., Eisenstadt and Sims, 2005; Withjack and Schlische, 2006; Withjack et al., 2007; Bonini et al., 2014) taking into account their specificities, e.g. dry sand does not behave as an ideal frictional-plastic material and clay has high cohesion preventing gravitational collapses (Mandl, 2000). Eisenstadt and Sims (2005) analyzed such differences also for tectonic inversion models, indicating that both wet and dry materials are good analogs, but wet clay is more appropriate than dry granular materials for simulating tectonic inversion/fault reactivation. As of today, however, dry granular materials are the most used experimental methods to study the role of pre-existing faults (see Bonini et al., 2012 for a review). In these studies thin mechanical discontinuities are simulated by introducing thin weak layers of materials with less friction or strength than the dry granular materials representing fault-hosting rocks (e.g., Bonini et al., 2011: Ahmad et al., 2014; Toscani et al., 2014; Di Domenica et al., 2014; Faccenna et al., 1995; Bonini, 1998; McClay et al., 2000; Dubois et al., 2002; Gartrell et al., 2005; Konstantinovskaya et al., 2007; Sani et al., 2007; Marques and Nogueira, 2008; Cerca et al., 2010; Pinto et al., 2010). Alternatively, another technique consists in extending the model before compressing it, in case of positive inversion, or the opposite, in case of negative inversion (e.g., McClay, 1989; Del Ventisette et al., 2005, 2006; Withjack et al., 2007). So far, wet-clay models have not been much used because the only known method for introducing pre-existing discontinuities was to pre-form the material before the experiment (e.g., Henza et al., 2010). This limitation has been recently overcome with a novel method enabling the modeler to introduce thin weaknesses in wet clay by precutting the material with an electrified blade (Cooke et al., 2013; Bonini et al., 2014, 2015; Hatem et al., 2015). The low voltage current running through the blade helps to break the van der Waals bonds within the clay mixture and limits the dragging, thereby preserving the initially imposed shape. Moreover, these precuts are especially suitable to simulate pre-existing faults because the friction onto their interface is the same as that of faults that dynamically form in the wet clay as a result of deformation. This novel technique allows the modeler to introduce very thin discontinuities in an easier and more accurate way than in other modeling setups based on granular materials, and to effectively simulate natural fault zones represented by a small gap between the fault blocks. Considering the specific goal of our study, that involves the simulation of pre-existing high-angle discontinuities with various orientations with respect to an initially blind, extensional fault, we adopt the wet clay as the analog material and use an electrified cutter to introduce pre-existing discontinuities.

2.2. Experimental apparatus and scaling

The experimental apparatus consists of a clay box with an inclined plane representing the master fault plane (Fig. 1). Motion on the fault is restricted to the central and inclined part of the box and guided by a mobile rigid sheet pulled by a stepper motor. The fault footwall is made up by a rigid block. Above this block lies the analog material, i.e. the wet clay. As a clay type we use kaolin, the preferred clay for analog modeling (e.g. Eisenstadt and Sims, 2005; Henza et al., 2010; Cooke and van der Elst, 2012), and specifically the CC31 China Clay (see data in the Appendix). The master fault dip is set at 45° based on worldwide compilations of normal faults showing that this is the most common value in tectonically active regions (Jackson and White, 1989; Collettini and Sibson, 2001).

For a proper scaling of our experiments we use geometric, kinematic, and dynamic similarity relationships (Hubbert, 1937; Ramberg, 1981). Our mixture of wet kaolin has a 60% of water content by mass; as a

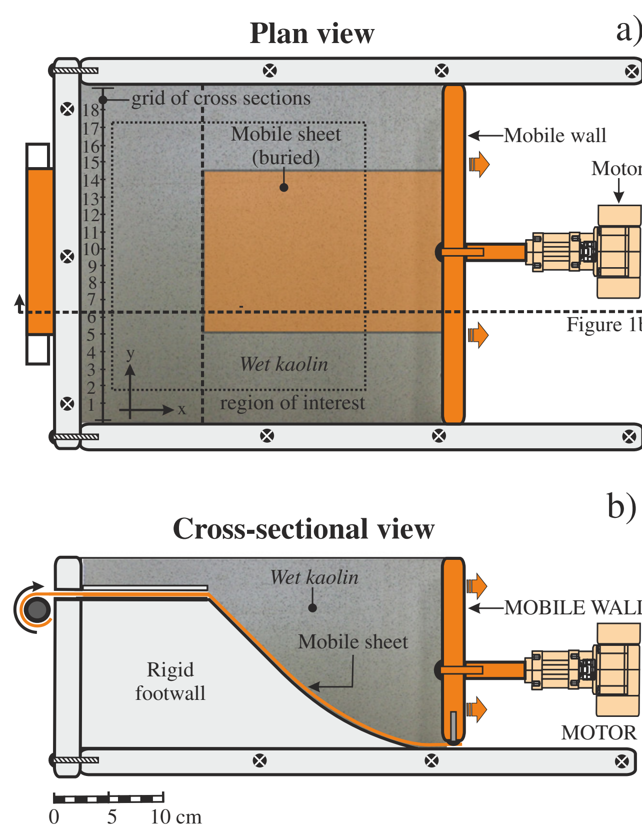

Fig. 1. Plan view (a) and cross-sectional view (b) of the experimental apparatus. Orange color marks the mobile parts.