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Disentangling magnetic subfabrics and their link to deformation processes in cleaved sedimentary rocks from the Internal Sierras (west central Pyrenees, Spain)

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ABSTRACT

Here we present a detailed study of the magnetic fabrics and subfabrics of remagnetized Upper Cretaceous limolites that crop out in the Internal Sierras (west central Pyrenees) affected by a penetrative pressure-solution cleavage. The bulk magnetic fabrics of these rocks (RT-AMS) show variable orientations that do not conform to what is typically reported for cleaved sedimentary rocks. In contrast, the paramagnetic subfabrics (LT-AMS) show remarkably constant directional properties, so that their K_{max} and K_{min} axes cluster parallel to the intersection lineation and to the poles to bedding, respectively. These LT-AMS subfabrics indicate a preferred orientation of phyllosillicates that is consistent with a syn-sedimentary (Late Cretaceous) period of NNE-oriented layer-parallel shortening. Noticeably, these phyllosillicate subfabrics are not further altered by the subsequent formation of cleavage in the Late Eocene–Early Oligocene. The ferrimagnetic subfabrics (AARM) also show remarkably constant orientation, so that their K_{max} axes are strikingly parallel to the shortening direction in the area. We interpret this preferred orientation of ferrimagnetic grains as being caused by subhorizontal shear associated to cleavage formation, which is consistent with the age and mechanisms (authigenic growth and rotation of pre-existing magnetite grains) proposed for the pervasive remagnetization that affects the studied rocks.

1. Introduction

Magnetic fabrics have been long used to decipher the tectonic evolution of fold and thrust belts during low-to-moderate deformation conditions. In particular, the evolution of magnetic fabrics from the external to the internal parts of orogenic belts, where a transition from weakly deformed to heavily cleaved rocks is typically observed, has been the focus of several studies (e.g. Borradaile and Tarling, 1981, 1984; Kissel et al., 1986; Averbuch et al., 1992; Parés and Dinarès-Turell, 1993; Sagnotti and Speranza, 1993; Parés et al., 1999; Larrasoaña et al., 2004). According to these studies, in the most external units of orogenic wedges, where deformation is very weak and restricted to syn-sedimentary layer-parallel shortening (LPS), tectonic deformation is able to overcome the initial sedimentary fabric and to reorient phyllosilicate grains according to the prevailing stress field. Thus, K_{max} axes tend to align perpendicular to the shortening direction whereas K_{min} axes remain parallel to the bedding plane. As deformation increases, development of pencil structures and weak cleavage modify the magnetic ellipsoid in such a way that K_{max} axes become tightly clustered parallel to fold axes and to the strike of thrust sheets, and K_{min} axes begin to develop a girdle parallel to the shortening direction. When cleavage is well-developed in response to increased deformation, the principal magnetic susceptibility directions parallel the flattening plane of the finite-strain ellipsoid, so that the K_{min} axes become perpendicular to tectonic foliation and the K_{max} axes parallel the elongation direction, which usually is the intersection of the bedding and cleavage planes (L_1) (Singh et al., 1975; Borradaile and Tarling, 1981; Kligfield et al., 1981; Hrouda, 1982; Borradaile, 1987; Aubourg et al., 1995; Borradaile and Henry, 1997; Parés et al., 1999; Aubourg et al., 2000; Parés and van der Pluijm, 2002). Further deformation might result in the re-alignment of K_{max} axes producing an obliquity of K_{max} respect to the structural foliation (Rathore, 1985; Aranguren et al., 1996; Borradaile et al., 1998), so that the angular deviation provides a sense of shear. In some occasions, K_{max} axes are found parallel to the transport direction of thrust sheets, while K_{min} axes remain clustered perpendicular to foliation (Averbuch et al., 1992; Aubourg et al., 1999).

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The anisotropy of magnetic susceptibility of rocks is typically measured at room temperature (RT-AMS), so that it results from the bulk contribution of all rock-forming minerals regardless of their magnetic behavior (Hrouda, 1982; Kelso et al., 2002; Martín-Hernández and Ferré, 2007). Since different minerals might form at different times and under different conditions, and might respond differently to tectonic deformation, separating their individual subfabrics is important for unraveling the geological history of rocks from its formation through their subsequent tectonic evolution (Borradaile and Henry, 1997; Aubourg et al., 1991, 2000; Robion et al., 1999; Aubourg and Robion, 2002; Kelso et al., 2002; Martín-Hernández and Ferré, 2007). Of particular importance in tectonic studies has been the separation of complex RT-AMS fabrics into meaningful paramagnetic and ferromagnetic subfabrics that have contributed to disentangle the tectonic evolution of orogenic wedges (Borradaile and Jackson, 2004).

Here we present the first detailed study of composite magnetic fabrics of remagnetized Upper Cretaceous sedimentary rocks from the Internal Sierras (Oliva-Urcia and Pueyo, 2007; Oliva-Urcia et al., 2008), which crop out within a domain of pressure-solution cleavage developed during the Tertiary compression in the internal part of the west central Pyrenees (Choukroune, 1976). Separation of the bulk magnetic fabrics into their paramagnetic and ferrimagnetic subfabrics, which has been based on magnetic methods and on mineralogical techniques, has made possible the unraveling of complex RT-AMS fabrics that do not show a common pattern with respect to tectonic elements. This, together with structural and paleomagnetic data available for the studied area, has enabled a more detailed determination of the deformational history of the Internal Sierras in the context of the Pyrenean orogeny.

