



Factors affecting the record of strain fabrics at the anisotropy of magnetic susceptibility: West-Central South-Pyrenean cleavage domain (Southern Pyrenees; NE Spain)

Ó. Pueyo Anchuela^{*}, A. Gil Imaz, A. Pocoví Juan

Grupo de Investigación Geotransfer, Departamento de Ciencias de la Tierra, Universidad de Zaragoza, Spain

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ABSTRACT

Anisotropy of magnetic susceptibility (AMS) is widely used to determine the petrofabric of sedimentary rocks. The identification of magnetic lineation parallel to the stretching direction or normal to the shortening direction is usual in weakly deformed environments. When deformation increase, AMS fabrics progress to magnetic foliation parallel to cleavage and magnetic lineation parallel to the expected amplification direction. In order to analyze the factors influencing the AMS fabrics in an area with a well developed cleavage, four sections across the cleavage Southern Pyrenean domain have been analyzed. The coeval development of cleavage, folding and thrusting and the relatively constant shortening direction during Pyrenean evolution produce an alignment of structures parallel to the tectonic grain of the mountain belt. Factors affecting the AMS cleavage record are related to the presence of ferrimagnetic fabrics linked to the shear parallel to the thrust movement, the influence of previous strain magnetic fabrics affecting both paramagnetic and ferromagnetic particles, the degree of competition between bedding-related and cleavage-related fabrics and the inhomogeneous deformation linked to local structures. These factors resulted in some cases in deviation of results from the expected cleavage-related magnetic fabrics in a sector with clear observation of cleavage at outcrop scale. The obtained data show that in central zones from the Pyrenees, the expected geometrical relations between strain and AMS are not observed and that a low sensitivity to cleavage can be apparently identified. However, a cleavage imprint in the magnetic parameters can be identified.

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1. Introduction

Magnetic fabric and especially *anisotropy of magnetic susceptibility* (AMS) is a widely used technique, developed along the past decades, for the petrofabric characterization (see revisions of Borradaile, 1988; Borradaile and Henry, 1997; Borradaile and Jackson, 2004, 2010; Hrouda, 1982; Tarling and Hrouda, 1993 among others). Since its preliminary applications (e.g. Graham, 1954), different systematic analysis to identify deformational processes (strain, shortening, stress, shear, etc.), emplacement conditions and evolution of igneous bodies (in granitoids, dykes or lava sheet flows), paleocurrents or early sedimentation processes have been the focus of these studies (see Martín-Hernández et al., 2004, for an application revision).

Simple geometrical relations between AMS and different deformational processes have been identified. These correlations permitted to infer processes, that sometimes are not evident at outcrop scale (e.g. Borradaile and Henry, 1997; Borradaile and Tarling, 1981; Hrouda, 1982; Kligfield et al., 1981; Parés and Dinarès, 1993; Parés et al.,

1999). Magnetic lineation as indicator of the stretching direction in compressive and extensive settings has been documented (Borradaile and Henry, 1997; Cifelli et al., 2009). As well, the magnetic lineation can be related with other more complex processes (Debacker et al., 2004, 2009; Martín-Hernández et al., 2005; Parés and Van der Pluijm, 2002a). In some cases, these processes are inferred in apparent non deformed settings as foreland basin or away from frontal thrusts without folds or bedding tilting (Cifelli et al., 2004, 2009; Kissel et al., 1986; Parés et al., 1999; Pueyo Anchuela et al., 2010a; Soto et al., 2009). In the Pyrenees these fabrics have been correlated with layer parallel shortening processes during pre-folding conditions (e.g. Larrasoña et al., 1997, 2004; Parés, 2004; Parés et al., 1999; Pueyo-Morer et al., 1997). These magnetic fabrics have been also interpreted as linked to realignment of paramagnetic particles within the bedding plane (Parés, 2004), the intersection lineation between platy minerals through the zone axis (Bouchez, 1997; Martín-Hernández, 2002) or composite magnetic fabrics between bedding-related and cleavage-related fabrics (Borradaile, 1988; Borradaile and Tarling, 1981; Debacker et al., 2004, 2009; Hirt et al., 2004; Housen et al., 1993; Parés and van der Pluijm, 2002a; Richter et al., 1993; Saint-Bezar et al., 2002).

