Revista de la Sociedad Geológica de España 35 (1)

ISSN (versión impresa): 0214-2708
ISSN (Internet): 2255-1379

https://doi.org/10.55407/rsge.94884

A SHORT GUIDE FOR THE STUDY OF ANISOTROPY OF MAGNETIC SUSCEPTIBILITY (AMS) IN DEFORMED ROCKS

Guía rápida para el estudio de rocas deformadas a partir del análisis de la Anisotropía de la Susceptiblidad Magnética (ASM)

Ruth Soto[1], Antonio M. Casas-Sainz[2], Belén Oliva-Urcia[3] y Teresa Román-Berdiel[2]

[1] Instituto Geológico y Minero de España (IGME), CSIC, Unidad de Zaragoza, 50006 Zaragoza, Spain. r.soto@igme.es
[2] Geotransfer (IUCA). Universidad de Zaragoza, 50009 Zaragoza, Spain. acasas@unizar.es, mtdjrb@unizar.es
[3] Universidad Autónoma de Madrid, 28049 Madrid, Spain. belen.oliva@uam.es

Abstract: *The analysis of the Anisotropy of Magnetic Susceptibility (AMS) constitutes a fast and non-destructive technique that has gained the acceptance of structural geologists because it provides valuable information related to the orientation and intensity of the strain ellipsoid of deformed rocks. Part of its strength results from the possibility of (i) characterizing very subtle rock deformation, and (ii) integrating a large number of data, widespread across large areas. Since the pioneer works in the 1950s, a considerable amount of papers applying this technique to a wide variety of issues in Earth Sciences and to almost all rock types (considering both age and lithology) has been published. Here we explore and expose the use of this valuable technique in modern structural geology and tectonics, as well as its benefits and limits.*

Keywords: *anisotropy of magnetic susceptibility, deformed rocks, strain, magnetic ellipsoid, magnetic fabrics.*

Resumen: *El análisis de la Anisotropía de la Susceptibilidad Magnética (ASM) constituye una técnica rápida y no destructiva muy valiosa en geología estructural y tectónica, ya que es capaz de proporcionar información relacionada con la orientación e intensidad del elipsoide de deformación en rocas deformadas. Parte de sus ventajas son, su capacidad para (i) caracterizar rocas muy débilmente deformadas, y (ii) integrar gran cantidad de datos provenientes de grandes áreas. Desde los trabajos pioneros de los años 1950s, gran cantidad de trabajos han utilizado esta técnica en diferentes áreas de las Ciencias de la Tierra y aplicada a, prácticamente, todos los tipos de rocas existentes tanto en edad como litología. En este trabajo exploramos y mostramos el uso actual de esta técnica en geología estructural y tectónica, así como sus beneficios y limitaciones.*

Palabras clave: *anisotropía de la susceptibilidad magnética, rocas deformadas, deformación, elipsoide magnético, fábrica magnética.*

Soto, R., Casas-Sainz, A.M., Oliva-Urcia, B., Román-Berdiel, T., 2022. A short guide for the study of anisotropy of magnetic susceptibility (AMS) in deformed rocks. *Revista de la Sociedad Geológica de España*, 35 (1): 56-70

Introduction

Anisotropy of Magnetic Susceptibility (AMS) analysis in Earth Sciences provides information about the mineral preferred orientation. It can be applied quickly and without destroying or modifying the oriented samples (e.g., Tarling and Hrouda, 1993). The analysis of AMS has been applied to practically all rock types and within a wide range of disciplines in Earth Sciences (i.e., sedimentology, volcanism, magma flow in plutonic rocks, glaciology, tectonics and marine geology). In structural geology, it represents a valuable and commonly-used technique because: (i) it is well established that the orientation of the magnetic ellipsoid in a rock often reflects the orientation of the strain ellipsoid (e.g., Graham, 1966; Borradaile and Jackson, 2004), taking into account that the minerals carrying the magnetic anisotropy control the correlation between magnetic fabric and strain (e.g., Borradaile, 1987; Housen and van der Pluijm, 1990; Biedermann *et al*., 2018), (ii) it can detect very incipient deformation before the development of other strain indicators (e.g., Cifelli *et al*., 2004; Parés, 2015; Almqvist and Koyi, 2018; Burmeister *et al*., 2009), and (iii) it provides valuable information on the origin and subsequent deformational history of rocks (e.g., Tarling and Hrouda, 1993; Borradaile and Henry, 1997). Magnetic fabric records the sum of all processes underwent by a deformed rock volume.

During the last decades, in order to validate the results obtained from magnetic fabrics, AMS measurements have been compared to numerous non-magnetic analyses, able to detect the crystallographic or shape preferred orientation of mineral grains and/or quantify the rock texture. This exercise has allowed to successfully validate AMS data by independently inferring the petrofabric of rocks and has shown its potential under different tectonic scenarios and/or rock types. Non-magnetic analyses include image analyses in rock samples and/or thin sections, XRD analyses, SEM-EDX observations (e.g., Kodama and Sun, 1990; Lüneburg *et al*., 1999; Oliva-Urcia *et al*., 2009), X-Ray goniometry (e.g., Van der Pluijm *et al*., 1994; de Wall and Worm, 1993), neutron goniometry (e.g., Hansen *et al*., 2004; Cifelli *et al*., 2005), EBSD (Electron Backscatter Diffraction) analyses (e.g., Prior *et al*., 1999; Bascou *et al*., 2005), high-resolution X-ray micro-computed tomography imaging (µXCT) (e.g., Schöpa *et al*., 2015; Zhu *et al*., 2017), electrical conductivity (e.g., Clark *et al*., 1988), acoustic velocity measurements (e.g., Robion *et al*., 2014) and high-resolution transmission electron microscopy (HRTEM) analysis (e.g., Mamtani *et al*., 2020). Furthermore, magnetic fabrics have been analysed in analogue models (i.e., sandbox models) under compression and strike-slip to characterize strain distribution (e.g., García-Lasanta *et al*., 2017a, b; Almqvist and Koyi, 2018; Schöfisch *et al*., 2021) and in numerical modelling, in this case analysing mineral alignment (e.g., Biedermann *et al*., 2018; Kuehn *et al*., 2019; Kusbach *et al*., 2019).

Since the reviews done by Borradaile and Jackson (2004, 2010) about AMS in deformed rocks and by Parés (2015) in deformed sedimentary rocks, numerous works and advances have been done using magnetic fabrics as strain markers of deformation under different tectonic scenarios. This works aims to serve as a non-exhaustive, simple guide for the study of anisotropy of magnetic susceptibility in deformed rocks (see Table 1).

What is the AMS and what are magnetic fabrics?

A brief description of the theoretical background of AMS and magnetic fabrics is described on this section. Numerous works and review papers can be consulted to go further on this line (e.g., Tarling and Hrouda, 1993; Borradaile and Jackson, 2004, 2010; Parés, 2015; Biedermann, 2018). The AMS consists of a method able to determine the magnetic fabric of a rock, which reflects the anisotropic behaviour of the magnetic properties of its components (e.g., Hrouda, 1982).

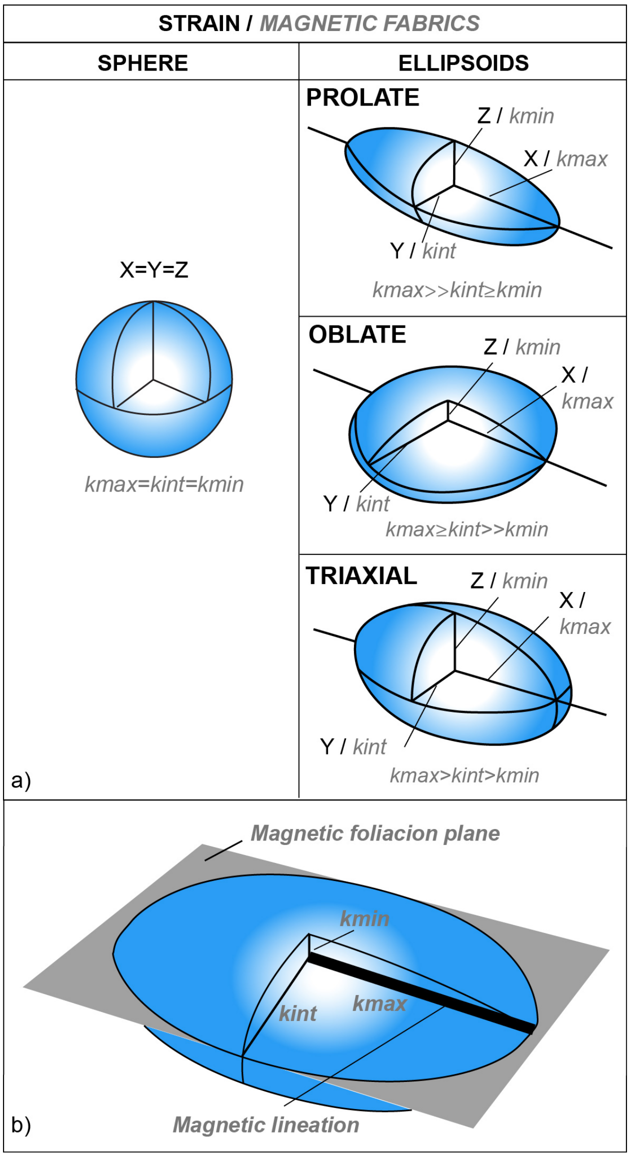

Fig. 1.- (a) Strain/magnetic ellipsoids (prolate, oblate and triaxial) compared with a sphere (Tarling and Hrouda, 1993 and Ramsay and Huber, 1983). (b) Magnetic ellipsoid showing the magnetic lineation and magnetic foliation (modified from Tarling and Hrouda, 1993).

