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Magnetic fabrics in the Western Central-Pyrenees: An overview

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A B S T R A C T

In the Western Central-Pyrenees numerous investigations during the past years have yielded an exceptional high density of localities (more than 700 sites) where the AMS and rock magnetic properties have been determined. This unique AMS dataset helps in understanding the orogenic evolution of the Pyrenees and its foreland basins. Processes related to AMS development in different structural units permit to identify: (i) an early recording of strain related to the transtensional or transpressional stages during the Early Triassic and Early Cretaceous, (ii) a moderate shortening related to the fold-and-thrust belt and foreland basin evolution during the Cretaceous–Tertiary orogenic stage, and (iii) a relatively strong deformation that produced cleavage related to the emplacement of basement thrusts in the Axial Zone during the Middle–Late Eocene. The main achievement of this contribution is the integration in cross-section and map-view of magnetic fabrics (orientation and parameters) in the western Central-Pyrenees, which allow constraining the processes affecting magnetic fabrics at the orogen scale. AMS results indicate: (i) a dominant bedding-controlled foliation, very sensitive to subtle layer parallel shortening (LPS) processes, especially in the foreland basins; (ii) magnetic lineations parallel to fold axes or strike of thrusts outside the cleavage front that can be deflected by vertical-axis rotations in particular areas; and (iii) an overall decrease of the definition of AMS fabrics (magnetic lineation or the anisotropy of the ellipsoid) associated with incipient cleavage and intersection lineation fabrics in the internal zones of the orogen. Therefore, AMS is a sensitive indicator to delineate the strain patterns at the orogen-scale, in particular, in those areas undergoing a modest degree of deformation.

1. Introduction

The anisotropy of magnetic susceptibility (AMS) is a proxy for mineral preferred orientation of rock volumes. It allows determining the petrofabric of rocks lacking strain markers, and unraveling deformational histories in a quick, inexpensive and non-destructive manner (Borradaile, 2001; Borradaile and Henry, 1997; Borradaile and Jackson, 2004, 2010; Graham, 1954; Ising, 1943; Martín Hernández et al., 2004; Nye, 1957; Tarling and Hrouda, 1993, for overviews of the technique).

The AMS technique has considerably progressed during the past decades because of instrumentation improvements, devices and laboratory standardization and statistical data analysis. Classical AMS analysis can be combined with measurements of rock magnetism, low-temperature AMS and anisotropy of the remanence (see Borradaille and Jackson, 2004, 2010; Potter, 2004, for review) to provide comprehensive integrated rock fabric studies. Moreover, the analysis of AMS has become a standard approach to correct the orientation of paleomagnetic vectors by the retro-deformation of strained rocks and compaction errors (e.g. Bilardello and Kodama, 2010; Tan and Kodama, 2002) or to detect strain deviation or vertical axis rotations in combination with paleomagnetic data (Hnat et al., 2008; Lefort et al., 2001; Pueyo et al., 2012a; Roperch et al., 2010).

AMS has been proposed as a suitable marker to study the evolution of strain in orogenic regions (based on the strain evolution suggested by Ramsay (1967); see Borradaille and Henry, 1997; Parés, 2004; Parés et al., 1999 for review). These models consider that AMS behaves as an active, sensitive and progressive marker of the deformational history. Some caveats, as the common bias between the magnetic foliation from the AMS ellipsoid and the strain foliation plane, and the high sensitivity of magnetic lineation to strain changes (e.g. Kmax parallel to Y strain axes or Kmax parallel to intersection lineation between different planar fabrics; e.g. Borradaile, 1988; Borradaile and Henry, 1997; Debacker

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et al., 2004; Housen, 1993; Tarling and Hrouda, 1993), must be taken into account.

