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Relationships between pore space anisotropy and anisotropy of physical properties of silicoclastic rocks from the Corbières–Minervois fold-and-thrust-belt (north-east Pyrenees, France)

P. Robion *, F. Humbert, J.-C. Colombier, S. Leghay, D. Frizon de Lamotte

Université de Cergy-Pontoise, Géosciences et Environnement Cergy, 5 mail Gay-Lussac Neuville-sur-Oise 95031 Cergy-Pontoise, France

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ABSTRACT

We present a study integrating petrophysical measurements along a general N–S section of the Corbières–Minervois fold and thrust belt (NE Pyrenees, France) in order to study the petrofabric of weakly deformed sediments. We focus on the relationship between the evolution of deformation measured with the anisotropy of various physical properties (anisotropy of magnetic susceptibility (AMS), anisotropy of P-waves velocity (APV) and anisotropy of electrical conductivity (AEC)) and the distribution of the porous space. The origin of AMS fabric is interpreted as recording a layer parallel shortening oriented N145, steadily throughout the studied section with local gradient associated with folding as sites close to the forelimbs. AEC is in good agreement with AMS results and records the same shortening direction. The most probable source of anisotropy for AMS and AEC is the preferred orientation of phyllosilicate minerals. APV, which reflects the distribution of porous space, is more complex and is controlled by the tectonic style of the magnetic fabric. The porosity is a flat-lying-bedding porosity, where the magnetic fabric is poorly evolved and it becomes a flat-lying-pressure-solution-cleavage porosity where the magnetic fabric is tectonic. At regional scale, we show that changes in anisotropy of petrophysical properties are controlled by individual structures, like regional fold or thrust fault and occurred mainly before folding as a consequence of a well-expressed NNE–SSW layer parallel shortening. The folds and thrust faults are developed subsequently from inherited E–W basement faults. This explains why the structural grain of the sedimentary cover, expressed notably by the magnetic lineation, is oblique to the major structures of the cross-section: the Alaric Anticline and the North-Mouthoumet Fault.

1. Introduction

The characterization of the distribution of deformation in folds and thrust belts is frequently done through the study of magnetic fabric in general and anisotropy of magnetic susceptibility (AMS) in particular (Amrouch et al., 2010; Anchuela et al., 2010; Burmeister et al., 2009; Callot et al., 2010; Evans et al., 2003; Hirt et al., 2004; Larrasoana et al., 2011; Lee and Angelier, 2000; Luo et al., 2009; Pares et al., 1999; Pueyo-Morer et al., 1997; Robion et al., 2007; Sans et al., 2003; Tavani and Cifelli, 2010; Weil and Yonkee, 2009). This method can quickly measure the petrofabric of rocks by producing a magnetic susceptibility tensor coaxial to the strain tensor (Kliegfield et al., 1981; Kneen, 1976). It is useful in fold and thrust belts or, more generally, in structural domains poor in strain markers because it provides information about subtle fabrics unreachable through the observation of meso-structures alone (Bakhtari et al., 1998; Saint-Bezar et al., 2002). One of the most classical results of AMS method is that magnetic fabric tracks the intersection between sedimentary fabric and layer parallel shortening (LPS) fabric given the trend of the regional shortening direction (Averbuch et al., 1992; Frizon de Lamotte et al., 2002; Graham, 1966; Kissel et al., 1986). Borradaile and Tarling (1981) were the first to propose a microstructural interpretation of this intersection fabric appealing for the composition between a primary sedimentary plane and a tectonic plane resulting from the development of pressure solution cleavages. At a mesoscopic scale, the influence of folding-related pressure solution cleavage on the fluid flow capability of reservoir rocks has long been addressed but only in terms of cleavage discontinuities (Tavani et al., 2004 and references therein). However, at mineral aggregate scale, AMS studies are the only method to address the problem of expression in terms of fabric of the pressure solution cleavage development. Roure et al. (2005) demonstrated that investigations of microstructural effects of deformation in sandstone or carbonate reservoirs could exert a significant control on reservoir properties in compressional petroleum systems. More specifically, the influence of fluids flow and void space distribution on fabrics were investigated

* Corresponding author. Tel.: +33 1 34 25 73 54; fax: +33 1 34 25 73 50.
E-mail address: philippe.robion@u-cergy.fr (P. Robion).

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by different authors with different approaches (Pfleiderer and Halls, 1994; Pfleiderer and Kissel, 1994; Sizaret et al., 2003, 2006; Souque et al., 2002) illustrating that magnetic fabric provides reliable information on void space distribution.

In this study we focus on the relationship between the evolution of deformation measured with the anisotropy of various physical properties (magnetic, acoustic and electric) and the distribution of porous space in a foreland basin and fold and thrust belts, forming presently the Corbières–Minervois fold and thrust belt. Balanced cross sections have been constructed along an N–S regional profile from an undeformed zone where Eocene deposits lie uncomfortably on the substratum (the Montagne Noire) to the Mouthoumet Massif which is carried out northward over the Cenozoic basin. In order to investigate pore fabric shape anisotropy we used the anisotropy of P-waves velocity (APV) measurements according to the method developed by Louis et al. (2003, 2004). This method was designed mainly for comparison of acoustic velocity and magnetic anisotropies as well as their relationships with microstructures (Louis et al., 2004), assuming that acoustic velocity measured in laboratory conditions is related to elastic anisotropy and reflects the anisotropic nature of both the solid matrix and the pore space. Recent developments (David et al., submitted for publication) provide a new experimental device for an automated approach to measure both APV and the anisotropy of electrical conductivity (AEC); the latter can be regarded as a proxy for transport properties (David, 1993). Using the initial knowledge of internal deformation classically provided by AMS method, we propose to apply APV and AEC tools to infer the timing of development of micro-scale structures, both the solid matrix and the pore space assumed to occur during tectonic history of the folded foreland.