Rock Type	Structural context	Magnetic lineation (ML)/foliation (MF) with respect to S0/cleavage	Magnetic lineation (ML) with respect to strain	Magnetic lineation (ML) with respect structural elements	Other characteristics	References
COMPRESSIONAL SETTINGS						
Sedimentary	Weak deformation	ML parallel to S0 MF parallel to S0	Controlled by layer-parallel shortening ML perpendicular to compression direction	ML parallel to thrusts and folds	Mainly oblate magnetic ellipsoids ML can be used as passive markers to infer vertical-axis rotations	Tarling and Hrouda, 1993 Parés et al., 1999 Soto et al., 2009 Parés, 2015 Pueyo-Anchuela et al., 2012
Sedimentary	Weak cleavage	ML parallel to S0	ML perpendicular to compression direction		Prolate magnetic ellipsoid Kint and Kmin distributed along a girdle in a plane parallel to compression direction	Borradaile, 1987 Aubourg et al., 1995 Borradaile and Henry, 1997 Parés et al., 1999
Sedimentary	Cleavage domains	MF parallel to cleavage plane		ML parallel to the elongation direction (usually the intersection between S0 and cleavage plane)	Transition from oblate (parallel to bedding) to oblate (parallel to cleavage) passing through triaxial magnetic ellipsoid stage	Parés et al., 1999 Oliva-Urcia et al., 2009 Aubourg et al., 2000
Sedimentary	Deformed diapirs	ML parallel to S0 in deformed diapirs MF parallel to S0 in deformed diapirs		In cases of strong compression magnetic lineation parallel to the intersection lineation	All magnetic ellipsoid types (strongly dependent on diamagnetic mineralogy)	Soto et al., 2017 Santolaria et al., 2015
Sedimentary	Shear zones		Magnetic scalar parameters can vary with strain in complex shear zones	ML parallel to transport direction of the thrust ML parallel to S-C planes		Ferré et al., 2014 Marcén et al., 2018
Igneous				ML and MF can be related to syn-emplacement deformation	Traditionally ML parallel to primary magmatic flows	Tarling and Hrouda, 1993 Bouchez, 1997 CañónTapia, 2004
High-grade metamorphic rocks	Crustal shear zones			MF parallel to the metamorphic foliation ML parallel to the stretching lineation or crenulation axis of minerals		Hrouda, 1982 Borradaile and Jackson, 2004 Ferré et al., 2014
EXTENSIONAL SETTINGS						
Sedimentary rocks	Extensional basins	ML parallel to S0 MF parallel to S0	ML parallel to extension extension	ML perpendicular to main normal faults	Usually oblate magnetic ellipsoids	Mattei et al., 1997 Cifelli et al., 2005
Sedimentary rocks	Diapirs			ML and MF consistent with diapiric flow and interaction with regional deformation	All magnetic ellipsoid types (strongly dependent on diamagnetic mineralogy)	Soto et al., 2014 Santolaria et al., 2015
Sedimentary rocks	Inverted extensional basins	ML parallel to S0 MF parallel to S0	ML parallel to previous extension direction	ML perpendicular to main previous normal faults	All magnetic ellipsoid types In case of posterior compressional-related cleavage, primary extensional magnetic fabric can be modified	Soto et al., 2007, 2008 Oliva-Urcia et al., 2013 García-Lasanta et al., 2018
	Shear extensional zones			MF parallel to fault or foliation planes ML parallel or perpendicular to transport direction	All magnetic ellipsoid types, depending on the intensity of deformation	Marcén et al., 2019
TRANSPRESSIONAL/TRANSTENSIONAL SETTINGS						
		ML variable, depending on the intensity of deformation		ML parallel, oblique or perpendicular to faults, depending on strain partitioning MF parallel or slight oblique to faults	Usually triaxial magnetic ellipsoids	Marcén et al., 2015 Román-Berdiel et al., 2019

Table 1.- Magnetic fabrics in different tectonic settings.

Magnetic susceptibility is a physical property that defines the capacity of any material to get magnetized when subjected to an external magnetic field (e. g. Tarling and Hrouda, 1993). The AMS measures the directional variations of the magnetic susceptibility. These directional variations can be mathematically described as a symmetric second-rank tensor with six independent matrix elements and represented by an ellipsoid (e.g., Nye, 1951), similar to the strain ellipsoid. This ellipsoid, usually called magnetic ellipsoid, is defined by the orientation and magnitude of three principal and perpendicular axes; kmax or k1 ≥ kint or k2 ≥ kmin or k3 (Fig. 1). The kmax axis represents the magnetic lineation, whereas the plane defined by kmax and kint represents the magnetic foliation (Fig. 1). Several scalar parameters derived from these three principal magnetic axes have been established to evaluate the anisotropy degree and the shape of the magnetic ellipsoid. For example, the parameters L (kmax/kint) and F (kint/kmin) used to characterize magnetic ellipsoids were adapted to magnetic fabrics from the equivalent petrofabric terms proposed by Flinn (1958) (Fig. 2), whose graphical representation (Flinn diagram) has been widely used in structural geology.

The bulk magnetic susceptibility (Km) results from the contribution of all dia-, para- and ferromagnetic minerals present in the rock. Each mineral type shows different magnetic behaviour depending on the temperature (except diamagnetic minerals), the capacity to retain a remanent magnetization or the intensity of the applied magnetic field (e.g., Tarling and Hrouda, 1993). To know which kind of minerals (i.e., dia-, para- and ferromagnetic minerals) contributes to the total AMS is important for subsequently validating structural interpretations. Many works published in the last three decades have made a considerable effort to elucidate this issue in different rock types (e.g., Parés and van der Pluijm, 2002a, 2014; Borradaile and Jackson, 2004, 2010; Martín-Hernández and Hirt, 2004; Bilardello, 2015; Martín-Hernández and Ferré, 2007; Elhanati *et al*., 2021).

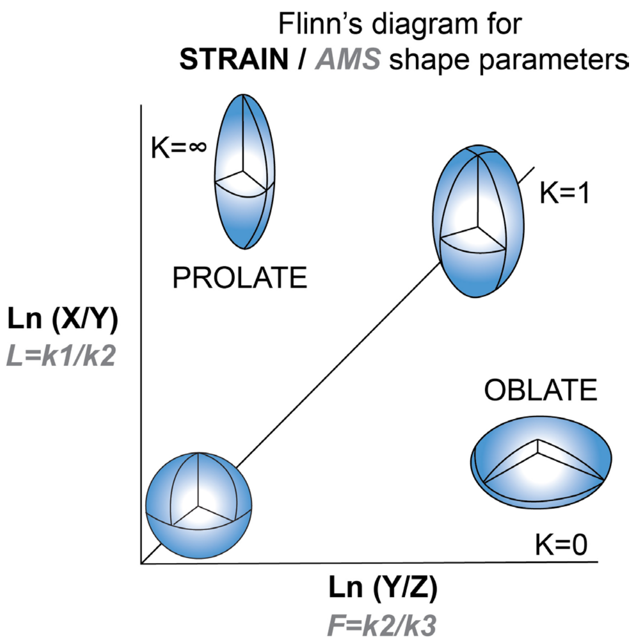

Fig. 2.- Flinn diagram for representing the shape of strain/ magnetic ellipsoids (modified from Ramsay, 1967). L=Lineation and F=Foliation.

The parallel evolution of strain analysis and AMS development in the 20th century

The work of J.G. Ramsay (e.g., Ramsay, 1967; Ramsay and Graham, 1970; Ramsay and Huber, 1983; Ramsay *et al*., 1983) brought about a discrete scientific revolution in Structural Geology, because of the introduction of a solid mathematical ground within which the (until then) qualitative geological observations could be framed. Quantitative analyses allowed reliable determination of orientation axes as well as quantification of the deformation ellipsoid and classification of rocks (adding new elements to petrological-based categories) based on these premises. Nevertheless, all this development was preferentially applied to medium-to-high grade metamorphic rocks in which deformation can be clearly observed, either from exposures or polished sections, or from thin sections under the microscope. Weakly deformed sedimentary rocks, including also very low-grade metamorphic rocks, were not usually considered in these analyses, mainly because of the common lack of strain markers, the smaller grain size and the poorer picture of deformational images under the microscope.

