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## Strain Localisation in Porous Sandstone as a Function of Tectonic Setting, Burial and Material Properties

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### SUMMARY

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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 are different and can be expressed as a function 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 the localization of strain is favored in an extensional setting and is characterized by shear bands with a large shear to compaction ratio and a low conjugate band angle. In contrast, distributed strain is favored in a contractional setting 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. We propose a model of strain localisation in porous sandstone as a function of tectonic stresses, burial depth, material properties, strain hardening and fluid pressure.

## Introduction

Deformation bands are brittle-ductile deformation structures in porous sandstones in which the petrophysical properties can be roughly different than the surrounding host rock. The origin of the band network geometry and the mechanical reasons for which they can be more or less cataclastic (i.e. efficient or transient membrane seal barrier) remains poorly analysed in the light of tectonic conditions, burial and material properties.

In this study, we present an analysis of three different band systems at two localities in Provence (France), which clarify the dependence of strain localisation to tectonic stresses and material properties. We examine (1) within the same lithology and petrophysical properties the dependence of strain distribution as a function of the tectonic regime, and (2) in two different lithologies, the dependence of strain distribution on sandstone material properties 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 tectonic stresses, burial, material properties, strain hardening and fluid pressures.

## Field study

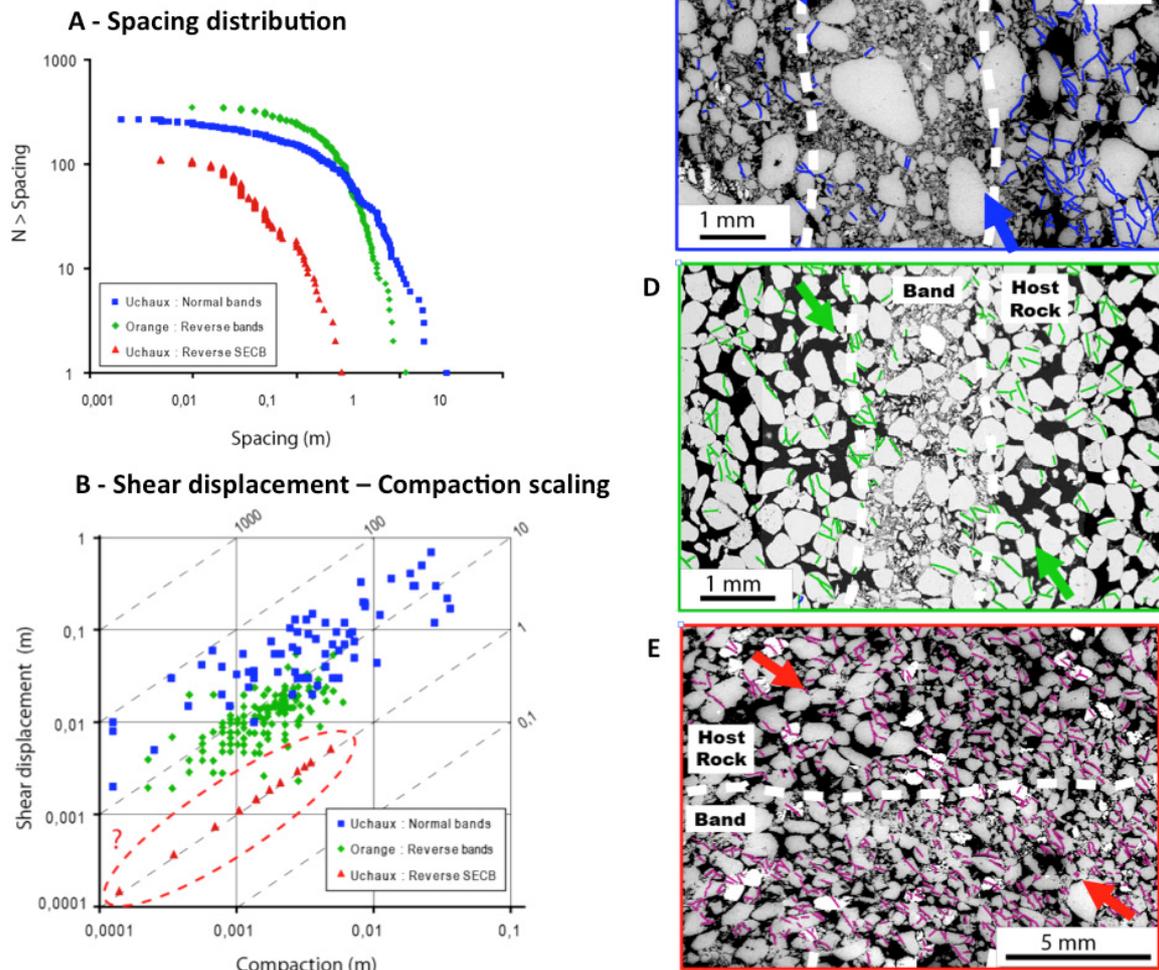
We have identified (1) a dense and closely spaced network of shear enhanced (reverse) compaction bands, (2) a regularly spaced less dense network of reverse compactional shear bands, and (3) a localized network of normal shear bands (red, green and bleu, respectively in Figures 1).

