Journal of Structural Geology 32 (2010) 1375–1391

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Evolution of fault zones in carbonates with mechanical stratigraphy – Insights from scale models using layered cohesive powder

Heijn W. van Gent [a,*], Marc Holland [a,1], Janos L. Urai [a], Ramon Loosveld [b]

[a] Structural Geology, Tectonics and Geomechanics, RWTH Aachen University, Lochnerstraße 4-20, D-52056 Aachen, Germany
[b] Shell Exploration & Production Company, 200 N. Dairy Ashford, Houston, TX 77079, USA

ARTICLE INFO

Article history:
Received 18 January 2008
Received in revised form
30 April 2009
Accepted 4 May 2009
Available online 19 May 2009

Keywords:
Analogue modelling
Dilatant faults
PIV
Hemihydrate
Graben
Carbonate
Caves
Cam-Clay
Fault zone

ABSTRACT

We present analogue models of the formation of dilatant normal faults and fractures in carbonate fault zones, using cohesive hemihydrate powder ($CaSO_4 \cdot ½H_2O$). The evolution of these dilatant fault zones involves a range of processes such as fragmentation, gravity-driven breccia transport and the formation of dilatant jogs.

To allow scaling to natural prototypes, extensive material characterisation was done. This showed that tensile strength and cohesion depend on the state of compaction, whereas the friction angle remains approximately constant. In our models, tensile strength of the hemihydrate increases with depth from 9 to 50 Pa, while cohesion increases from 40 to 250 Pa. We studied homogeneous and layered material sequences, using sand as a relatively weak layer and hemihydrate/graphite mixtures as a slightly stronger layer.

Deformation was analyzed by time-lapse photography and Particle Image Velocimetry (PIV) to calculate the evolution of the displacement field. With PIV the initial, predominantly elastic deformation and progressive localization of deformation are observed in detail. We observed near-vertical opening-mode fractures near the surface. With increasing depth, dilational shear faults were dominant, with releasing jogs forming at fault-dip variations. A transition to non-dilatant shear faults was observed near the bottom of the model. In models with mechanical stratigraphy, fault zones are more complex. The inferred stress states and strengths in different parts of the model agree with the observed transitions in the mode of deformation.

1. Introduction

Carbonate reservoirs contain a large part of the world's hydrocarbon supply (Arnott and Van Wunnik, 1996; Otrtuno-Arzate et al., 2003; Borkhataria et al., 2005; Ehrenberg and Nadeau, 2005). Many carbonates at shallow depth are strong relative to the mean effective stress; because their cohesion and high tensile strength allow them to sustain open fractures and cavities over many scales. These dilational structures focus the flow of fluids, influencing the hydraulic behaviour considerably (Arnott and Van Wunnik, 1996; Sibson, 1996; Billi et al., 2003; Ferrill and Morris, 2003; Otrtuno-Arzate et al., 2003; Billi and Storti, 2004; Crider and Peacock, 2004; Holland et al., 2006; Galland et al., 2006; Bussolotto et al., 2007; Breesch et al., 2009). This increase of structural permeability (Sibson, 1996) with deformation is important for hydrocarbon production (Arnott and Van Wunnik, 1996; Sapra, 1997; Van Konijnenburg et al., 2000; Kerans, 2002; Ehrenberg and Nadeau, 2005; Casabianca et al., 2007). Dilatant faulting could also help to explain the formation of some fault caves that have formed in association with tectonic faults and are not solely the result of dissolution (e.g. Gilli et al., 1999; Margielewski and Urban, 2003).

One cause for the formation of open segments along a fault is the change of the dip angle of shear fractures, which is quite common in mechanically stratified sequences (Wallace, 1861; Dunham, 1948, 1988; Ramsay and Huber, 1987; Peacock and Zhang, 1993; Sibson, 1996, 2000; Mandl, 2000; Ferrill and Morris, 2003; Schöpfer et al., 2007a). Ferrill and Morris (2003) described kite-shaped dilational jogs along fault traces in bedded carbonates in the Cretaceous Buda Limestone (western Texas, USA), deformed at a depth of less than 1 km. The faults show a systematic increase of the dip angle in the more competent layers of the succession, and steeper fault segments dilate to form open jogs. The cavities presently contain a calcite vein fill, resulting from increased vertical infiltration and along-strike fluid flow.