In parallel to strain analysis, but in a non-overlapping scientific field, the measurement of Anisotropy of Magnetic Susceptibility (AMS) began to be applied to the study of the petrofabric of rocks (Khan, 1962; Uyeda *et al*., 1963; Rees, 1965). This technique strongly developed during the following decade, with the works of the Czech magnetic school (Hrouda and Janák, 1971; Janák, 1972; Janák and Kropáček, 1973), later involved in the Agico company. The latter was responsible for the development of the most reliable devices for measuring AMS in rocks. It is worth noting that the distinction between "classical" structural geology and geophysical techniques was a common playground during the 20th century, here including the plate tectonics paradigm. Interestingly, the AMS measurement technique focused mainly in sedimentary and low-grade metamorphic rocks, that were commonly neglected in studies of classical structural geology. During the last two decades of the 20th century and the beginning of the 21th century, the orientations of the magnetic ellipsoids were compared to paleostress ellipsoids confirming that AMS could be considered as a reliable indicators of palaeostress directions in weakly deformed mudrocks (Borradaile and Tarling, 1981; Kissel *et al*., 1986; Lee *et al*., 1990; Sagnotti *et al*., 1994, 1999; Mattei *et al*., 1997, 1999; Borradaile and Hamilton, 2004; Cifelli *et al*., 2004, 2005; Soto *et al*., 2007, 2009). Sedimentary fabrics (associated with compaction), layer-parallel shortening (LPS) under compressional regimes (e.g., Borradaile, 1987, 1991; Borradaile and Henry, 1997; Parés, 2004), or layer-parallel extension (LPE) under extensional regimes in sedimentary and low-grade metamorphic rocks (e.g., Mattei *et al*., 1999; Cifelli *et al*., 2005) gained significance under the light of the orientation of the magnetic lineation and allowed characterizing weak deformation in rocks (e.g., Larrasoaña *et al*., 2004, 2011; Pueyo-Anchuela *et al*., 2010; Pocoví *et al*., 2014; Parés and Anastasio, 2018). The magnetic lineation results from the reorientation of mineral grains (e.g., phyllosilicates) according to the prevailing stress field (Richter *et al*., 1993; Benn, 1994). Therefore, magnetic lineation is (i) perpendicular to the shortening direction in compressional settings (e.g., Kissel *et al*., 1986; Mattei *et al*., 1997; Sagnotti *et al*., 1998, 1999; Parés *et al*., 1999; Parés and van der Pluijm, 2002b; Parés, 2004; Larrasoaña *et al*., 2004) and (ii) parallel to the stretching direction in extensional contexts (Mattei *et al*., 1997, 1999; Sagnotti *et al*., 1994; Cifelli *et al*., 2004, 2005; Borradaile and

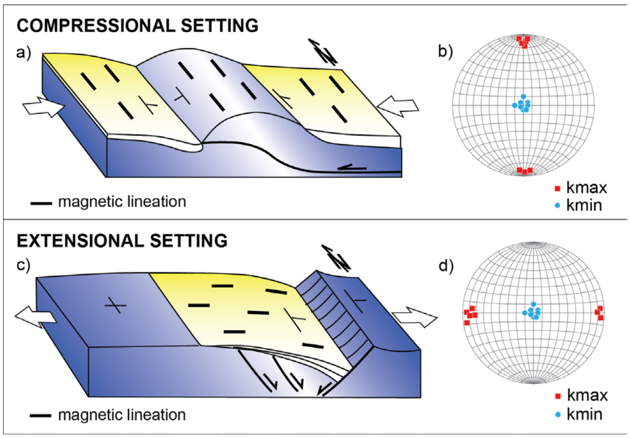

Fig. 3.- (a, b) Magnetic ellipsoid showing kmax and kmin axes in compressional scenarios. In these contexts, the magnetic lineation is usually parallel to fold axes or the strike of thrusts. (c, d) Magnetic ellipsoid showing kmax and kmin axes in extensional scenarios. There, the magnetic lineation usually coincides with the stretching direction and is perpendicular to the main normal faults.

Hamilton, 2004; Soto *et al*., 2007, 2009) (Fig. 3), where anisotropic syn-tectonic growth of certain minerals (i.e., magnetite) can also occur (e.g., Calvín *et al*., 2018).

In contrast with the direct use of magnetic axis orientation to characterize deformation in sedimentary rocks, parameters of the magnetic ellipsoid are not easily translated to the strain parameters defined by Ramsay (1967) and other authors. This is because of the influence of the magnetic anisotropy of each mineral, which does not necessarily correspond to the way in which that same mineral is oriented under the prevailing stress field (e.g., Biedermann, 2018). A reliable comparison between the magnetic ellipsoid and the strain parameters has been found in areas with homogeneous lithology and significant changes of strain values within small distances (Boiron *et al*., 2020; Gracia-Puzo *et al*., 2021). A typical oblate-to-prolate-to-oblate path is found when tectonic shortening increases, from the compaction to the purely tectonic fabric (Parés and van der Pluijm, 2002a).

Interpretation of magnetic fabrics in different tectonic scenarios

Compressional settings

Application to sedimentary rocks in compressional scenarios. Most published works related with AMS deal with its application to deformed rocks in compressional settings. Among them, sedimentary deformed rocks have received more attention compared with igneous or metamorphic rocks. In mudrocks deformed under compression Parés *et al*. (1999) proposed an evolutionary model analogous to the structural model by Ramsay (1967) and Ramsay and Huber (1983). According to Parés *et al*. (1999) the shape and orientation of the magnetic ellipsoide change as strain increases following a well-defined pattern (Fig. 4). This model has been widely used in the literature (see Parés, 2015 and references therein) and evolves from bedding-related to cleavage-related magnetic fabrics. The earliest stage of deformation is represented by an oblate magnetic ellipsoid with kmax axes grouped perpendicular to the shortening direction and kmin axes perpendicular to bedding (Fig. 4). As deformation increases, coeval to the formation of pencil structures and weak cleavage stages (fracture or rough cleavage), the magnetic fabric is characterized by prolate magnetic ellipsoids with kmax axes still perpendicular to the shortening direction and kint and kmin axes distributed along a girdle perpendicular to kmax (Fig. 4). In the latest stages, when slaty cleavage develops, kmin axes evolve into a cluster oriented normal to the cleavage planes (Fig. 4). Among sedimentary rocks, lithologies other than shales, such as sandstones (i.e., coarser grained sediments) or limestones are not so commonly used in AMS deformation studies due to the possible influence of paleocurrents (e.g., Rees, 1965; Felletti *et al*., 2016) or the possibility of occurrence of inverse magnetic fabrics due to mineralogical effects (e.g., Černý *et al*., 2020), respectively.

Under weak compression, the AMS presents a great potential, because it can detect magnetic lineations perpendicular to the shortening direction even in apparently

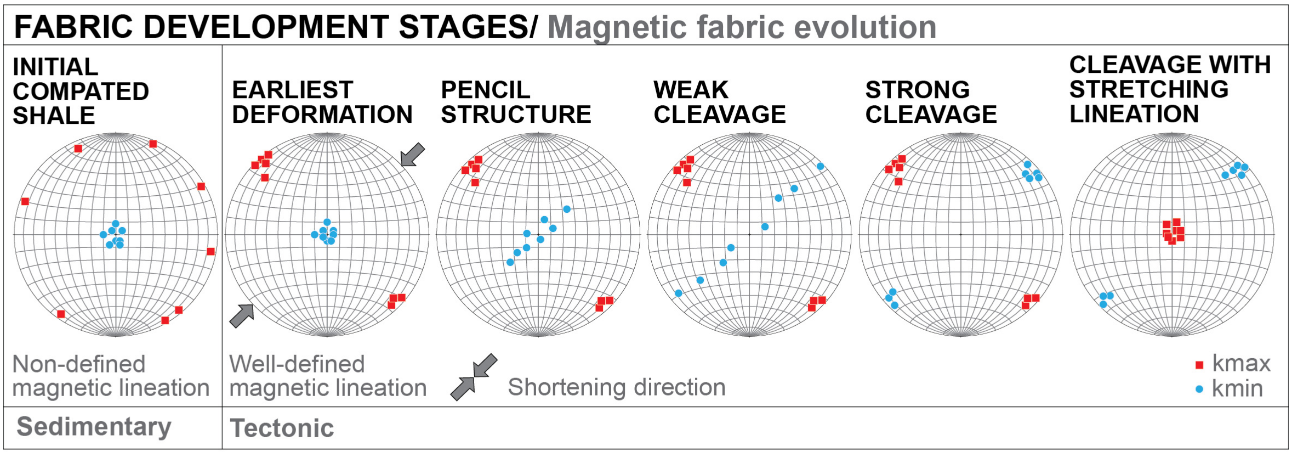

Fig. 4.- Fabric development stages in deformed shales (after Ramsay and Huber, 1983) in black capital letters and examples of stereoplots showing kmax and kmin magnetic susceptibility axes related to magnetic fabric evolution in progressively cleaved mudrocks (after Parés *et al*., 1999) in grey lower-case letters.

undeformed foreland basins (i.e., with subtle evidences of deformation and showing fracture systems) (e.g., Ebro foreland basin; Soto *et al*., 2009, 2016). Other applications of AMS analysis in compressional settings are listed below. (1) In squeezed salt diapirs, the magnetic lineation seems to record the diapiric flow, but it can also be reoriented by the subsequent compression (e.g., Santolaria *et al*., 2015; Soto *et al*., 2014, 2017; Heinrich *et al*., 2019). Since inferring the petrofabric inside diapirs is usually difficult due to poor-quality outcrops and poorly developed meso-scale structures, AMS in diapiric bodies constitutes a very promising tool to infer the petrofabric of evaporitic cores and/or associated rocks diagnosing ductile flow. (2) The application of AMS to shear zones of major thrusts has shown magnetic lineations parallel to the transport direction, related to ductile S-C structures (e.g., Ferré *et al*., 2014; Marcén *et al*., 2018) or to the intersection of S and C planes (e.g., Parés and van der Pluijm, 2002b). Spatial variations in the magnetic ellipsoid orientation and magnitude of the magnetic scalar parameters have also helped unravelling complex heterogeneous shear zones (e.g., Marcén *et al*., 2018). (3) Magnetic lineations can also be used as passive markers of deformation to calculate vertical-axis rotations when AMS is acquired during pre-tilting deformation (Mochales *et al*., 2010; Pueyo-Anchuela *et al*., 2012).