The first set is composed of conjugate **shear-enhanced compaction bands** (SECB), very closely spaced and showing wide variations in band thickness distribution. In thin section, force chains are recognized oblique to the bands, and bisecting their conjugate geometry at  $45^\circ$ . The orientation of the force chains (parallel to beds) suggest that shear, if any, must be of reverse movement and would then be in the opposite sense to the apparent offset due to compaction.

The second set is composed of conjugate E-W trending **compactional shear bands** of reverse sense. They show a regular spacing and a positive correlation between shear displacement and compaction. In thin section, a moderate cataclasis is observed and chains of fragmented particles are bisecting their conjugate geometry at  $\sim 38^\circ$  and therefore nearly parallel to the bedding. The mean ratio of *shear displacement* to *compaction* is 7.6 (with  $0.8 < D_s/D_c < 20$  and a standard deviation of 4.1), then close to 8 times higher than in the SECB band system.

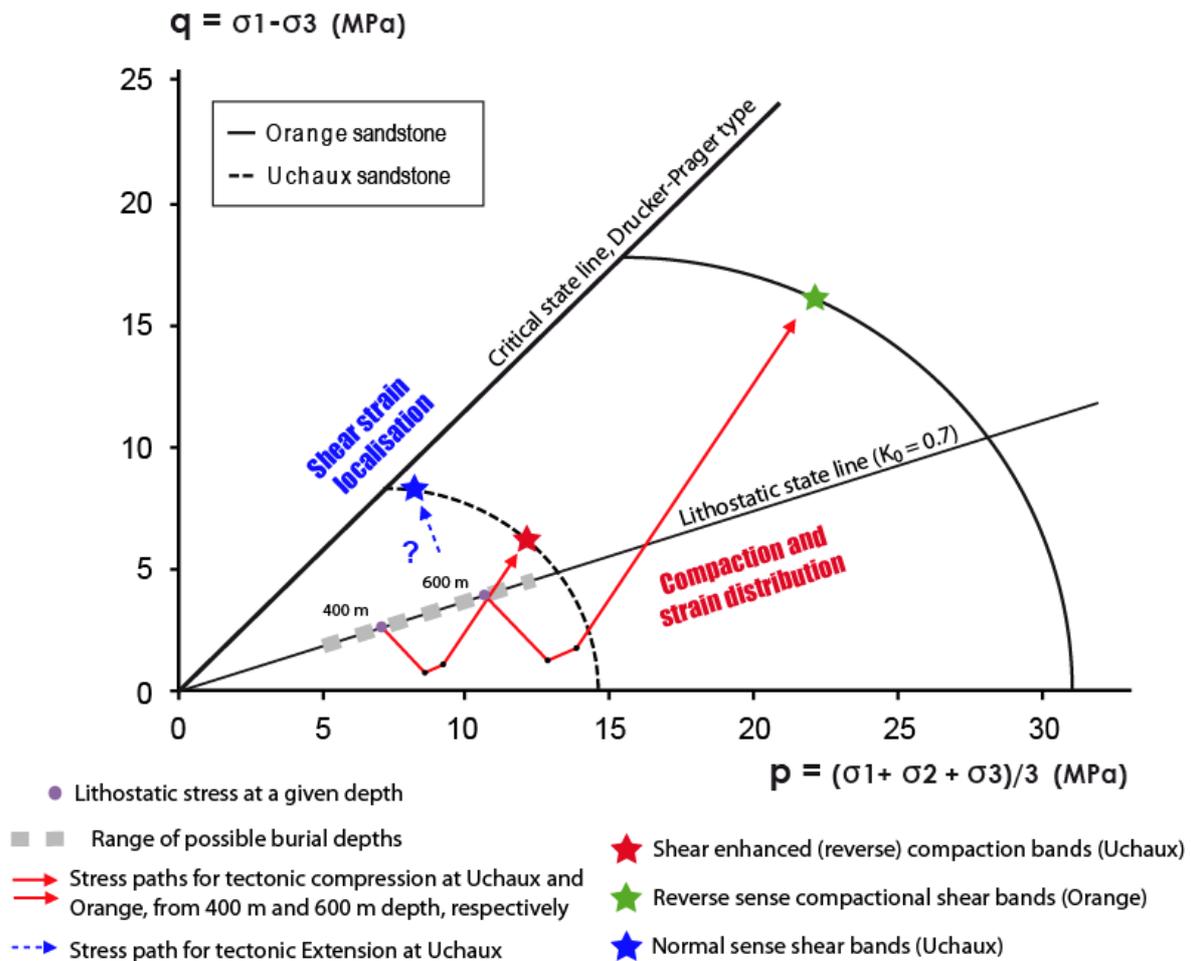
The third set consists of conjugate N-S oriented **shear bands** of normal sense, interacting with strike-slip fault zones by increasing their dip and their density. They show no clear regular spacing (clustered around the strike-slip faults) and a positive correlation between shear displacement and compaction. The degree of cataclasis is clearly the highest of the three studied band sets and force chains are bisecting their conjugate geometry at  $\sim 20^\circ$  and are therefore nearly vertical. The ratio of shear displacement to compaction is more variable than the other band sets with an average value of 23.7 (with  $0.4 < D_s/D_c < 90$  and a standard deviation of 19.7), and then also clearly the highest of the three studied band systems.