* Corresponding author. Tel.: +49 241 80 95416; fax: +49 241 80 92358.
E-mail address: h.vangent@ged.rwth-aachen.de (H.W. van Gent).
[1] Present address: GeoMechanics International, Emmerich-Josef Straße 5, 55116 Mainz, Germany.

0191-8141/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2009.05.006

Another cause for open fractures is Mode I tensile fracturing near the surface. In the basalts of north-eastern Iceland, tensile deformation structures dominate in the upper hundreds of meters, which grade through hybrid mode structures to pure shear faults at depths of roughly 1 km (Angelier et al., 1997).

Good quality outcrops of massively dilatant fault zones in carbonates are rare. Outcrops in Tertiary carbonates on Jebel Hafeet, on the border between the United Arab Emirates and Oman, expose some examples in carbonates deformed at shallow depths. Jebel Hafeet is one of a series of foreland anticlines of the Oman Mountains (Noweir, 2000). The young back-thrust-related anticline shows abundant normal fault systems parallel to the fold axis, which are interpreted to be related to outer-arc extension and uplift (Fig. 1). These normal fault zones in the area can be massively dilatant. Apertures of several decimetres are common, predominantly filled with carbonate veins, crushed wall rock or sediments (Fig. 1a and b). These sediments differ from the wall rock and often show a clear stratification. This suggests episodic sedimentation within the fault zones by either gravitational or hydraulic transport. Wide surface fissures are common on the mountain crest. These open structures strike parallel to the fold axis of the anticline (Fig. 1c and d), have opening magnitudes of more than a meter, and show angular blocks of carbonate, dislodged and rotated between the parallel walls (Fig. 1c), but their depth is difficult to access due to both the material infill and the outcrop conditions. The dilatant structures of the fault zones must have a strong effect on hydraulic circulation, suggesting that the caves of the Jebel Hafeet region are fault-related.

The present study is a follow-up of the experiments of Holland et al. (2006) with hemihydrate powder ($CaSO_4 \cdot ½H_2O$) to study the deformation of layered cohesive rocks in the upper crust through a series of scaled analogue models of a buried graben system in carbonates. In the first section of this paper, experiments to measure the material's characteristics are presented. The second section presents the results of a series of scaled analogue models of normal faults in hemihydrate powder, focussing on the effects of mechanical stratigraphy.

Physical modelling has a long history in geosciences (e.g. Cloos, 1930; Hubbert, 1937). Depending on the tectonic and structural processes modelled, a large variety of materials have been used; the most common is sand (Buiter et al., 2006; Schreurs et al., 2006). Recent studies on sand have shown complex strain-hardening behaviour prior to Mohr–Coulomb failure and asymptotic strain-softening (Schellart, 2000; Lohrmann et al., 2003; Panien, 2004; Schreurs et al., 2006). Dry sand does not have a tensile strength, only a small apparent cohesion and is unable to sustain open fractures (Schellart, 2000; Holland et al., 2006). The large grain size of sand produces relatively wide shear zones, as opposed to discrete failure planes (Horsfield, 1977; Lohrmann et al., 2003).

Much less attention has been given to model materials with tensile strength. Wet clay has been used as a material for brittle deformation, but the presence of open fractures was not analyzed in detail (Cloos, 1930; An, 1998). Cohesive materials were used to model volcano-tectonic processes and pit chain formations on Mars (Cailleau et al., 2003; Sims et al., 2003). Other materials include sand made cohesive by capillary forces (Cardozo et al., 2002), cement mixtures for the modelling of coal mine collapse (Xiao, 1993), fine grained silica powder (Galland et al., 2006) and dry hemihydrate powder (Holland et al., 2006). However, the