Application to igneous rocks in compressional scenarios. The application of AMS to igneous rocks emerged lately when compared to sedimentary or metamorphic rocks (e.g., Khan, 1962; King, 1966; Wing-Fatt and Stacey, 1966). This technique has been traditionally used to characterize the primary magmatic flows and/or the location of preferential pathways for magma ascent of plutonic, volcanic and subvolcanic rocks (e.g., Tarling and Hrouda, 1993; Bascou *et al*. 2005; Hrouda *et al*. 2005; Ort *et al*., 2015; Nagaraju and Parashuramulu, 2019) (Fig. 5). The comparison between AMS orientation and lava flow directions is not straightforward since it depends on the carrier minerals of the AMS (e.g., Cañón-Tapia, 2004). In structural geology and tectonics, magnetic fabrics of igneous rocks are useful to analyse the syn-emplacement deformation of rocks or the post-emplacement solid-state ductile structures formed during orogenesis (e.g., Bouchez, 1997; Cañón-Tapia, 2004; Antolín-Tomás *et al*., 2009; Silva *et al*., 2010; Fodor *et al*., 2020; Porquet *et al*., 2017 and references therein). In numerous classically considered post-tectonic granites, AMS has revealed unexpected internal structures favoring their interpretation as syn-tectonic (e.g., Bouchez, 1997; Aranguren *et al*., 2003). AMS in lavas can result very useful because it can help to detect different magnetic fabric types (zones) in the same lava flow related to rheology, flow dynamics and/or flow-induced shear strain (e.g., Cañón-Tapia, 2004; Caballero-Miranda *et al*. 2016, and references therein).

Application to high-grade metamorphic rocks in compressional scenarios. The interpretation of magnetic fabrics in high-grade metamorphic rocks can be complicated by deformation, metamorphism and/or magnetic mineralogy (e.g., Borradaile and Jackson, 2004; Ferré *et al*., 2014 and references therein; Mertanen and Karell, 2012). In deformed metamorphic rocks, magnetic fabric analyses have been applied to characterize crustal shear zones with different strain gradients (e.g., Kontny *et al*., 2012; Merz *et al*., 2019). In normal conditions, several examples of AMS in metamorphic rocks have shown that the magnetic foliation is parallel to the metamorphic foliation and the magnetic lineation parallel to the stretching lineation or crenulation axis of minerals (e.g. Kligfield *et al*., 1977; Hrouda, 1982).

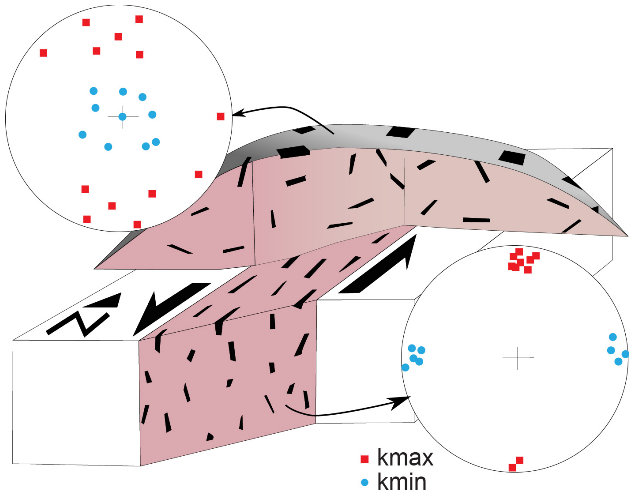

Fig. 5.- Magnetic fabrics related to magma flow in plutonic rocks. The different situations correspond to a transtensional shear band contemporary with magma intrusion at deep levels and expansion of magma in the upper crust defining an intrusion with laccolith geometry. Note that the magnetic fabrics are better defined when the intrusion is strongly constrained by the deformation field.

Extensional settings

Although the application of AMS to the study of extensional contexts developed long after its application in compressive contexts, the resulting publications have widely demonstrated its usefulness in all types of rocks (granites, high metamorphic rocks, dikes and sedimentary sequences, e.g., Staudigel *et al*., 1992; Bouillin *et al*., 1993; Sagnotti *et al*., 1994; Román-Berdiel *et al*., 1995, among the first works). It has also been demonstrated that the technique has a high sensitivity, especially in those contexts where the extensional deformation is weak, inhomogeneous and localized, and where strain markers are scarce or not available.

The application of the analysis of AMS to extensional contexts (e.g., back-arc basins, intracontinental extensional basins, etc.) has revealed that a well-defined tectonically controlled magnetic lineation can develop also in these contexts. Numerous works have largely demonstrated that the magnetic lineation coincides with the stretching direction obtained from mesostructural analysis of brittle structures (e.g., faults and joints) (Sagnotti *et al*., 1994; Mattei *et al*., 1997, 1999; Cifelli *et al*., 2005; Soto *et al*., 2007, 2012; Oliva-Urcia *et al*., 2010, 2013, 2016; García-Lasanta *et al*., 2014, 2015). This magnetic lineation is oriented subparallel to the local bedding dip direction (Mattei *et al*., 1997, 1999; Marcén *et al*., 2019) or perpendicular to the main normal

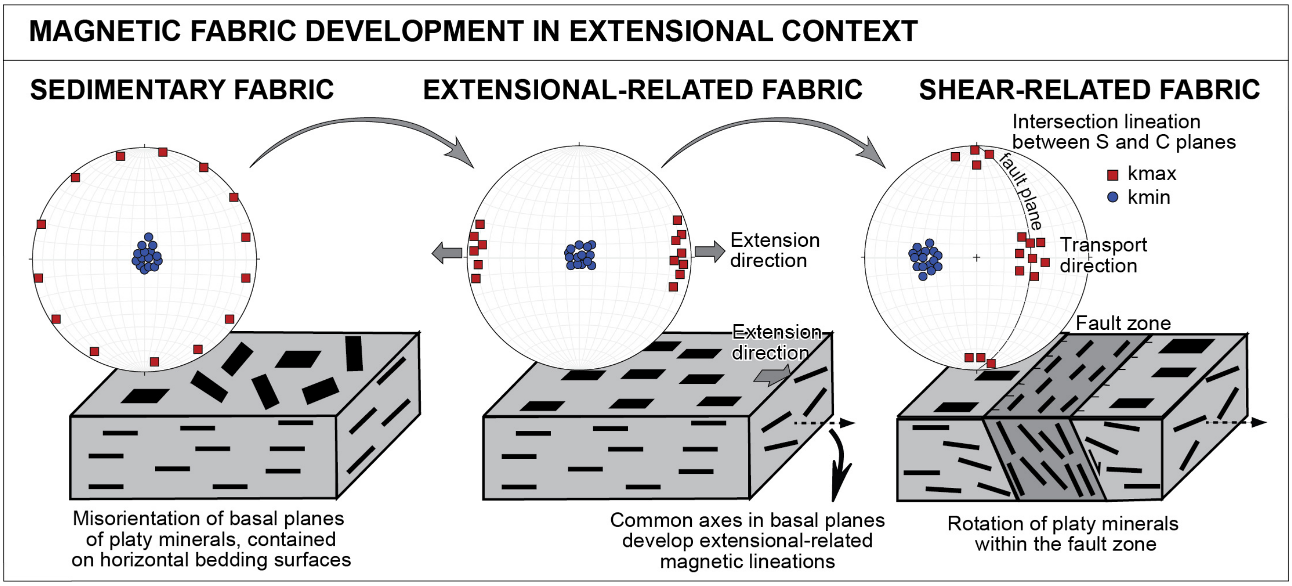

Fig. 6.- Sketch showing the relation between deformation and magnetic fabrics in extensional context (modified from Marcén *et al.*, 2019). Note that in shear-related deformation contexts, mechanical rotation of platy minerals occurs within the fault zone and kmin axes change from perpendicular to bedding plane (sedimentary fabric) to perpendicular to fault planes (shear-related fabric).

faults (Cifelli *et al.*, 2005). In the same way that the evolution of the magnetic fabric has been described as the strain path in mudrocks under compression, the evolution of magnetic ellipsoids with strain has also been described for extensional scenarios (Marcén *et al.*, 2019) (Fig. 6). In this case, the magnetic fabric changes from an extension-related fabric (with magnetic foliations parallel to bedding and magnetic lineations clustered parallel to the local extension direction) to shear-related fabrics (with magnetic foliations parallel to faults or to foliation planes and magnetic lineations parallel or perpendicular to the transport direction) when strain increases, approaching the fault zones limiting the basins (Fig. 6). Magnetic lineations in extensional settings have been defined by the crenulation of the clay minerals (i.e., paramagnetic minerals) parallel to the stretching direction (Mattei *et al.*, 1999) or by the intersection axis resulting from the girdling of phyllosilicates basal planes parallel to the stretching direction (Cifelli *et al.*, 2004, 2005).

