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Control of tectonic setting and large-scale faults on the basin-scale distribution of deformation bands in porous sandstone (Provence, France)

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ABSTRACT

From outcrops located in Provence (South-East France), we describe the distribution, the microstructures, and the petrophysical properties of deformation band networks related to both contractional and extensional tectonic events. In contraction, pervasively distributed networks of reverse-sense compactional shear bands are observed in all folded sand units of the foreland, whereas localized networks of clustered reverse-sense shear bands are only observed close to a large-scale thrust. In extensional setting, networks of clustered normal-sense shear bands are generally observed adjacent to map-scale faults (100 m–10 km scale), although some randomly distributed bands are also observed between these faults. Normal-sense cataclastic faults, i.e. zone of deformation bands containing a localized slip-surface, are also observed to be restricted to sand units, suggesting that faults initiated in the sands during extension, but not during contraction. Shear bands and faults show cataclastic microstructures with high-permeability reduction whereas compactional shear bands show crush microbreccia or protocataclastic microstructures with moderate permeability reduction. This basin-scale analysis underlines the major role of tectonic settings (thrust-fault versus normal-fault andersonian-stress regime) and the influence of inherited large-scale faults on the formation/localization of low-permeability shear bands. We also provide a geometrical analysis of the band network properties (spacing, thickness, shear/compaction ratio, degree of cataclasis, petrophysical properties) with respect to the median grain size, porosity and grain sorting of host sand. This analysis suggests that grain size, although less important than stress-state conditions and the presence of large-scale faults, has a non-negligible effect on band network geometry. No correlations are observed between the grain sorting, porosity and band network geometry.

1. Introduction

In porous sandstone, strain localization occurs by the formation of tabular structures commonly referred to as deformation bands (Aydin and Johnson, 1978; Aydin et al., 2006; Fossen et al., 2007). These structures of millimeter to centimeter thickness are considered as the precursors to faults (Aydin, 1978; Antonellini and Aydin, 1995; Shipton and Cowie, 2003). They can interact to form clusters of bands and faults containing localized slip-surface (Wibberley et al., 2007; Johansen and Fossen, 2008) but are also observed as distributed band networks unrelated to faults (Davis, 1999; Cashman and Cashman, 2000). Deformation bands can be classified as dilation, shear, or compaction bands as a function of shear and porosity change, or more commonly by combinations of shear and compaction in compactional shear bands (Fossen et al., 2007). They accommodate strain localization by grain rearrangement and/or cataclasis without developing sharp discontinuities (Aydin et al., 2006). Furthermore, deformation bands affect the petrophysical properties of the sandstone (Fossen and Bale, 2007; Tueckmantel et al., 2010) and can potentially affect fluid flow in reservoir settings (Antonellini et al., 1999; Fisher and Knipe, 2001; Ballas et al., 2012; Exner and Tschegg, 2012). The influence of deformation band development on host rock permeability was analyzed by several studies in laboratory (Zhu et al., 1997; Vajdova

