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Changes in structural style of normal faults due to failure mode transition: First results from excavated scale models

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The effects of failure mode transition from tensile to shear on structural style and fault zone architecture have long been recognized but are not well studied in 3D, although the two modes are both common in the upper crust of Earth and terrestrial planets, and are associated with large differences in transport properties. We present a simple method to study this in physical scale models of normal faults, using a cohesive powder embedded in cohesionless sand. By varying the overburden thickness, the failure mode changes from tensile to hybrid and finally to shear. Hardening and excavating the cohesive layer allows post mortem investigation of 3D structures at high resolution. We recognize two end member structural domains that differ strongly in their attributes. In the tensile domain faults are strongly dilatant with steep open fissures and sharp changes in strike at segment boundaries and branch points. In the shear domain fault dips are shallower and fault planes develop striations; map-view fault traces undulate with smaller changes in strike at branches. These attributes may be recognized in subsurface fault maps and could provide a way to better predict fault zone structure in the subsurface.

1. Introduction

It is well known that brittle rocks can fail in opening-mode, shearing-mode or in hybrid mode (Hancock, 1985; Engelder, 1999; Ferrill and Morris, 2003; Ramsey and Chester, 2004; Chemenda et al., 2011). Tensile and shear failure modes are both common in the upper crust (Mandl et al., 1977; Price and Cosgrove, 1990; Mandl, 2005) and the transition from tensile to shear failure (for the same material) occurs with an increase in effective mean stress. In a normal faulting stress regime, fault dip decreases with the transition to shear failure (Fig. 1).

Experimental evidence of failure mode transition due to changes in confining pressure has been presented by Paterson (1978), Ramsey and Chester (2004), Bobich (2005) and Rodriguez (2005) based on triaxial experiments on Marble and Sandstone as well as by Chemenda et al. (2011) and Nguyen et al. (2011) based on pressed TiO_2 powder. These tests showed that with increasing confining pressure the fracture style changes and the angle between the fracture and maximum principle stress direction increases. Schöpfer et al. (2007a, 2007b) used a similar geometry in discrete element models to calibrate and model failure mode transition in 2D fault zones. When the hard layers fail in tension wider and more complex fault zones develop; whereas when the whole layered model fails in shear the fault zones tend to be narrower and there is a smaller change in dip across layer boundaries. Patton et al. (1998) studied experimental faulting in layered limestone samples under confining pressures of 100 and 200 MPa. Two-dimensional crosscuts of the experiments showed that lower pressures lead to extensional failure and more irregular faults.

Dilational faulting has received much less attention than shear faulting, although it has been argued to be common, for example in Mid Oceanic Ridge basalts where dilational faults may host large life forms in caves under the sea floor (Holland et al., 2006) and in carbonates at shallow depths (e.g. van Gent et al., 2010). Field examples of dilational normal faults have been described in a variety of rock types and geologic settings. Ferrill and Morris (2003) characterized fault refraction and dilational normal faults in mechanically layered carbonates of central and west Texas; the authors also described dilational normal faults in mechanically layered carbonates and clastic sedimentary strata in the North Pennine Orefield, England. Ferrill et al. (2014) studied normal fault refraction and dilational normal faulting in mudrock and chalk in south-central Texas. Van Gent et al. (2010) observed dilatant faults in competent carbonates of the United Arab Emirates. Several

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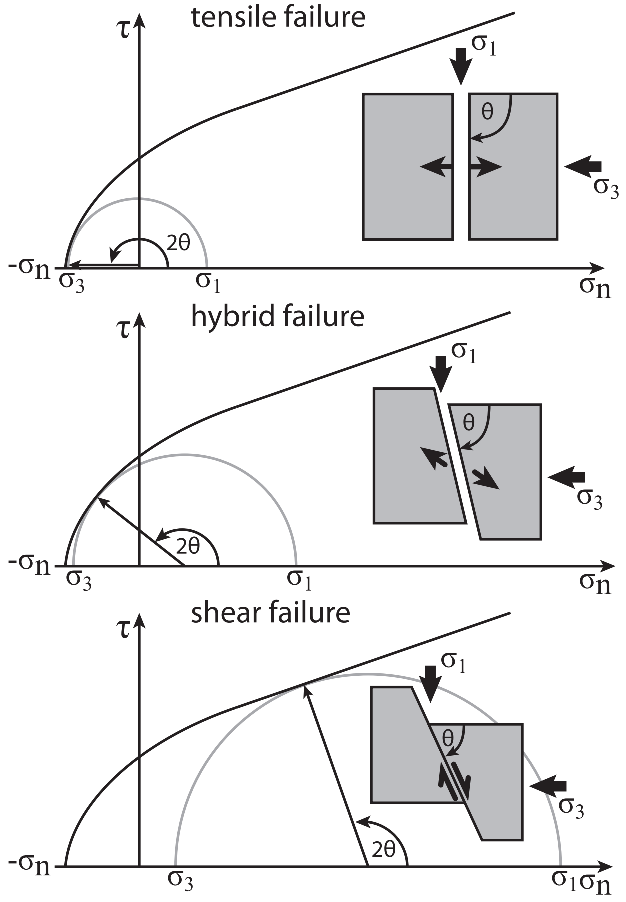