Extensional magnetic lineations are acquired during the early (i.e., syn-sedimentary) stages of deformation (e.g., Cifelli *et al.*, 2004; García-Lasanta *et al.*, 2013), and they can be preserved in spite of the occurrence of subsequent

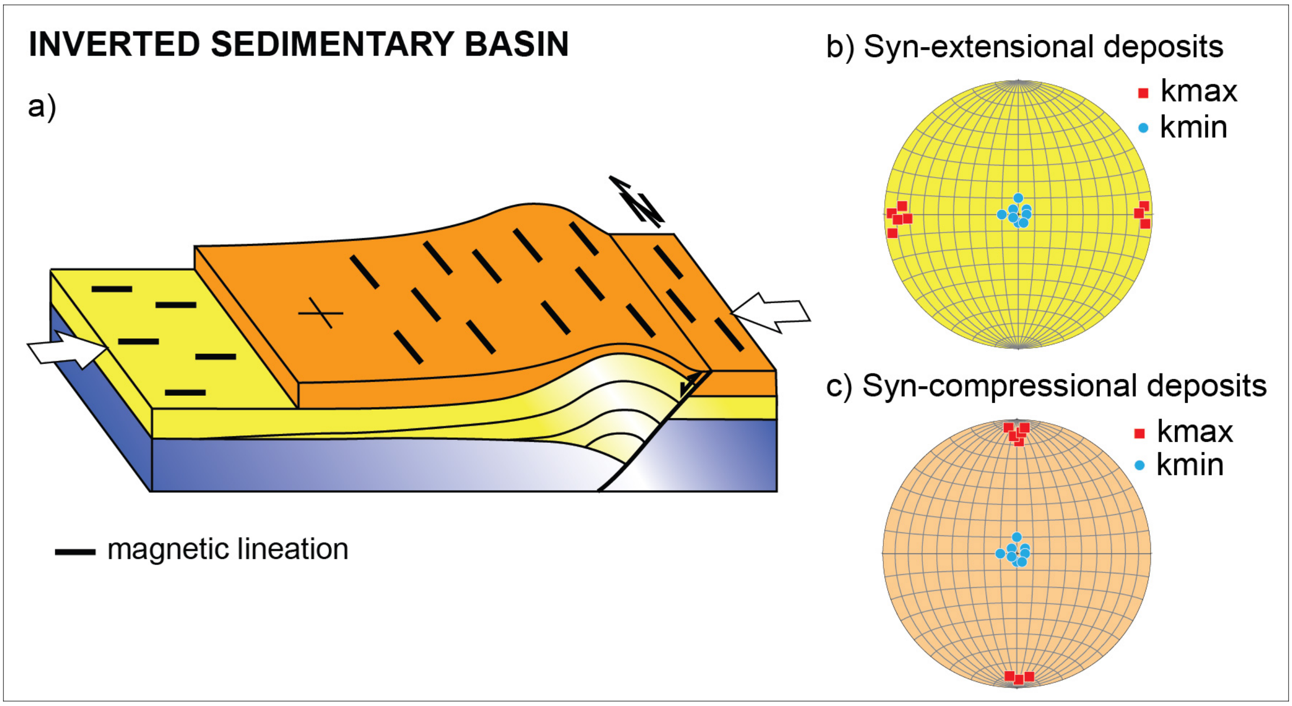

Fig. 7.- (a) Magnetic fabrics in inverted sedimentary basins. Stereoplots showing the kmax and kmin magnetic ellipsoid axes that can be found in syn-extensional (b) and posterior syn-compressional deposits (c).

tectonic events (Soto *et al*., 2007; Oliva-Urcia *et al*., 2013). Primary extensional magnetic lineations can be modified only in areas with intense deformation associated with a subsequent compressional stage (i.e., development of compression-related cleavage, Oliva-Urcia *et al*., 2013). Therefore, magnetic lineations parallel to the previous stretching direction acquired during the extensional basinal stage are common in inverted sedimentary basins (e.g., Soto *et al*., 2007, 2019; García-Lasanta *et al*., 2018 and references therein) (Fig. 7). Compared to syn-extensional brittle mesostructure analysis, AMS records deformation associated with the near deformation field, during shorter intervals of time (i.e., earliest stages of deformation), whereas brittle mesostructure analysis records longer time spans (Soto *et al*., 2007). This makes AMS very useful in inverted basins, where its application allows obtaining information on the extensional stage, prior to the tectonic inversion (Soto *et al*., 2007, 2008, 2019; García-Lasanta *et al*., 2018 and references therein).

Transpressional/transtensional settings

Deformation at the grain scale, and hence magnetic fabrics in transpressional and transtensional scenarios, are strongly dependent on strain partitioning between different structures (e.g., Goldstein and Brown, 1988; Housen *et al*., 1995; Jones and Tanner, 1995; Fossen and Tikoff, 1998; Díaz-Azpiroz *et al*., 2014; Barcos *et al*., 2015). Under homogeneous strain conditions, intermediate-plunging lineations are typical of both transpressional and transtensional settings. However, strain partitioning imposes other constraints that must be also applied to magnetic fabric analysis, namely the co-existence of lineations parallel to the strike of faults and parallel to the dip direction of faults, even when all lineations are parallel to the transport direction of each individual fault (Marcén *et al*., 2015; Román-Berdiel *et al*., 2019). The bimodality in the lineation orientation further complicates the interpretation of magnetic fabrics because it adds another variable to the existing dichotomy between transport-parallel and transport-perpendicular magnetic lineations. This implies that thorough studies, including low-temperature AMS (and subfabric analysis in general), detailed mapping and analysis of polished and thin sections under the microscope, must be done in order to characterize the movement of the fault and the possible subfabrics corresponding to different types of magnetic minerals. Magnetic foliation is usually more constant, and commonly parallel or slightly oblique to the trace of the faults, what also gives hints about the compatibility with their sense of movement.

AMS discussion and interpretation, use with caution

The use of AMS to characterize deformed rocks presents numerous advantages widely known by the scientific community (i.e., quick, inexpensive, effective and non-destructive technique). These advantages, however, should not lead to erroneous interpretations of AMS data in terms of structural geology and tectonics. These errors usually come from misinterpretations of the relationships between the magnetic signal and the petrofabric (e.g., Borradaile and Jackson, 2004). To know the contribution of the magnetic carriers to the total AMS is crucial, since both the shape and the crystallographic preferred orientations of mineral grains and the magnetic interactions between ferro- and ferrimagnetic particles are the main sources of the AMS in a rock (e.g., Borradaile and Jackson, 2004, 2010; Biedermann, 2018). In this section we briefly explain three important factors, which are closely interconnected, to be considered when interpreting AMS data. (1) Magnetic subfabric analyses accompanying AMS data to correctly interpret tectonic magnetic lineations and/or foliations in case of coexistence of paramagnetic and ferrimagnetic minerals. (2) Absence of magnetic mineral artifacts that can mask AMS data related to deformation. (3) Presence of composite magnetic fabrics related to different tectonic processes.

Magnetc subfabric interpretation

The common coexistence of diamagnetic, paramagnetic and ferrimagnetic s.l. minerals in a rock makes relevant the separation of magnetic subfabrics (e.g., Borradaile and Jackson, 2004, 2010). Minerals in a rock can form at different times and also respond to deformation differently. This means that paramagnetic minerals can show a magnetic fabric different from that the one indicated by the ferrimagnetic minerals present in the same rock. Thus, in case of complex magnetic ellipsoids and to properly understand their structural significance, separation into para- and ferrimagnetic subfabrics, even in cases where the contribution of ferrimagnetic grains might be considered as secondary, is crucial. The use of the following techniques is very useful to check the match or mismatch between the paramagnetic and ferrimagnetic subfabric; (i) AMS at low temperature (AMS-LT) allows to enhance the paramagnetic signal (e.g., Parés and van der Pluijm, 2002a, 2014), and (ii) the anisotropy of anhysteretic remanent magnetization (AARM), the anisotropy of the isothermal remanent magnetization (AIRM) and the high field AMS (HF-AMS) allow to separate the ferrimagnetic subfabric (e.g., Kelso *et al*., 2002; Borradaile and Jackson, 2004, 2010; Martín-Hernández and Hirt, 2004; Martín-Hernández and Ferré, 2007; Elhanati *et al*., 2021).

Here we describe several examples where magnetic subfabric separation was necessary to correctly interpret AMS data. In fine-grained sedimentary rocks where phyllosilicates are abundant, AMS-LT is usually used to confirm that paramagnetic minerals are the main carriers to the total AMS (e.g., Parés and van der Pluijm, 2002a). In red beds where hematite (i.e., ferrimagnetic mineral) is present, usually phyllosilicates mimic the hematite subfabric, and the LT-AMS subfabric and the total MS fabric overlap (see García-Lasanta *et al*., 2015). In remagnetized limestones sampled in inverted extensional basins (e.g., Cameros basin and Central High Atlas), the LT-AMS and the total AMS do not overlap (García-Lasanta *et al*., 2014; Calvín *et al*., 2018). The LT-AMS gives information about the subfabric of phyllosilicates, and the AARM (among other methods) reflects the subfabric carried by magnetite. In this case, the kmax axes of the magnetite subfabric are parallel to the extension direction linked to the basinal stage and the remagnetization event (Calvín *et al*., 2018). In remagnetized siltstones affected by penetrative pressure-solution cleavage, the orientation of the paramagnetic ellipsoids was consistent with the orientation of layer-parallel shortening related to an early diagenetic or sedimentary period, whereas the orientation of the ferrimagnetic ellipsoids responded to subhorizontal shear associated to subsequent cleavage formation, a process that did not alter the earlier paramagnetic subfabric (Oliva-Urcia *et al*., 2009).