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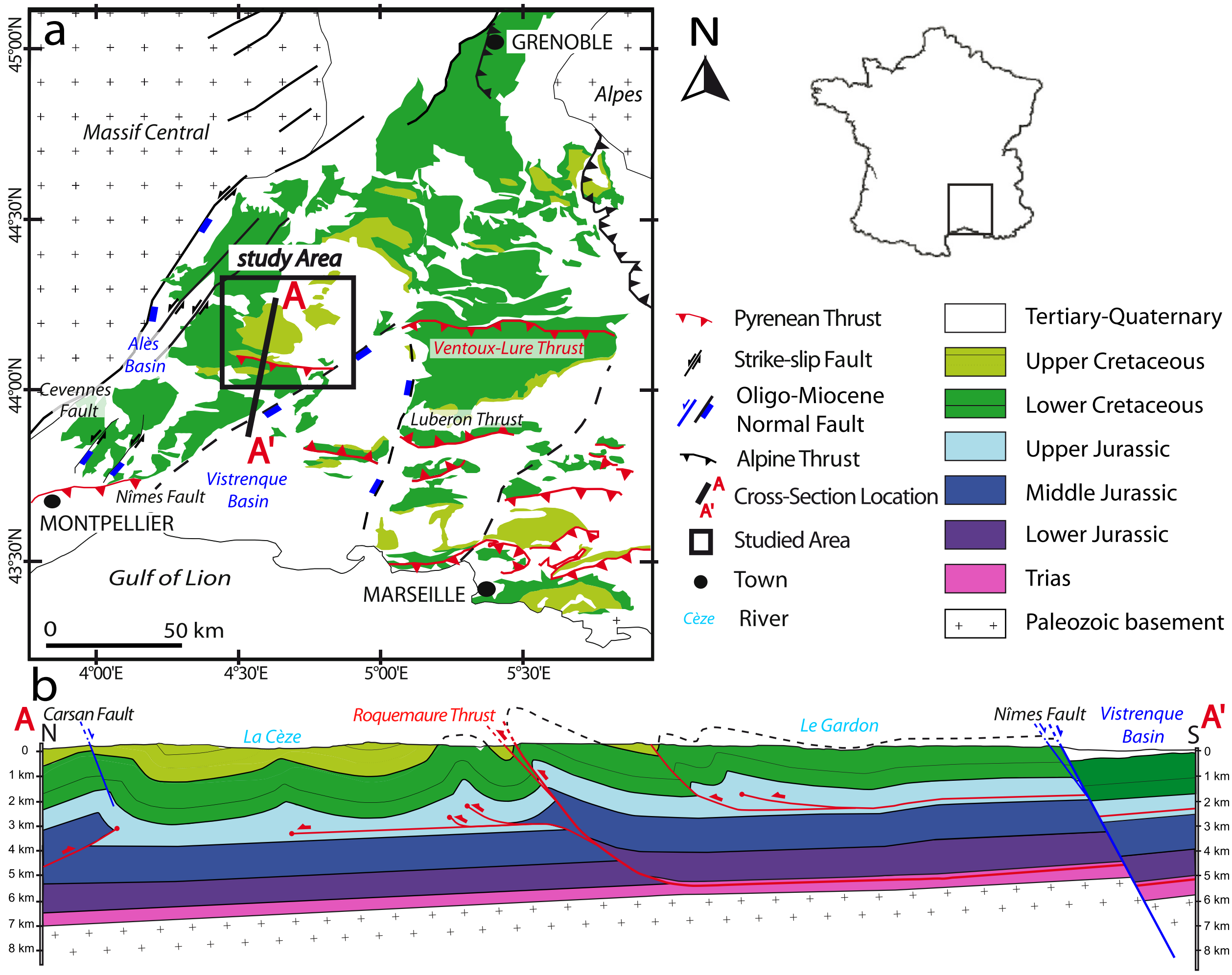

Figure 1. Tectonic setting of the South-East basin. a) Geologic map simplified from the geologic map of France, 1:1.000.000. b) Cross-section of the study area.

et al., 2004; Zhu et al., 2007). These tests show permeability reduction with formation of cataclastic compaction and shear bands (Lothe et al., 2002; Fortin et al., 2005; Dautriat et al., 2009; Baud et al., 2012). Hence, the role of deformation bands and faults on fluid flow represents a critical point in the management of some porous sandstone reservoirs (see Faulkner et al., 2010 for recent review).

Different types of deformation bands are observed in a large range of settings (see Fossen et al., 2007 for a review), and no clear relationships are actually brought out between the setting conditions (burial, stress-state conditions, host sand properties) and the band system organization and characteristics. Several factors are described as controlling the deformation band organization and petrophysical properties. Solum et al. (2010) suggested that the stress-state could influence the distribution of bands. The evolution of cataclastic faulting described by Saillet and Wibberley (2010) and the model of strain localization developed by Soliva et al. (2013) support this conclusion. Large permeability reductions are often measured for bands related to extensional settings (Antonellini and Aydin, 1994; Ballas et al., 2012; Saillet and Wibberley, 2013) whereas only low permeability reductions are generally observed for bands related to contractional settings (Sun et al., 2011; Ballas et al., 2013). This suggests a potential control of the tectonic setting (stress-state conditions) on the petrophysical properties of deformation bands. However, less common large permeability decreases are also measured on reverse-sense bands (Solum et al., 2010; Fossen et al., 2011), which suggests that numerous other parameters such as the burial depth (Fisher and Knipe, 2001; Fossen, 2010), the presence of large-scale fault and fold development (Okubo and Schultz, 2005; Schultz, 2011; Brandenburg et al., 2012), the constitutive parameters of the host sands (Schultz et al., 2010; Fossen et al., 2011) or their mechanical properties (Chemenda et al., 2012) can influence deformation bands initiation, distribution and permeability in addition to the stress-state. A series of questions remain then to be treated concerning the determination of which parameters control the distribution, microstructures and petrophysical properties of deformation band, in particular at the basin-scale, in order to understand their potential control on fluid flow in reservoir settings.

In this paper, we analyze the distribution and the geometric attributes of deformation band networks and faults formed in different sand-dominated units of the South-East basin (France), deformed under contractional and extensional regimes. Their microstructures and related petrophysical properties are analyzed to discuss the potential control of these bands on fluid flow. The influence of the tectonic setting and the presence of large-scale faults on the distribution of low-permeability deformation bands at the basin-scale is analyzed. The impact of the median-grain size, grain sorting and porosity of host rock on the band networks organization is also investigated.