AMS strongly mimics the preferred orientation of some paramagnetic minerals because of their crystallographic characteristics, grain size and degree of alignment (e.g. Borradaille and Henry, 1997; Parés, 2004; Parés et al., 1999). For ferromagnetic minerals, such as magnetite, AMS is mainly defined by the grain-shape anisotropy or the magnetically interaction of equidimensional particles along planes or lines (Fuller, 1963; Grégoire et al., 1995; Hargraves et al., 1991; Stephenson, 1993). In the case of paramagnetic minerals, clay minerals and micas are usually reliable strain markers, although their planar habit only allows defining a lineation from the statistical intersection of platy minerals (e.g. Martín Hernández et al., 2005; Parés, 2004).

AMS, which also occurs with the analysis of deformation, may reflect the addition of finite strain (Borradaille and Henry, 1997; Ramsay, 1967; Ramsay and Huber, 1983). Furthermore, any correlation between the strain and AMS ellipsoids can be affected by secondary fabrics or inverse anisotropies when present, or where the deformation processes are not coaxial (Borradaile, 1988; Borradaile and Henry, 1997; Parés and Van der Pluijm, 2002). The presence of an early magnetic fabric (sedimentary, diagenetic or tectonic) can decrease the sensitivity of AMS to record new strain processes (Borradaille, 1988; Parés and Van der Pluijm, 2002). In turn, in complex areas affected by several deformational stages, an early magnetic fabric can help to characterize the previous tectonic stage (e.g. Oliva-Urcia et al., 2010a, 2010b; Soto et al., 2007, 2008), which can be difficult to characterize by strain markers when they are obliterated by the subsequent tectonic event.

In fold-and-thrust belts, the transition between bedding-related fabrics (Kmax = Kint = bedding) to cleavage related fabrics (Kmax = Kint = cleavage) shows different stages related to the deformational history, the susceptibility carriers and the orientation of previous magnetic fabrics. The first step of this transition shows Kmax parallel to fold axes (intermediate strain axis), and to the intersection lineation between bedding and cleavage. This distribution has been analyzed with mathematical and experimental models (Borradaille, 1988; Housen et al., 1993) and by studying the changes in the ellipsoid anisotropy in cleavage domains with a previous bedding-related fabric (Debacker et al., 2004; Hirt et al., 2004; Parés, 2004). In the second step cleavage-related oblate fabrics appear (following the strain ellipsoid (Ramsay, 1967) applied to AMS by Borradaile and Henry (1997) and Parés (2004)). However, this progression can be biased depending on the mineralogy, the relationships between the orientation of different strain ellipsoids and the existence of anisotropies that condition the record of subsequent deformation (Borradaille, 1988; Housen et al., 1993; Parés and Van der Pluijm, 2002; Debacker et al., 2004: Hirt et al., 2004; Robion et al., 2007).

The Pyrenees represents a well studied mountain chain where the factors that can modify the AMS record of deformational processes can be analyzed at orogenic scale. The Pyrenean AMS dataset includes more than 2500 AMS sites, since the preliminary works from Girdle (1961), most of them in granitic bodies (Pueyo et al., 2006 and references therein). The Pyrenees shows intermediate to low deformation intensity (with moderate pressure and temperature conditions), and well-exposed and well-dated syn-tectonic materials. In the Central Pyrenees, more than 700 sites (Fig. 1a and b) can be found in different types of sedimentary rocks and tectonic settings, thus representing a suitable zone for the analysis of the relations between AMS, strain, structural setting and deformational events. Previous works have shown a rather clear correspondence between AMS and tectonic processes at local scale in different tectonic units in the Pyrenees (Izquierdo-Llavall et al., 2013b; Larrasoaña et al., 1997, 2004; Mochales et al., 2010; Oliván et al., 2008; Oliva-Urcia et al., 2009, 2010a, 2010b; Parés, 2004; Parés et al., 1999; Pueyo Anchuela et al., 2010a, 2010b, 2012b; Pueyo-Morer et al., 1997; Sánchez et al., 2012; Soto et al., 2003, 2009). These studies reveal (i) the record of extensional pre-Pyrenean tectonic deformation (Oliva-Urcia et al., 2010a, 2010b), (ii) pervasive, pre-folding layer-parallel shortening (Parés et al., 1999; Pueyo-Morer et al., 1997; Larrasoaña et al., 1997; Oliván et al., 2008; Oliva-Urcia et al., 2009; Mochales et al., 2010; Sánchez et al., 2012) that can be identified from the inner domain of the chain to several kilometers into the foreland basin (Parés et al., 1999; Pueyo Anchuela et al., 2010a), (iii) the presence of cleavage-related magnetic fabrics parallel to macroscopic cleavage (Izquierdo-Llavall et al., 2013b; Oliva-Urcia et al., 2010b; Parés and Dinarès, 1993; Pueyo Anchuela et al., 2010b, 2012b) and (iv) shear fabrics related to thrust emplacement (Oliva-Urcia et al., 2009; Pueyo Anchuela et al., 2010b, 2012b; Pueyo et al., 2004, 2007). In this work, an analysis is carried out aiming to obtain a model of AMS evolution that integrates tectonic characteristics, deformational history, lithology and magnetic fabric patterns and helps in evaluating the factors and characteristics of the AMS analysis at the orogen scale.