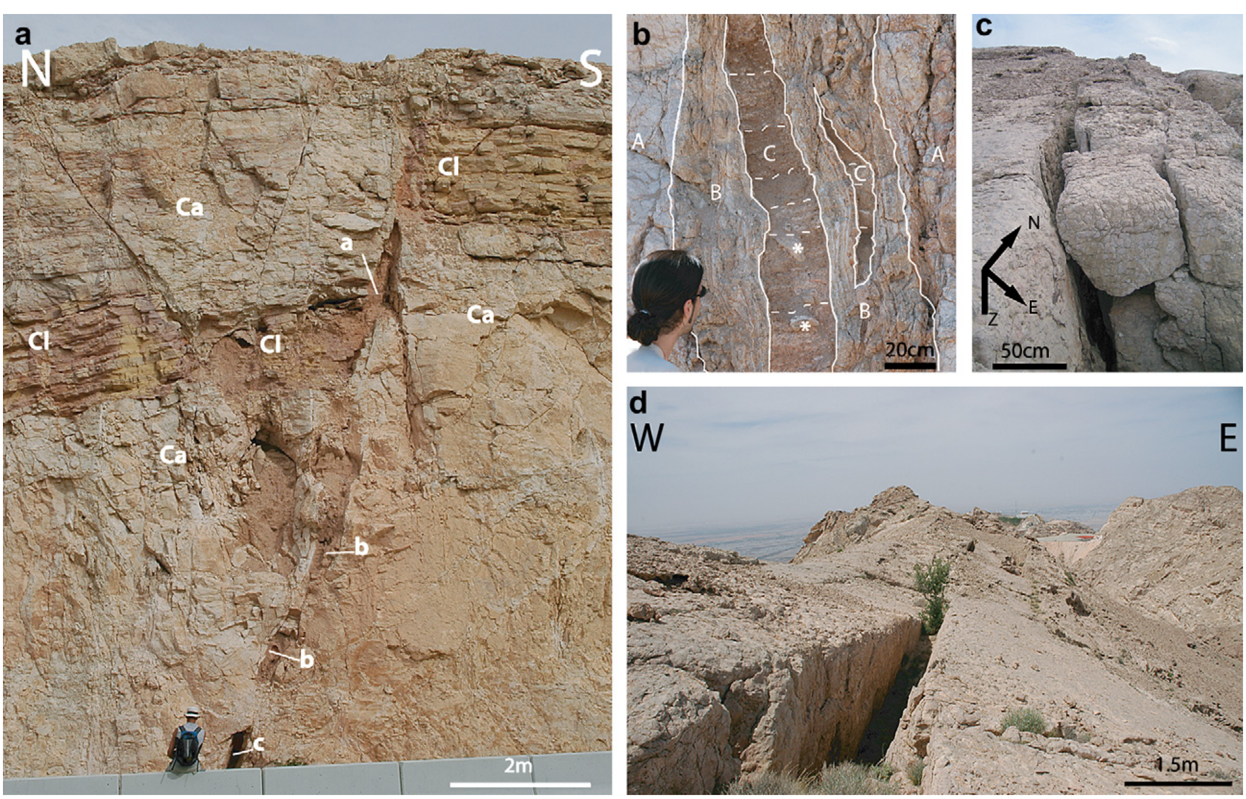

Fig. 1. (a) Normal fault zone in a competent carbonate (Ca), with approximately 3 m offset, showing strongly variable internal structure, width of the fault cavities and clastic infill. Material from a mechanically weaker, slightly more clayey carbonate layer (Cl) is included in the fault zone both between the up- and downthrown parts of the clastic deposits (a), as well as in cavities further down-dip (b). Also note the empty cavity in the bottom of the picture (c). (b) Opening-mode fracture showing layered clastic infill. On the wall rock (A) a rim of precipitated calcite (B) covers the fracture walls. The centre of the fracture (C) is filled with stratified unconsolidated sediments. Stars indicate decimetre size clasts. (c, d) Tensile open mode fissures parallel to the fold crest of Jebel Hafeet. Within the massive fissures blocks of wall rock are rotated (all images taken at Jebel Hafeet, U.A.E.).