Magnetic fabrics related to folding and progressive deformation have been also described (magnetic lineation parallel to fold axis

^{*} Corresponding author. Tel.: +34 670021113; fax: +34 976442523.

E-mail address: opueyo@gmail.com (Ó. Pueyo Anchuela).

and to the Y strain axis; Borradaile and Henry, 1997). When cleavage develops, magnetic lineation is parallel to bedding strike, cleavage strike or the intersection lineation between both, and later on, the magnetic lineation becomes parallel to the amplification direction (e.g. Borradaile and Tarling, 1981; Debacker et al., 2004, 2009; Hirt et al., 2004; Oliva-Urcia et al., 2009; Parés and Dinarès, 1993; Rochette and Vialon, 1984).

Different magnetic fabric types have been found in AMS studies in the Pyrenees (Averbuch et al., 1992; Larrasoña et al., 1997; Mochales et al., 2010; Oliva-Urcia et al., 2009; Parés, 2004; Parés and Dinarès, 1993; Pueyo-Morer et al., 1997; Parés et al., 1999; Pueyo et al., 2004; Pueyo Anchuela et al., 2007): i) LPS fabrics (magnetic lineation parallel to bedding strike with independence of cleavage), 2) intersection lineation fabrics (with magnetic lineation parallel to intersection lineation and magnetic foliation coinciding with bedding or cleavage planes), and 3) shear fabrics (magnetic lineation parallel to the regional thrust movement either contained within bedding or horizontal with independence of bedding).

Concerning the Aragón and Aragón–Subordán valleys, four different patterns have been identified up-to-date (Pueyo Anchuela et al., 2007, 2010b): i) fabrics with magnetic lineation parallel to bedding strike, ii) magnetic foliation parallel to the bedding and magnetic lineation parallel to the main Pyrenean trend after bedding restoring, iii) magnetic lineation contained within bedding and normal to structures, and iv) magnetic lineation parallel to the intersection lineation and Kmin axis perpendicular to bedding or between bedding and cleavage poles (Pueyo Anchuela et al., 2007, 2010b). This distribution of fabric types has been interpreted as passively folded LPS fabrics (Larrasoña et al., 1997; Parés, 2004; Parés et al., 1999; Pueyo Anchuela et al., 2007), magnetic lineation parallel to shear linked to thrust movement (Oliva-Urcia et al., 2009; Pueyo Anchuela et al., 2007, 2010b; Pueyo et al., 2004) or intersection lineation fabrics between bedding and cleavage planes (Pueyo Anchuela et al., 2010b).

More recently, integrated magnetic fabric analysis (AMS, Anisotropy of anhysteretic remanent magnetization: AARM and AMS measured at low temperature, LTAMS) in the Internal Sierras, Southern Pyrenees (Oliva-Urcia et al., 2009) has indicated the presence of a magnetic lineation parallel to the bedding strike or the intersection lineation for the more paramagnetic fabrics and magnetic lineation contained in the bedding and normal to the main structural trend for the more ferrimagnetic ones. In this case, AMS seems to be controlled by the different contribution between ferrimagnetic and paramagnetic fabrics.

In the turbiditic basin, south of the Internal Sierras, similar magnetic fabric patterns have been identified (Pueyo Anchuela et al., 2010b). Locally, magnetic foliation is parallel to cleavage and magnetic lineation parallel to intersection lineation or to the dip direction of cleavage, related to overturned fold limbs and highly paramagnetic fabrics (Pueyo Anchuela et al., 2010b). From these analyses, two main conclusions can be inferred. On one hand, magnetic subfabrics can be present without showing evidences in the usual AMS studies, and therefore many of the AMS fabrics are the result of the competition between different subfabrics (Oliva-Urcia et al., 2009; Pueyo Anchuela et al., 2010b, 2011). This situation indicates that some AMS fabrics can be controlled by the intensity of certain processes, magnetic mineralogies and local changes in the deformation gradient along the studied zones.

In order to analyze the different factors affecting the AMS along the cleavage area in the Southern Pyrenees (Choukroune and Séguret, 1973a) a study mainly attending to the Mesozoic and Tertiary rocks has been developed. Sites are located near the Pyrenean Axial zone, on the cover rocks of the Gavarnie nappe. The sampling was performed along the so-called Pyrenean cleavage domain where there is a nearly constant cleavage orientation. For this study 72 sites has been analyzed by means of AMS (1434 samples). In some of them AARM (259 samples) and LTAMS (552 samples) were

analyzed in order to identify the potential presence of subfabrics and their mineralogical characteristics.