Ferromagnetic granites (i.e., magnetite-bearing granites; see Bouchez, 1997) show mixed para/ferro (iron-bearing silicates/magnetite) fabric type. The subfabric ellipses are usually coaxial and the separation of subfabrics is not necessary (e.g., Nédélec and Bouchez, 2015). In paramagnetic granites (i.e., magnetite-free granites, with bulk magnetic susceptibilities Km generally below 500 x 10-6 SI; see Bouchez, 1997), a mixture of biotite and amphibole is the most frequent case, resulting in a mixed para/para subfabric. Subfabrics of biotite and amphibole are considered coaxial, and the resulting bulk magnetic fabric is well-defined both in foliation and lineation, but not in magnitude (i.e., anisotropy degree), which depends of the intrinsic anisotropy and respective amounts of each mineral species (e.g., Nédélec and Bouchez, 2015). Special attention should be put when turmaline or cordierite are present, because their 'inverse' magneto-crystalline paramagnetic anisotropy (kmin parallel to the prism axis) may interfere with other mineral fabrics (e.g., Nédélec and Bouchez, 2015).

Mineralogical artefacts

Mineralogical changes (i.e., formation of new minerals) related to the deformational processes are common. Widespread mineralizations can occur during diagenesis, related to hydrothermal events and/or to fluid migration associated with the formation and subsequent compressional deformation of sedimentary basins and also in fold-and-thrust belts. The neoformation of minerals could mask the previous magnetic fabric having structural significance, especially if the new magnetic mineralogy is dominated by ferrimagnetic minerals (Gaillot *et al*., 2006; Mattsson *et al*., 2021), and at the same time, they can provide information on the evolving strain field. In addition, another common phenomenon to be taken into account when working with ferroan carbonates is their inverse magnetic fabric (that is, kmax axis corresponds to the minimum axis of the petrofabric) (e.g., Rochette, 1988; Černý *et al*., 2020).

Hematite is ubiquitous in red beds and can be a neoformed mineral. It presents a strong magnetocrystalline anisotropy with its kmin axis located parallel to the c-axis, and the kmax axis in the basal plane (Morrish, 1994; Martín-Hernández and Guerrero-Suárez, 2012). The new formation of hematite can provoke magnetic ellipsoid axes switching with respect to the bedding or foliation planes (strain axis), both in igneous rocks (i.e., Mondal and Mamtani, 2014; Gonçalves *et al*., 2020), and in red beds (Oliva-Urcia *et al*., 2016).

In magmatic rocks, where magnetite is more abundant than in sedimentary rocks, "abnormal" (Fanjat *et al*., 2012) or unexpected fabrics (k axes do not follow strain axes) are found more often, either related to interaction or to elongated shapes of magnetite particles (Fanjat *et al*., 2012 and references therein). In multi-domain (MD) grains of magnetite, the AMS axes correspond with the magnetite crystal, whereas for single-domain (SD) crystals the magnetic axes inversely correlate with the grain shape (e.g., Rochette, 1988; Cañón-Tapia, 1996; Biedermann, 2020; Mattsson *et al*., 2021 and references therein).

The ferrimagnetic s.l. sulphides greigite and/or phyrrotite are authigenic minerals, that constitute intermediate phases precursor of pyrite (paramagnetic mineral). Their preservation in the sedimentary record is related to the abundance of iron relative to more limited dissolved sulphide (Roberts, 2015 and references therein). Pyrrhotite has strong magnetocrystalline anisotropy with the easy direction of magnetization in the basal plane and the c-axis perpendicular to the basal plane containing the axis of hard magnetization (Sagnotti, 2007 and references therein). Greigite has also a strong magnetocrystalline anisotropy (Sagnotti, 2007 and references therein). Their presence can develop "composite" magnetic fabric due to their relationship with posterior tectonic events. The term «composite magnetic fabrics» refers to the combination in a rock of different preferred orientation of minerals contributing significantly to magnetic anisotropy (Housen *et al*., 1993). They can be developed under different/subsequent strain scenarios or grain sizes with different orientation distribution (see next section). Their combination provides a magnetic ellipsoid which usully does not follow the strain ellipsoid and requires further magnetic and non-magnetic analyses to properly decipher the total AMS (Debacker *et al*., 2004).

Composite magnetic fabrics

One of the major contributions of AMS to the study of deformed rocks is the possibility of analyzing the different processes that sum up, in different proportions, to the total fabric of the rock. Ferro-, para- and diamagnetic contributions to the total susceptibility (and its anisotropy) provide the means for understanding the different processes involved during the periods of basin formation and inversion, especially when different p-T conditions, and therefore, different magnetic minerals, characterize each of these stages (e.g., Calvín *et al*., 2018; García-Lasanta *et al*., 2018). This is particularly true, for example, in fault zones (Román-Berdiel *et al*., 2019; Casas-Sainz *et al*., 2018; Marcén *et al*., 2015) where para- and ferro-magnetic fabrics coexist and can be coaxial or not, depending on the intensity of deformation and the timing of their formation. Ferromagnetic fabrics can reflect the transport direction of faults *vs*. paramagnetic fabrics, whose lineation can be either parallel or perpendicular to the transport direction. In the second case, phylosillicates are interpreted to be arranged according to the S/C fabrics related to shear zones.

The confrontation between the competing effects of sedimentary, compaction-related and tectonic-related fabrics has been a common issue when comparing different fabric types in compressed sedimentary basins (Parés and van der Pluijm, 2002b; Pueyo-Anchuela *et al*., 2010; García-Lasanta *et al*., 2014). In this case, when the magnetic mineralogy is homogeneous (i.e., same mineralogical composition), the analysis of scalar parameters derived from the magnetic ellipsoid axes is a good marker of the strain path for rocks in different parts of the basin and can be used as an indicator of the prevalence of one kind of fabric against the other (Gracia-Puzo *et al*., 2021). In weakly deformed rocks, the orientation of foliation, rather than that of the lineation (whose direction remains usually parallel to the strike of beds and axes of folds), is the most sensitive feature that can help to define the degree of tectonic deformation. The distribution of poles to the magnetic foliation and their scattering (clustered or distributed along a great circle containing the poles to bedding and cleavage) is also a qualitative and reliable indicator (Parés, 2004, 2015).

Conclusions

Anisotropy of Magnetic Susceptibility (AMS) analyses applied to structural geology and tectonics have demonstrated their high versatility and applicability. In deformed rocks, magnetic fabrics reflect the strain ellipsoid detecting even very incipient deformation, despite the correspondence between the orientation and magnitude of the magnetic and strain ellipsoids cannot be straightforward. AMS analysis can help to characterize rock volume deformation under different tectonic scenarios (i.e., extension, compression or strike-slip) of different rock types (i.e., sedimentary, igneous and metamorphic rocks). This work explores the use of this valuable technique in modern structural geology and its benefits and limits.

Acknowledgements and funding

This study has been supported by projects CGL2017-84901-C2-2-P, PID2019-108753GB-C22 and PID2020-114273GB-C22 from Spanish Ministry of Science. This study represents a contribution from the GeoAp (E01-20R) and the GeoTransfer (E32-20R) Research Groups (Aragón Government). The authors acknowledge the careful and constructive revisions from Josep M. Parés and Andrea Biedermann and from the Editor, Nieves López-González.

Author contributions

Manuscript preparation, R.S., A.C, B.O. and T.R.; methodology, R.S., A.C, B.O. and T.R.; data curation, R.S., A.C, B.O. and T.R.; figures, R.S., A.C, and T.R.; research/analysis, R.S., A.C, B.O. and T.R.; manuscript review, R.S., A.C, B.O. and T.R.; coordination and supervision, R.S.; funding acquisition, R.S., A.C, and T.R.

References

Almqvist, B.S., Koyi, H., 2018. Bulk strain in orogenic wedges based on insights from magnetic fabrics in sandbox models. Geology, 46(6): 483-486. https://doi.org/10.1130/G39998.1

Antolín-Tomás, B., Roman-Berdiel, T., Casas-Sainz, A., Gil-Peña, I., Oliva, B., Soto, R., 2009. Structural and Magnetic Fabric Study of the Marimanha Granite (Axial Zone of the Pyrenees). International Journal of Earth Sciences, 98(2): 427-441. https://doi.org/10.1007/s00531-007-0248-1

Aranguren, A., Cuevas, J., Tubía, J.M., Román-Berdiel, T., Casas-Sainz, A., Casas-Ponsati, A., 2003. Granite laccolith emplacement in the Iberian arc: AMS and gravity study of the La Tojiza pluton (NW Sapin). J. Geol. Soc. London, 160: 435-445. https://doi.org/10.1144/0016-764902-079

Barcos, L., Balanyá, J. C., Díaz-Azpiroz, M., Expósito, I., Jiménez-Bonilla, A., 2015. Kinematics of the Torcal Shear Zone: Transpressional tectonics in a salient-recess transition at the northern Gibraltar Arc. Tectonophysics, 663: 62-77. https://doi.org/10.1016/j.tecto.2015.05.002

Bascou, J., Camps, P., Dautria, J.M., 2005. Magnetic versus crystallographic fabrics in a basaltic lava flow. Journal of Volcanology and Geothermal Research, 145(1): 119-135. https://doi.org/10.1016/j.jvolgeores.2005.01.007