2. Geological setting

The area of investigation is localized in the western boundary of the Corbières–Minervois transfer zone, which is the arc joining the northern folded foreland of the Pyrenees to the Languedoc-Provence thrust belt (Fig. 1). This domain is characterized by a thin (less than 1000 m) sedimentary cover of lacustrine limestone, siltstone to sandstone, and siltstone of Maastrichtian to Lutetian age supporting Bartonian molasses and resting directly on the Paleozoic substratum (Cluzel, 1977; Ellenberger, 1967). The studied cross-section (Fig. 2) runs from the southern border of the Montagne Noire massif, where quite flat Cenozoic rocks are resting unconformably on Paleozoic rocks folded during the Variscan orogeny, to the Mouthoumet massif, where Paleozoic rocks are carried out thrusted over steep vertical Cenozoic rocks. In between, large folds, namely the Alaric anticline and the Montlaur and Talairan synclines, are exposed. As elsewhere in the Corbières–Minervois, the tectonic style is typically thick-skinned: the sedimentary cover remains attached to the Paleozoic substratum (Robion et al., 2007). The anticlines are asymmetric with a steep or overturned forelimb and a gently dipping backlimb. Except the major fault bounding the Mouthoumet Massif, thrust faults are scarce and of minor importance. Normal faults developed at a late stage of the structural evolution and controlled the development of Miocene extensional basins cutting though the previous contractional structures (Fig. 1). At large scale, the sedimentary cover, together with the Paleozoic substratum, is involved in large ramp-related folds (Averbuch et al., 1992; Frizon de Lamotte et al., 1997; Grelaud et al., 2000; Souque et al., 2003). The folds exhibit an "en-échelon" pattern relative to the North Pyrenean Fault, which bounds the North Pyrenean Zone, locally called "nappe des Corbières orientales" in which a quite complete Mesozoic cover is exposed (Fig. 1).

Since about two decades, individual folds belonging to the Corbières–Minervois belt have been studied using both structural analysis and AMS measurements. In particular, work done in the Lagrasse and Oupia folds (Averbuch et al., 1992; Frizon de Lamotte et al., 2002; Grelaud et al., 2000) have shown that magnetic fabric reflects an early phase of LPS preceding the folding. It also shows that AMS can be used to define deformation gradients. At a smaller scale, an interesting structural feature is the development of a pervasive solution cleavage, well visible in the field in the siltstone (Averbuch et al., 1992; Ellenberger, 1967; Louis et al., 2006; Tavani et al., 2004). Robion et al. (2007) have shown that the main factor explaining the development of cleavage in such a context is the low initial anisotropy of rocks due to hardening by pedological processes occurring before burial. The trends of the magnetic lineation from these different studies are reported on the Fig. 1. At this scale, the clear tendency is a progressive rotation of the lineation trend from E–W in the western region to NE-SW and even N–S in the eastern and northern regions. This is interpreted as a change of the shortening direction from N–S to NW–SE and finally E–W as an effect of the development of the Corbières–Minervois transfer zone.

3. Sampling and methodology

3.1. Sampling

All physical properties were measured on cylindrical specimen of 25 mm in diameter and 22.5 mm in height. For AMS measurements 91 samples, split into 7 sites, were collected along a N–S cross-section in the Carcassone Molasse deposits of Bartonian age and in the Eocene deposits in the vicinity of the Mouthoumet thrust-fault. Specimens were drilled with a gasoline drilling machine and directly oriented in the field. Additionally, an oriented hand block was collected on each site for the acoustical and electrical measurements. These blocks were afterwards squared off in laboratory and at least three cores were drilled from three faces perpendicular to one another following the protocol proposed by Louis et al. (2004).

Even if all sampled rocks have more or less equivalent ages and a lithology relatively constant within a given site, decreasing grain size is observed along the north–south profile from the Minervois Basin to the Talairan Syncline (Figs. 1 and 2). In the Minervois Basin, the sites ZSBP02, ZSBP06 and ZSBP07 exhibit sandstones, with sometimes high calcareous contents (site ZSBP02), containing millimeter sized rock fragments or lithic fragments set in a compact matrix. Samples from site ZSP07 located in the northern part of the basin are close to greywacke type of rocks. Without fragments, grain size is inhomogeneous and evolves mainly from micron sized angular grains to particles with 700 μm length particles. Samples from site ZSBP01 located in the Montlaur Syncline are quite similar to the ones from Minervois Basin whereas those from Talairan Syncline (sites ZSBP03, ZSBP04 and ZSBP05) are composed of siltstones (site ZSBP04) and fine grain sandstones (sites ZSBP03 and ZSBP05), with a grain size homogenous for the three sites. Only site ZSBP05 contains scarce millimeter sized fragments. All sites show a matrix composed by both some clay-particles and large amount of calcite. In Fig. 3 we show two sets of SEM images performed on samples coming from the sites ZSP07 and ZSP04. Energy-dispersive X-ray analysis allowed us to obtain the map of specific chemical elements that are associated to the main species identified in our samples. Si has been selected for identification of silicates grains (quartz grains can be distinguished as they are darker due to their higher Si content), Ca for calcite and

Fig. 1. Structural map of the Corbières Fold and Thrust Belt with the location of the cross-section (A–B) presented on Fig. 2. The sites sampled for the physical measurements are located along A–B and labeled from ZSP01 up to ZSP07.