1.1. Geological setting

The Pyrenees represents the collision belt formed during the alpine compression between the European and Iberian plates from Santonian/Campanian to Miocene times (Choukroune, 1992; Muñoz, 1992, 2002; Teixell, 1996). The inner domain (Axial Zone; Fig. 1) contains Hercynian materials involved in the alpine folds and thrusts and defining an antiformal stack (Fig. 2a, b; Teixell, 1996; Muñoz, 1992). The Southern Pyrenees is characterized by thrusts defining a southward piggy back sequence associated with syn-tectonic sedimentation and foreland basin development (Jaca and Pamplona piggyback and Ebro foreland basins).

The present-day architecture of the Western Central Pyrenees is mainly related to the alpine cycle. This cycle begins with Permian red beds sedimented in strike-slip basins (Fig. 2c; Arthaud and Matte, 1975), followed by extensional basins with continental and marine sedimentation during most of the Mesozoic. The sinistral strike-slip movement of Iberia with respect to Europe during the Albian was responsible for the formation of pull-apart basins along the North Pyrenean fault zone (e.g. Mauléon basin, see Debroas, 1990; Oliva-Urcia et al., 2010b and references therein). During the Late Cretaceous, marine platform sedimentation (Calcaires des Canyons; Fournier, 1905; and Larra; Teixell, 1992) occupied most of the South-Pyrenean and Axial Zones (Campanian to Maastrichtian: Zuriza marls and Marboré sandstones; Souquet, 1967; Teixell, 1992), with turbiditic sedimentation towards the North. Santonian detrital deposits are the first evidences of compressional movements (Teixell, 1992, 1996 and references therein).

Paleocene and Lower Eocene deposits are characterized by carbonatic platform units, changing to a platform-turbiditic trough system during the Middle Eocene (Hecho Group; Mutti, 1977, 1984). Sequences of marls of external marine platform (Barnolas and Gil-Peña, 2001; Puigdefàbregas and Souquet, 1986), define the last marine episodes of the Upper Eocene. These sequences prograde to the southwest with progressively younger ages. An abrupt continentalization took place during Priabonian times in relation to the seaway closure caused by the western Pyrenees uplift (Costa et al., 2009; Puigdefàbregas, 1975).

Subsequent upper Eocene–Oligocene continental deposits are represented by a 3500–4000 m thick sequence including the Campodarbe Formation (Puigdefàbregas, 1975). Younger units (Oligocene–Miocene) formed by detrital deposits crop out in the foreland (Uncastillo Fm) and piggy-back basins (Anastasio, 1992; Arenas et al., 2001; Millán, 1996; Muñoz, 2002; Nichols, 1984; Puigdefàbregas and Souquet, 1986; Teixell, 1992, 1996).

1.2. Structure; geometry and kinematics

Three main basement thrust units, Lakora–Eaux Chaudes, Gavarnie and Guarga, define the structure of the Axial Zone in the Central-Western Pyrenees (Teixell, 1992). Thrust systems involving the Mesozoic–Tertiary cover are related to the basement thrusts including