Benn, K., 1994. Overprinting of magnetic fabrics in granites by small strains: numerical modelling. Tectonophysics, 233(3-4): 153-162. https://doi.org/10.1016/0040-1951(94)90238-0

Biedermann, A.R., 2018. Magnetic anisotropy in single crystals: A review. Geosciences, 8(8): 302. https://doi.org/10.3390/geosciences8080302

Biedermann, A.R., 2020. FinIrrSDA: A 3-D model for magnetic shape and distribution anisotropy of finite irregular arrangements of particles with different sizes, geometries, and orientations. Journal of Geophysical Research: Solid Earth, 125(12): e2020JB020300. https://doi.org/10.1029/2020JB020300

Biedermann, A.R., Kunze, K., Hirt, A.M., 2018. Interpreting magnetic fabrics in amphibole-bearing rocks. Tectonophysics, 722: 566-576. https://doi.org/10.1016/j.tecto.2017.11.033

Bilardello, D., 2015. Isolating the anisotropy of the characteristic remanence-carrying hematite grains: a first multispecimen approach. Geophysical Journal International, 202(2): 695-712. https://doi.org/10.1093/gji/ggv171

Boiron, T., Aubourg, C., Grignard, P. A., Callot, J.P., 2020. The clay fabric of shales is a strain gauge. Journal of Structural Geology, 104130. https://doi.org/10.1016/j.jsg.2020.104130

Borradaile, G., 1987. Anisotropy of magnetic susceptibility: rock composition versus strain. Tectonophysics, 138(2-4): 327-329. https://doi.org/10.1016/0040-1951(87)90051-5

Borradaile, G.J., 1991. Correlation of strain with anisotropy of magnetic susceptibility (AMS). Pure and applied geophysics, 135(1): 15-29. https://doi.org/10.1007/BF00877006

Borradaile, G.J., Tarling, D.H., 1981. The influence of deformation mechanisms on magnetic fabrics in weakly deformed rocks. Tectonophysics, 77(1-2): 151-168. https://doi.org/10.1016/0040-1951(81)90165-7

Borradaile, G.J., Hamilton, T., 2004. Magnetic fabrics may proxy as neotectonic stress trajectories, Polis rift, Cyprus. Tectonics, 23: TC1001, 1-11. https://doi.org/10.1029/2002TC001434

Borradaile, G.J. Henry, B., 1997. Tectonic applications of magnetic susceptibility and its anisotropy. Earth-Science Reviews, 42(1-2): 49-93. https://doi.org/10.1016/S0012-8252(96)00044-X

Borradaile, G.J., Jackson, M., 2004. Anisotropy of magnetic susceptibility (AMS): magnetic petrofabrics of deformed rocks. In: Magnetic fabric: Methods and Applications. Geological Society Special Publications 238, (F. Martín-Hernandez, C.M. Lueneburg, C. Aubourg, M. Jackson, Eds). Geological Society of London, London, 299-360. https://doi.org/10.1144/

GSL.SP.2004.238.01.18

Borradaile, G.J., Jackson, M., 2010. Structural geology, petrofabrics and magnetic fabrics (AMS, AARM, AIRM). Journal of Structural Geology, 32(10): 1519-1551. https://doi.org/10.1016/j.jsg.2009.09.006

Bouchez, J.L., 1997. Granite is never isotropic: an introduction to AMS studies of granitic rocks. In: Granite: From Segregation of Melt to emplacement fabrics, (J.L. Bouchez, D.H.W. Hutton, W.E. Stephens, Eds). Kluwer, Dordrecht, 95-112. https://doi.org/10.1007/978-94-017-1717-5_6

Bouillin, J.P., Bouchez, J.L., Lespinasse, P., Pecher, A., 1993. Granite emplacement in an extensional setting: an AMS study of the magmatic structure of Mnte Capanne (Elba, Italy). Earth and Planetary Science Letters, 118: 263-279. https://doi.org/10.1016/0012-821X(93)90172-6

Burmeister, K.C., Harrinson, M.J., Marshak, S., Ferre, E.C., Bannister, R.A., Kodama, K.P., 2009. Comparison of Fry strain ellipse and AMS ellipsoid trends to tectonic fabric trends in very low-strain sandstone of the Appalachian fold-thrust belt. Journal of Structural Geology, 31(9): 1028-1038. https://doi.org/10.1016/j.jsg.2009.03.010

Caballero-Miranda, C.I., Alva-Valdivia, L.M., González-Rangel, J.A., Gogitchaishvili, A., Urrutia-Fucugauchi, J., Kontny, A., 2016. Vertical AMS variation within basalt flow profiles from the Xitle volcano (Mexico) as indicator of heterogeneous strain in lava flows. Journal of Volcanology and Geothermal Research, 311: 9-28. https://doi.org/10.1016/j.jvolgeores.2016.01.003

Calvín, P., Villalaín, J.J., Casas-Sainz, A.M., 2018. Anisotropic magnetite growth in remagnetized limestones: Tectonic constraints and implications for basin history. Geology, 46(9): 751-754. https://doi.org/10.1130/G45158.1

Cañón-Tapia, E., 1996. Single-grain versus distribution anisotropy: a simple three-dimensional model. Physics of the Earth and Planetary Interiors, 94(1-2): 149-158. https://doi.org/10.1016/0031-9201(95)03072-7

Cañón-Tapia, E., 2004. Anisotropy of magnetic susceptibility of lava flows and dykes: a historical account. In: Magnetic fabric: Methods and Applications, Geological Society Special Publications 238, (F. Martín-Hernandez, C.M. Lueneburg, C. Aubourg, M. Jackson, Eds). Geological Society of London, London, 205-225. https://doi.org/10.1144/GSL.SP.2004.238.01.14

Casas-Sainz, A. M., Gil-Imaz, A., Simón, J. L., Izquierdo-Llavall, E., Aldega, L., Román-Berdiel, T., Caricchi, C., 2018. Strain indicators and magnetic fabric in intraplate fault zones: Case study of Daroca thrust, Iberian Chain, Spain. Tectonophysics, 730: 29-47. https://doi.org/10.1016/j.tecto.2018.02.013

Černý, J., Melichar, R., Všianský, D., Drahokoupil, J., 2020. Magnetic Anisotropy of Rocks: A New Classification of Inverse Magnetic Fabrics to Help Geological Interpretations. Journal of Geophysical Research: Solid Earth, 125(11): e2020JB020426. https://doi.org/10.1029/2020JB020426

Cifelli, F., Mattei, M., Hirt, A.M., Günther, A., 2004. The origin of tectonic fabrics in “undeformed” clays: the early stages of deformation in extensional sedimentary basins. Geophys. Res. Lett., 31: L09604. https://doi.org/10.1029/2004GL019609

Cifelli, F., Mattei, M., Chadima, M., Hirt, A. M., Hansen, A., 2005. The origin of tectonic lineation in extensional basins: combined neutron texture and magnetic analyses on “undeformed” clays. Earth and Planetary Science Letters, 235(1-2): 62-78. https://doi.org/10.1016/j.epsl.2005.02.042

Debacker, T.N., Robion, P., Sintubin, M., 2004. The anisotropy of magnetic susceptibility (AMS) in low-grade, cleaved pelitic rocks: influence of cleavage/bedding angle and type and relative orientation of magnetic carriers. In: Magnetic fabric: Methods and Applications, Geological Society Special Publications 238, (F. Martín-Hernandez, C.M. Lueneburg, C. Aubourg, M. Jackson, Eds). Geological Society of London, London, 77-107. https://doi.org/10.1144/GSL.SP.2004.238.01.08

de Wall, H., Worm, H.U., 1993. Field dependence of magnetic anisotropy in pyrrhotite: effects of texture and grain shape. Physics of the Earth and Planetary Interiors, 76(1-2): 137-149. https://doi.org/10.1016/0031-9201(93)90063-F

Díaz-Azpiroz, M., Barcos, L., Balanyá, J.C., Fernández, C., Expósito, I., Czeck, D.M., 2014. Applying a general triclinic transpression model to highly partitioned brittle-ductile shear zones: A case study from the Torcal de Antequera massif, external Betics, southern Spain. Journal of Structural Geology, 68: 316-336. https://doi.org/10.1016/j.jsg.2014.05.010

Elhanati, D., Issachar, R., Levi, T., Weinberger, R., 2021. A practical approach for identification of magnetic fabric carriers in rocks. Journal of Geophysical Research: Solid Earth, 126(5): e2020JB021105. https://doi.org/10.1029/2020JB021105

Fanjat, G., Camps, P., Shcherbakov, V., Barou, F., Sougrati, M. T., Perrin, M., 2012. Magnetic interactions at the origin of abnormal magnetic fabrics in lava flows: a case study from Kerguelen flood basalts. Geophysical Journal International, 189(2): 815-832. https://doi.org/10.1111/j.1365-246X.2012.05421.x

Felletti, F., Dall’Olio, E., Muttoni, G., 2016. Determining flow directions in turbidites: an integrated sedimentological and magnetic fabric study of the Miocene Marnoso Arenacea Formation (northern Apennines, Italy). Sedimentary Geology, 335: 197-215. https://doi.org/10.1016/j.sedgeo.2016.02.009

