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A model of strain localization in porous sandstone as a function of tectonic setting, burial and material properties; new insight from Provence (southern France)

Roger Soliva[a,*], Richard A. Schultz[b,1], Gregory Ballas[a,2], Alfredo Taboada[a,3], Christopher Wibberley[c,4], Elodie Saillet[d,5], Antonio Benedicto[e,6]

[a] University of Montpellier II, Laboratoire Géosciences Montpellier, Place E. Bataillon, 34095 Montpellier cedex 5, France
[b] ConocoPhillips Company, 600 North Dairy Ashford, Houston, TX 77079, USA
[c] TOTAL, CSTJF, Av. Larribau, 64018 Pau, France
[d] Strathclyde University, Department of Civil Engineering, Glasgow, UK
[e] AREVA NC, Direction des Géosciences, Paris-La Défense, France

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ABSTRACT

The analysis of three cataclastic band sets from Provence (France) reveals that the band density, their conjugate angles, their ratio of shear displacement to compaction, and the amount of cataclasis within the bands differ and can be expressed as functions of tectonic setting and petrophysical properties. We identify (1) a dense and closely spaced network of shear-enhanced (reverse) compaction bands; (2) a regularly spaced less dense network of reverse compactional shear bands; and (3) a localized network of normal shear bands. The field data show that strain localization is favored in an extensional regime and is characterized by shear bands with a large shear to compaction ratio and a small conjugate band angle. In contrast, distributed strain is favored in a contractional regime and is characterized by compactional bands with a low ratio of shear to compaction and a large conjugate band angle. To explain the mechanical origin of this strain localization, we quantify the yield strength and the stress evolution in extensional and contractional regimes in a frictional porous granular material. We propose a model of strain localization in porous sands as a function of tectonic stresses, burial depth, material properties, strain hardening and fluid pressure. Our model suggests that stress reduction, inherent to extensional regime, favors strain localization as shear bands, whereas stress increase during contraction favors development of compactional bands.

1. Introduction

The geometry of brittle strain localization in the Earth's crust was described as dependent on a series of factors including strain rate (e.g. England, 1983), initial weakness (e.g. Fletcher and Hallet, 1983), layering (Soliva and Schultz, 2008) or tectonic style and velocity conditions (Buck, 1991; Tikoff and Wojtal, 1999). In porous sandstone, it is well known from mechanical testing and theory that cataclastic strain localization is favored for large deviatoric stress states, promoting cataclastic shear bands, whereas distributed strain is favored for smaller deviatoric stresses and larger mean stress that promotes material compaction by porosity collapse in cataclastic compaction bands (e.g. Bésuelle, 2001; Rudnicki, 2004; Baud et al., 2004; Fortin et al., 2005). Field data also implicitly show that distributed strain is generally inherent to band systems having a large component of compactional displacement (Sternlof et al., 2005; Wibberley et al., 2007; Fossen et al., 2007; Schultz et al., 2008; Eichhubl et al., 2010; Saillet and Wibberley, 2010). However, the degree of dependence of the strain distribution with respect to the ratio of shear displacement to compaction has not been investigated. More recent band system analyses have been especially designed to decipher strain distribution in porous sandstone as a function of tectonic strain regime (extensional and contractional) (Solum et al., 2010). However the data interpretation in that paper is complicated because the study sites chosen differ in tectonic regime, structural context (tectonic style and boundary condition) and petrophysical properties (Fossen and Rotevatn, 2012) Tables 1–2.

* Corresponding author. Tel.: +33 (0) 4 67 14 32 78; fax: +33 (0) 4 67 14 36 42.
E-mail addresses: soliva@gm.univ-montp2.fr, solivaroger@yahoo.fr (R. Soliva).
[1] Tel.: +1 281 293 3975; fax: +1 281 293 2548.
[2] Tel.: +33 (0) 4 67 14 34 87; fax: +33 (0) 4 67 14 36 42.
[3] Tel.: +33 (0) 4 67 14 36 40; fax: +33 (0) 4 67 14 36 42.
[4] Tel.: +33 (0) 5 59 83 57 93; fax: +33 (0) 5 59 83 56 15.
[5] Tel.: +44 (0) 141 548 3010; fax: +44 (0) 141 552 0775.
[6] Tel.: +33 (0) 1 34 96 37 10; fax: +33 (0) 1 36 29 27 00.

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In this paper, we present an analysis of three different band systems from two study areas, which demonstrate that (1) within the same lithology of the same area (i.e. same petrophysical properties) the geometrical properties of a band system differ as a function of the tectonic regime; and (2) in different lithologies, different band networks occur for the same tectonic conditions. Based on these observations and the theory of plastic yielding in porous granular sandstones, we propose a model of band system formation as a function of tectonic stresses, burial and material properties.

2. Geological setting and host rock properties

The study area is located in the center of the South East Basin, France, between the Nîmes and the Cevennes faults (Fig. 1). This area experienced two major tectonic deformations (Arthaud and Seguret, 1981; Tempier, 1987; Seranne et al., 1995). The first is Pyrenean Paleocene to early Oligocene folding and thrusting due to a N–S compression. This contractional deformation stage caused the formation of E–W folds across the whole area enclosed between the Nîmes and Cevennes faults (Seguret et al., 1996; Sanchis and Seranne, 2000). These folds are interpreted to relate to thrust ramps cutting partially or entirely through the sedimentary cover. This mainly thin-skinned tectonic style was also accompanied by strike-slip movement along crustal-scale bounding faults. These large lateral ramps are the Nîmes and the Cevennes faults inherited from Mesozoic Thetysian extensional events and perhaps from the Hercynian orogeny.