2. Geological context

The Pyrenees are the collision chain developed between the European and Iberian plates during the Alpine compression (from Santonian or Campanian to Miocene times; Muñoz, 1992, 2002; Teixell, 1992, 1996). The Axial Zone of the Pyrenees is represented by outcrops of Hercynian rocks, involved in imbricated, thick skinned basement thrust sheets (Teixell, 1996). The separation between north and south Pyrenean zones has been traditionally established along the North-Pyrenean fault and the change of the structural vergence (Choukroune and Séguret, 1973b). The South Pyrenean zone is composed by south-verging folds and thrusts affecting the Hercynian basement units. These basement thrusts progressed to the S with different detachment levels in a thin-skinned manner through the Upper Cretaceous, middle Eocene deposits (e.g. Choukroune and Séguret, 1973b; Labaume et al., 1985; Teixell, 1992, 1996) and Triassic evaporites in the proximities of the frontal thrusts (Millán Garrido, 1996; Teixell and García-Sansegundo, 1995).

The stratigraphical series of the studied area consists in: i) Paleozoic rocks affected by both Hercynian and Alpine structures (Precambrian, Devonian, and Carboniferous) and Permian red beds, ii) carbonatic rocks deposited in marine platforms from the Cenomanian to Campanian (Calcaires des Cañons; Fournier, 1905; and Larra carbonatic rocks; Souquet, 1967; Teixell, 1992), iii) external platform marls and siliciclastic shallow platform deposits (Zuriza, Tuca Blanca and Marboré units, Campanian to Maastrichtian in age; Teixell, 1992), iv) Paleocene and lower Eocene platform deposits (Barnolas and Teixell, 1995; Barnolas et al., 1991) and v) turbiditic Eocene Flysch deposits (Hecho Group; Mutti, 1977, 1984).

The Axial Zone presents a W-plunging, antiformal geometry in the studied zone, with continuous outcrops of Devonian, Carboniferous, Permian sedimentary rocks and late-Hercynian granitoids in the Eastern sector (in this work in the Aragón and Aragón–Subordán valleys, Teixell, 1992). To the west of these two valleys, the pre-Upper Cretaceous units disappear between the Aragón–Subordán and Veral–Roncal valleys. The emplacement of the Gavarnie Nappe is the main responsible for the uplift of the Paleozoic rocks to the East. This nappe also tilted to the South previous thrust-systems (Larra and Monte Perdido thrust systems; Teixell, 1992). In some of the studied sections at the Internal Sierras area up to 5 tilted fold-and-thrust units can be observed (Teixell, 1992, 1996).

The Pyrenees developed from the basement thrusting and basin inversion between Iberian and European plates that began during the Late Cretaceous and Paleogene and progressed until Miocene times (e.g. Muñoz, 2002). The main deformational phases are related to (i) an imbricated fold-and-thrust system (Larra system) with thin-skinned geometry during the mid–late Lutetian to Bartonian (Soler and Puigdefàbregas, 1970; Teixell, 1992, 1996), with a sub-horizontal detachment and south-verging fold-and-thrusts; (ii) this system was later tilted by the emplacement of the Gavarnie nappe, involving the basement with thick-skinned geometry, during Priabonian to Rupelian times (Puigdefàbregas, 1975; Teixell, 1992). The emplacement of the Gavarnie nappe is the main responsible for the antiformal stack of the Axial Zone in the studied zone.

These two thrust systems were later affected by other basement thrusts, with minor influence in the overall geometry. These nappes can be summarized in the intermediate nappe (Teixell, 1992); Ordesa nappe (from Oliva-Urcia, 2004; Oliva-Urcia and Pueyo, 2007 to the E of the studied zone), Guarga nappe (Millán Garrido, 1996; Teixell, 1992, 1996) and the Guara–Gedre nappe (Millán Garrido et al., 2006).

Thrusting from Late Cretaceous to Miocene times indicates a similar shortening direction. Structural trends along the main part of the

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