Using thicknesses of sediments still present and potentially eroded above, we estimate that all the band sets have been buried between 300 and 700 m (400 m at Uchaux and 600 m at Orange). Both the orientation and kinematic analysis of the first (compaction) and the second (reverse movement) band sets relate them to the Pyrenean compression. The tectonic origin of the third band set is probably related to the Oligocene rifting.



**Figure 1** Strain localisation in porous sandstones as shown by the scaling properties of the bands and the three different degrees of cataclasis observed in each type of band. A Cumulative frequency diagram of band spacing. B Graph of shear displacement vs. compaction. C, D and E are photomicrographs of the three band sets. C. Thin section photomicrograph of the normal shear bands from Uchaux showing a high degree of cataclasis. D Thin section photomicrograph and fracture mapping of the reverse compactional shear bands from Orange, showing moderate cataclasis. E. Thin section photomicrograph and fracture mapping of the reverse SECB from Uchaux, showing a low degree of cataclasis.

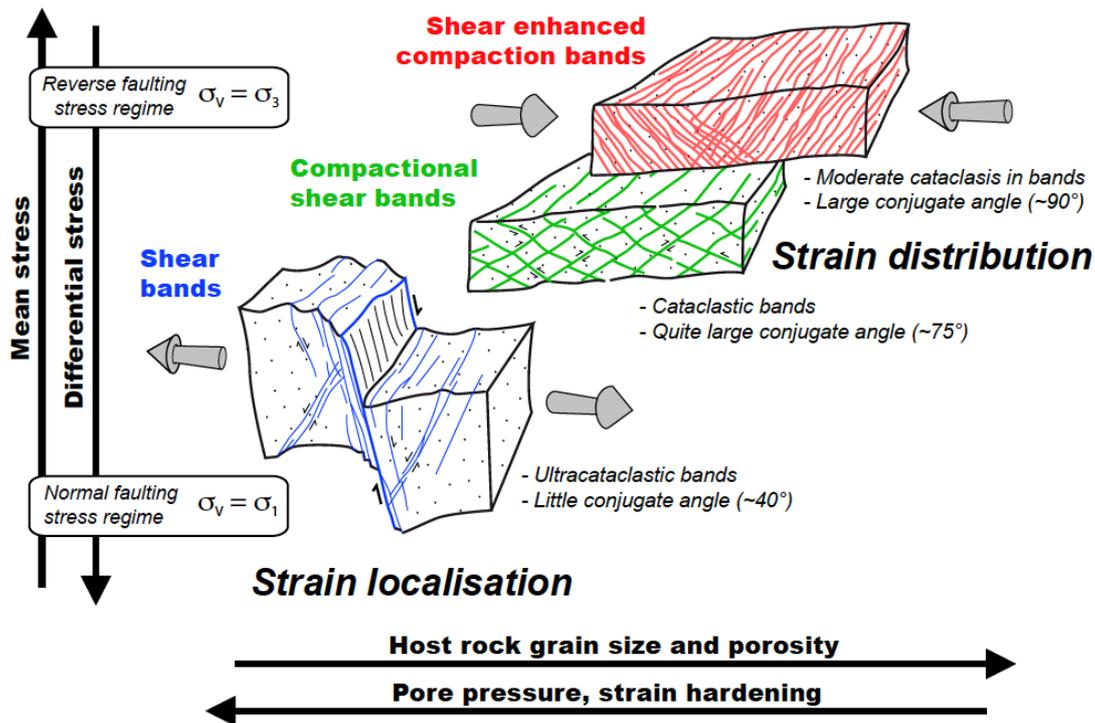
Localization of strain appears to be favored in extensional tectonic settings and is characterized by normal sense shear bands with a large shear to compaction ratio, a large amount of cataclasis and a low conjugate band angle. In contrast, spatially more distributed strain is favored in contractional tectonic settings and is characterized by reverse sense compactional bands with moderate cataclasis, a low ratio of shear to compaction and a large conjugate band angle.



**Figure 2** Graph of  $q$  vs  $p$  stresses including Druker-Prager – cap envelopes, burial and tectonic stress paths. The cap sides of the envelopes have been using porosity and grain size values for the Uchaux and Orange porous sandstones. Burial and tectonic stress paths have been calculated using a  $K_0 = 0.7$ . Colored stars represent the expected stress conditions to create the three deformation bands sets studied. Two different depths, 400 and 600 m are used for Uchaux and Orange, respectively. These graphs show that shear strain localization is favored in extensional stress conditions whereas strain distribution is favored for contractional conditions.