Fig. 1. Schematic illustration representing the Mohr-Coulomb failure criterion for tensile, hybrid and shear failure.

authors have studied basalts in Hawaii and Iceland which show massively dilatant extensional faults (Gudmundsson and Bäckström, 1991; Angelier et al., 1997; Acocella et al., 2000; Holland et al., 2006; Ferrill et al., 2011b). Soden and Shipton (2013) investigated dilational faults on Gran Canaria and found mechanical property variations to be a controlling factor for the development of extension fractures. Ferrill et al. (2012) described a small-displacement fault in Texas, USA, comprising features of both dilatant and shear failure. The features included local changes of fault dip expressed by calcite covering steeper parts and shallower dipping lower parts containing slickenlines. The authors interpret these as indicators for hybrid failure. Comparable structures have also been described by Ferrill et al. (2014) in chalk beds of the Eagle Ford Formation, Texas. Micarelli et al. (2005) investigated two faults in a limestone layer formed at different depths in the SE-Basin, France. They observed brittle processes such as dilational jogs in the low pressure regime, whereas at greater depths the faults consist of shear zones connecting en-echelon pull-aparts, which are most likely caused by hybrid failure. Under non-cohesive overburden, voids are filled with sand from the overburden. Depending on the amount of dilatancy this process forms either pit craters or large along-strike/elongated collapse grabens. These pit craters were described by Ferrill et al. (2004, 2011b) on Mars and in Iceland.

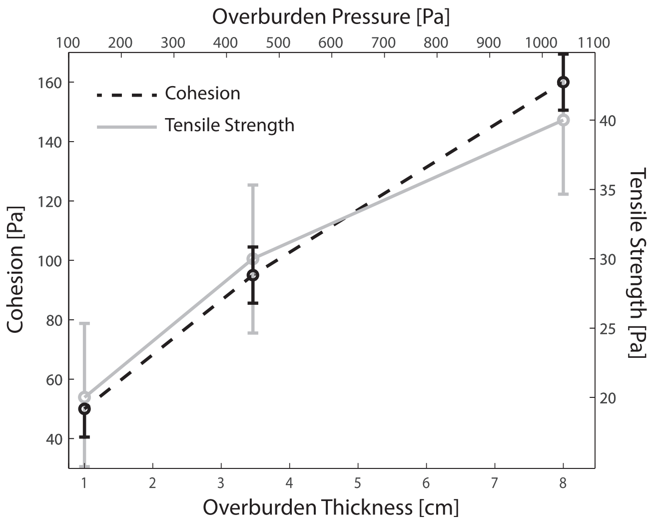

Fig. 2. Relationship of cohesion, tensile strength and overburden pressure (thickness of overburden sand). Data compiled from van Gent et al., 2010. Error bars represent a possible range of values that might occur due to initial compaction during experiment setup.

In summary, although faulting in hybrid and extensional failure modes is important in the upper crust, corresponding 3D geometries are not well understood. In this study we present the first results of scale models of normal fault zones that develop in layered models, with different failure modes in the cohesive layer enclosed between two cohesionless layers which fail in shear. We aim to relate map-view structures to geometries of the fault zones. We use well characterized cohesive powders which have previously been used to study extensional and hybrid fracturing in scaled models (Walter and Troll, 2001; Galland et al., 2003, 2006; Ferrill et al., 2004; Holland et al., 2006; van Gent et al., 2010; Abdelmalak et al., 2012). The failure mode of the cohesive layer is changed from tensile to shear by increasing the overburden thickness and by that increasing the overburden pressure.

2. Methods

We used a model consisting of a 25 mm layer of hemihydrate powder on top of a sand layer covered by varying amounts of overburden sand to vary the failure mode of the cohesive layer. These models scale to represent cohesive layers embedded in cohesionless material in the upper few km of the crust (van Gent et al., 2010). Boundary conditions follow Eisenstadt and Sims (2005) with an asymmetric extensional graben above a moving base layer (cf. Fig. 3). Adding water post-mortem hardens the powder and allows the faults to be studied after removal of the cover sand. Particle imaging velocimetry (PIV) is used to study the velocity field. Three-dimensional models of the excavated brittle layers are acquired by photogrammetry and allow the fault dips, map-view fault geometry and fault zone structure to be analyzed.

2.1. *Material properties and scaling*

Properties of sand and hemihydrate powder at small stresses are well known from previous studies. In the following we summarize material properties and scaling.

2.1.1. *Sand*

We used quartz sand from Carlo Bernasconi AG, Switzerland (Quartz sand TYPE A 0.08–0.2 mm) that has been used as a standard for the BENCHMARK project (Schreurs et al., 2006). It has a packing density of 1324 kg/m^3. For the small overburden pressures used in our presented experiments the failure envelope of the cohesionless sand is non-linear (Maksimovic, 1989; Schellart, 2000; Noorsalehi-Garakani et al., 2013). Its mechanical properties under