2. Geological setting and sampling

The Pyrenean orogen is an asymmetric mountain belt formed between the Eurasian and Iberian plates during Cretaceous to Miocene times (Muñoz, 1992). The southern part of the west central Pyrenees is characterized by a set of south verging, imbricated thrust sheets that developed in a piggyback fashion as deformation progressed towards the foreland (Teixell, 1996, 1998) (Fig. 1). The northernmost of these units, the Lakora thrust, evolved from Late Cretaceous (Santonian) to Middle Eocene (Bartonian) times involving cover and basement rocks (Séguret, 1972; Labaume et al., 1985; Teixell, 1992, 1996). Further to the south is the Larra-Monte Perdido cover thrust system, which formed during Middle Eocene (Lutetian–Bartonian) as a footwall splay of the Lakora basement thrust (Labaume et al., 1985; Teixell, 1992, 1996, 1998). Further deformation between the Late Eocene and the Early Oligocene (Priabonian–Rupelian) caused the southward emplacement of the underlying Gavarnie basement thrust sheet and resulted in an episode of major folding and increased tectonic loading (Teixell, 1992, 1996). This led to formation of a pressure-solution cleavage domain, with a fan-shaped geometry in the Axial Zone, the Internal Sierras, and the northern part of the Jaca-Pamplona basin (Fig. 1) (Choukroune, 1976). The temporal and geometrical relationships between cleavage and folding suggest that the cleavage formed during the latest stages of emplacement of the Gavarnie thrust sheet, likely from Late Eocene onwards (Choukroune and Séguret, 1973; Choukroune, 1976; Labaume et al., 1985; Teixell, 1992; Holl and Anastasio, 1995). Subsequent deformation active till the earliest Miocene (Aquitanian) moved the Guarga thrust sheet to the south, affecting the overlying thrust sheets, and exhumed the internal portions of the orogen (Labaume et al., 1985; Teixell, 1992, 1996).

The studied area is located at the western part of the Internal Sierras, a major topographic feature that bounds the Pyrenean Axial Zone to the south (Fig. 1). The Internal Sierras are make up of Mesozoic–Tertiary rocks, which are affected by the Larra-Monte Perdido thrust system. This system has 3–5 km of displacement to the south and a N200 (Séguret, 1972) or SW transport direction (Teixell et al., 2000) in the studied sector of the Internal Sierras. We have focused our sampling on Campanian to Maastrichtian limolites from the Zuriza Marls and Marboré Sandstones formations, that were deposited during the Upper Cretaceous in the Iberian margin of the former Pyrenean rift (Séguret, 1972; Teixell, 1992; Martín-Chivelet et al., 2002). These rocks display a slaty cleavage with anastomosing cleavage planes that have a strong fissility (>10 for the Zuriza Marls Fm. in the scale of Durney and Kisch, 1994; see Teixell et al., 2000) (Fig. 2). In the studied area, cleavage planes strike E–ESE, dip moderately to the North, and often have a down dip stretching lineation, which indicates that the cleavage has a ductile behavior and has undergone shear deformation (Teixell et al., 2000). Calculation of burial depths from balancing cross-section indicates that the Upper Cretaceous rocks reached a temperature of 200 °C (Teixell et al., 2000), which is consistent with the 250 °C estimated from chemical analysis of fluid inclusions in veins (Travé et al., 1997; McCaig et al., 2000) and the 300 °C deduced from vitrinite reflectance data (Teixell et al., 2000). There is evidence for an earlier layer-parallel shortening in the area (Teixell et al., 2000).

Extensive paleomagnetic results from the Internal Sierras indicate that limolites from the Zuriza and Marboré formations are affected by a pervasive remagnetization that is carried by magnetite, has a systematic reverse polarity, and was acquired after folding and after the emplacement of the Gavarnie basement thrust (Oliva-Urcia and Pueyo, 2007; Oliva-Urcia et al., 2008). In many cases (i.e. 30% of the studied sites), a primary prefolding magnetization also carried by magnetite is preserved in these rocks. The remagnetization has been related to the development of the cleavage domain in the Internal Sierras during the latest Eocene (Oliva-Urcia and Pueyo, 2007), which is consistent with the Middle–Late Eocene age of the youngest sediments affected by cleavage in the area (turbidites from the Hecho group; Labaume et al., 1985; Teixell, 1996). The presumed mechanism for explaining the remagnetization event is the liberation and reorientation of previously existing magnetite grains during formation of pressure-solution cleavage planes, although dissolution of pre-existing magnetite grains and precipitation of new magnetic phases (Suk et al., 1990, 1993; Housen et al., 1993a; Lewchuk et al., 2003; Zegers et al., 2003; Evans and Elmore, 2006) cannot be excluded (Oliva-Urcia et al., 2008).

We have collected nine sites from Upper Cretaceous belonging to the Zuriza Marls Fm. (sites 4–8) and Marboré Sandstones Fm. (sites 1–3 and 9), in the western sector of the Internal Sierras. At every site, 10 standard paleomagnetic cores were drilled with a portable, water-refrigerated drill machine. These sites were selected because: (1) they are located in a very similar structural setting, near the floor thrust of the Larra-Monte Perdido system and affected by the pressure-solution cleavage; and (2) they display different angular relationships between bedding and cleavage, which might help to enhance any genetic link between magnetic fabrics and deformation. Sites 1–3 come from an outcrop where an excellent example of cleavage refraction is observed affecting the limolites from the Marboré Sandstone Fm. Sites 5 and 6 were drilled in the Zuriza Marls Fm. located in the northern limb of a gentle, metric-scale hangingwall anticline. Sites 7 and 8, also drilled in the Zuriza Marls Fm., are located in the northern limb of a decametric anticline, and site 9, coming from an outcrop of the Marboré Sandstones Fm., is located in the southern limb of the same structure. Site 4 was drilled in limolites from the Zuriza Marls Fm., in the only outcrop where a stretching lineation, subvertical in attitude, has been found in the field.