## Mechanics

To explain the mechanical origin of this strain localization, we propose a model of stress evolution and plastic yielding in porous granular sandstones (Figure 2). The stress path model suggests that strain localization with a large component of shear is favored in extensional settings since the deviation of stresses from a burial path must evolve by an increase of deviatoric stresses and a reduction of the mean stress. This stress reduction, inherent to extensional settings implies a high probability of the stress path to cross the critical state line or the cap side of the envelope in its upper part. In contrast, distributed strain on multiple bands having a large component of compaction is likely to occur in contractional settings because of the high rate of increase of the mean stress and the larger probability to cross the middle or lower part of the yield cap. A stress permutation scenario related to the horizontal stress increase from a lithostatic state is proposed for contractional settings to explain the occurrence of reverse sense compactional bands and the low probability to obtain strike slip sense bands.



**Figure 3** Model of strain localization or distribution as shear or compaction dominated bands respectively, as a function of several parameters including mean and differential stress, sandstone grain size, porosity, pore pressure and strain hardening. Both the strain distribution, the sense of shear, the amount of cataclasis and the conjugate angles are controlled by the relative interplay between the parameters cited above.

## Conclusions

The main results are summarized in the following points:

- (1) In the same lithology (Uchaux porous sandstones) it is possible to obtain significant differences in the band network geometry and degree of cataclasis as a function of the tectonic regime applied (Pyrenean compression and Oligocene extension).
- (2) In two different lithologies (Uchaux and Orange sandstones), it is possible to obtain two different band network geometry and degree of cataclasis in the same contractional tectonic regime (Pyrenean compression).
- (3) The average ratio of *shear displacement* to *compaction* has been estimated to be around 1 for the shear enhanced compaction bands from Uchaux, around 8 for the compactional shear bands from Orange and much more variable but around 24 for the shear bands from Uchaux (Figure 1B).
- (4) The band kinematics, i.e. *shear displacement* to *compaction*, has been related to the mean and the differential stresses, grain size, porosity, fluid pressure and strain hardening (Figure 3).
- (5) Band initiation as strike-slip seems least probable in compressive context because of the large *coefficient of Earth pressure at rest* (ratio between the lateral to the axial stresses) inherent to such a compliant, frictional and incohesive granular material