The second stage of deformation is Oligocene rifting due to a NW–SE extension. This extension formed a series of small-scale half grabens restricted to the sedimentary cover that also reactivated the Cevennes and Nîmes faults, resulting in the Ales and the Camargue basin in-fill during the Oligocene (Roure et al., 1992; Seranne et al., 1995; Ford and Stahel, 1995). This NW–SE extension is kinematically consistent with other European rifting that is well expressed in the Rhine graben, and was followed to the south by the Gulf of Lion marine rifting event during the Miocene.

The three deformation band sets studied in this paper were analyzed from two study sites. The first one, the Uchaux site, located at the Boncavaï quarry (between Mornas and Uchaux; Figs. 1 and 2), is located on the southern limb of the E–W Mondragon anticline

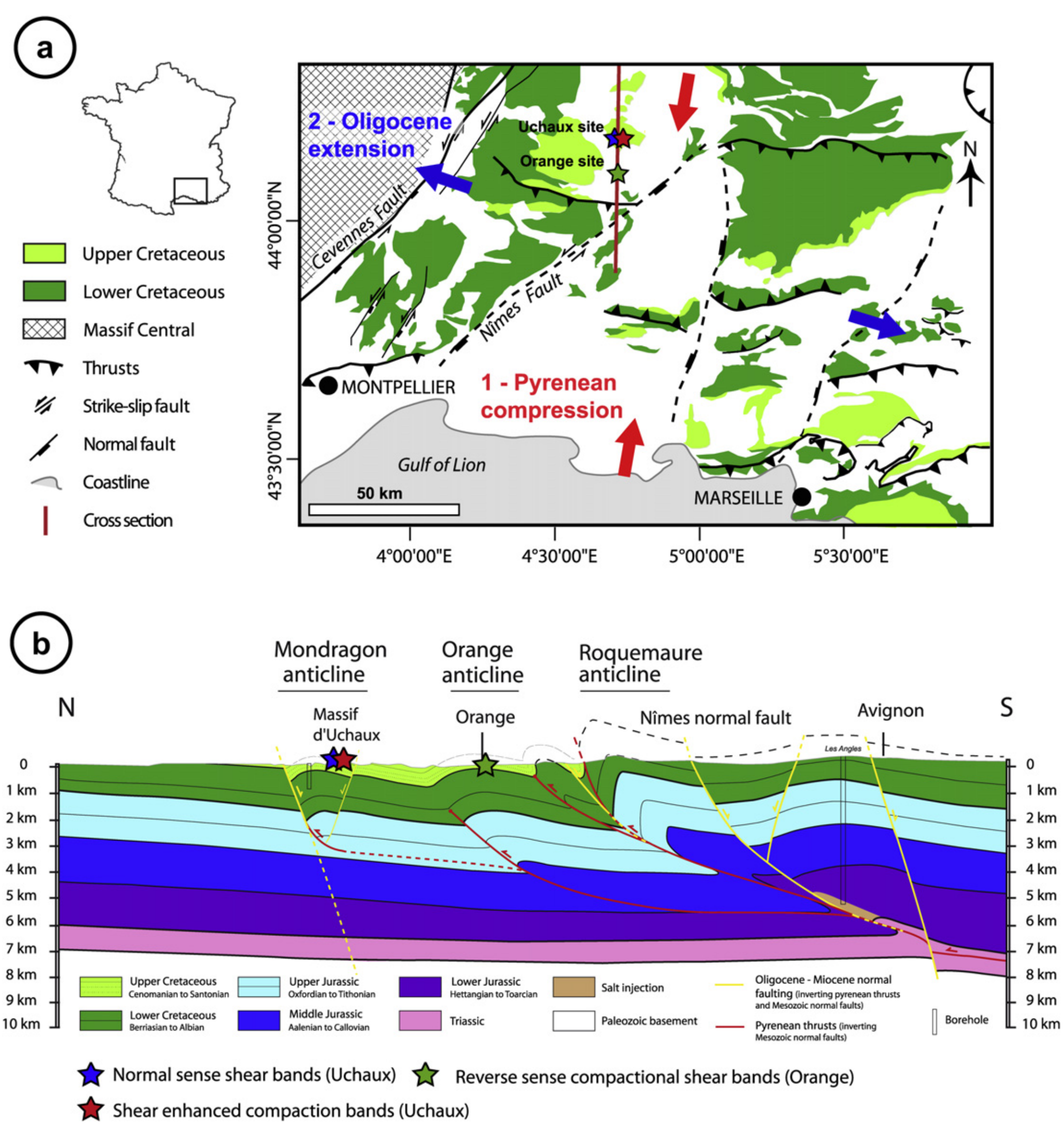

Fig. 1. Location of study areas. (a) Simplified geological map of the French south east basin. Stars in color show the studied outcrops and the red line is the position of the cross section presented in (b). Arrows show primary shortening direction for the Pyrenean event and the Oligocene extension. (b) North–South cross section across the study area and location of the studied outcrops. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)