Ferré, E.C., Gébelin, A., Till, J.L., Sassier, C., Burmeister, K.C., 2014. Deformation and magnetic fabrics in ductile shear zones: a review. Tectonophysics, 629: 179-188. https://doi.org/10.1016/j.tecto.2014.04.008

Flinn, D., 1958. On tests of significance of preferred orientation in three-dimensional fabric diagrams. The Journal of Geology, 66(5): 526-539. https://doi.org/10.1086/626533

Fodor, L.I., Márton, E., Vrabec, M., Koroknai, B., Trajanova, M., Vrabec, M., 2020. Relationship between magnetic fabrics and deformation of the Miocene Pohorje intrusions and surrounding sediments (Eastern Alps). International Journal of Earth Sciences, 109(4): 1377-1401. https://doi.org/10.1007/s00531-020-01846-4

Fossen, H., Tikoff, B., 1998. Extended models of transpression and transtension, and application to tectonic settings. In: Continental Transpressional and Transtensional Tectonics, Geological Society Special Publications 135, (R.E. Holdsworth, R.A. Strachan, J.E. Dewey, Eds). Geological Society, London, 15-33. https://doi.org/10.1144/GSL.SP.1998.135.01.02

Gaillot, P., de Saint-Blanquat, M., Bouchez, J.L., 2006. Effects of magnetic interactions in anisotropy of magnetic susceptibility: Models, experiments and implications for igneous rock fabrics quantification. Tectonophysics, 418(1-2): 3-19. https://doi.org/10.1016/j.tecto.2005.12.010

García-Lasanta, C., Oliva-Urcia, B., Román-Berdiel, T., Casas, A.M. Pérez-Lorente, F., 2013. Development of magnetic fabrics in sedimentary rocks: insights from early compactional structures (ECS). Geophysical Journal International, 194 (1): 182-199. https://doi.org/10.1093/gji/ggt098

García-Lasanta, C., Oliva-Urcia, B., Román-Berdiel, T., Casas, A.M., Hirt, A.M., 2014. Understanding the Mesozoic kinematic evolution in the Cameros basin (Iberian Range, NE Spain) from magnetic subfabrics and mesostructures. Journal of Structural Geology, 66: 84-101. https://doi.org/10.1016/j.jsg.2014.05.013

García-Lasanta, C., Oliva-Urcia, B., Román-Berdiel, T., Casas, A.M., Gil-Peña, I., Sánchez-Moya, Y., Sopeña, A., Hirt, A.M. Mattei, M., 2015. Evidence for the Permo-Triassic transtensional rifting in the Iberian Range (NE Spain) according to magnetic fabrics results. Tectonophysics 651-652: 216-231. https://doi.org/10.1016/j.tecto.2015.03.023

García-Lasanta, C., Izquierdo-Llavall, E., Román-Berdiel, T., 2017a. Magnetic fabric analysis in analogue models of clays. Geogaceta, 61: 103-106.

García-Lasanta, C., Román-Berdiel, T., Izquierdo-Llavall, E., Casas-Sainz A., 2017b. Magnetic fabric analysis in analogue models of clays. European Geosciences Union General Assembly. Geophysical Research Abstracts, 19: 18643-2.

García-Lasanta, C., Oliva-Urcia, B., Casas-Sainz, A. M., Román-Berdiel, T., Izquierdo-Llavall, E., Soto, R., Villalaín, J.J., 2018. Inversion tectonics and magnetic fabrics in Mesozoic basins of the Western Tethys: A review. Tectonophysics, 745: 1-23. https://doi.org/10.1016/j.tecto.2018.08.005

Goldstein, A.G., Brown, L.L., 1988. Magnetic susceptibility anisotropy of mylonites from the Brevard Zone, North Carolina, USA. Physics of the earth and Planetary Interiors, 51(4): 290-300. https://doi.org/10.1016/0031-9201(88)90070-2

Gonçalves, A., Sant'Ovaia, H., Noronha, F., 2020. Geochemical Signature and Magnetic Fabric of Capinha Massif (Fundão, Central Portugal): Genesis, Emplacement and Relation with W-Sn Mineralizations. Minerals, 10(6): 557. https://doi.org/10.3390/min10060557

Gracia-Puzo, F., Aubourg, C., Casas-Sainz, A., 2021. A fast way to estimate the clay fabric from shale fragments. Key example from a strained thrust footwall (Pyrenees). Journal of Structural Geology, 104443. https://doi.org/10.1016/j.jsg.2021.104443

Graham, J.W., 1966. Significance of magnetic anisotropy in Appalachian sedimentary rocks. In: The Earth Beneath the Continents, Geophysical Monographs 10, (J.S. Steinhart, T.J. Smith, Eds). American Geophysical Union, 627-648. https://doi.org/10.1029/GM010p0627

Hansen, A., Chadima, M., Cifelli, F., Brokmeier, H.G., Siemes, H., 2004. Neutron pole figures compared with magnetic preferred orientations of different rock types. Physica B: Condensed Matter, 350(1): 120-122. https://doi.org/10.1016/j.physb.2004.04.008

Heinrich, F.C., Schmidt, V., Schramm, M., Mertineit, M., 2019. Anisotropy of magnetic susceptibility in salt rocks from the German Zechstein Basin, Sondershausen mine. Geophysical Journal International, 219(1): 690-712. https://doi.org/10.1093/gji/ggz326

Housen, B.A., van der Pluijm, B.A., 1990. Chlorite control of correlations between strain and anisotropy of magnetic susceptibility. Physics of the Earth and Planetary Interiors, 61. https://doi.org/10.1016/0031-9201(90)90114-D

Housen, B.A., Richter, C., van der Pluijm, B.A., 1993. Composite magnetic anisotropy fabrics: experiments, numerical models and implications for the quantification of rock fabrics. Tectonophysics, 220(1-4): 1-12. https://doi.org/10.1016/0040-1951(93)90219-A

Housen, B.A., van Der Pluijm, B.A., Essene, E.J., 1995. Plastic behavior of magnetite and high strains obtained from magnetic fabrics in the Parry Sound shear zone, Ontario Grenville Province. Journal of Structural Geology, 17(2): 265-278. https://doi.org/10.1016/0191-8141(94)E0045-Z

Hrouda, F., 1982. Magnetic anisotropy of rocks and its application in geology and geophysics. Geophys. Surveys, 5: 37-82. https://doi.org/10.1007/BF01450244

Hrouda, F., Janák, F., 1971. A study of the hematite fabric of some red sediments on the basis of their magnetic susceptibility anisotropy. Sedimentary Geology, 6(3): 187-199. https://doi.org/10.1016/0037-0738(71)90035-2

Hrouda, F., Chlupáčová, M., Schulmann, K., Šmíd, J., Závada, P., 2005. On the effect of lava viscosity on the magnetic fabric intensity in alkaline volcanic rocks. Studia Geophysica et Geodaetica, 49(2): 191-212. https://doi.org/10.1007/s11200-005-0005-5

Janák, F., 1972. Magnetic susceptibility anisotropy of various rock types and its significance for geophysics and geology. Geophysical Prospecting, 20(2): 375-384. https://doi.org/10.1111/j.1365-2478.1972.tb00640.x

Janák, F., Kropáček, V., 1973. A brief outline of the magnetic susceptibility anisotropy of various rock types. Studia Geophysica et Geodaetica, 17(2): 123-130. https://doi.org/10.1007/BF01613682

Jones, R.R., Tanner, P.G., 1995. Strain partitioning in transpression zones. Journal of Structural Geology, 17(6): 793-802. https://doi.org/10.1016/0191-8141(94)00102-6

Kelso, P.R., Tikoff, B., Jackson, M., Sun, W., 2002. A new method for the separation of paramagnetic and ferromagnetic susceptibility anisotropy using low field and high field methods. Geophysical Journal International, 151(2): 345-359. https://doi.org/10.1046/j.1365-246X.2002.01732.x

Khan, M.A., 1962. The anisotropy of magnetic susceptibility of some igneous and metamorphic rocks. Journal of Geophysical Research, 67(7): 2873-2885. https://doi.org/10.1029/JZ067i007p02873

King, R.F., 1966. The magnetic fabric of some Irish granites. Geological Journal, 5(1): 43-66. https://doi.org/10.1002/gj.3350050106

Kissel, C., Barrier, E., Laj, C., Lee, T.Q., 1986. Magnetic fabric in "undeformed" marine clays from compressional zones. Tectonics, 5: 769-781. https://doi.org/10.1029/TC005i005p00769

Kligfield, R., Lowrie, W., Dalziel, I.W.D., 1977. Magnetic susceptibility as a strain indicator in the Sudbury Basin, Ontario. Tectonophysics, 40(3-4): 287-308. https://doi.org/10.1016/0040-1951(77)90070-1

Kodama, K.P., Sun, W.W., 1990. SEM and magnetic fabric study of a compacting sediment. Geophysical Research Letters, 17(6): 795-798. https://doi.org/10.1029/GL017i006p00795

Kontny, A., Engelmann, R., Grimmer, J.C., Greiling, R.O., Hirt, A., 2012. Magnetic fabric development in a highly anisotropic magnetite-bearing ductile shear zone (Seve Nappe Complex, Scandinavian Caledonides). International Journal of Earth Sciences, 101(3): 671-692. https://doi.org/10.1007/s00531-011-0713-8

Kuehn, R., Hirt, A. M., Biedermann, A. R., Leiss, B., 2019. Quantitative comparison of microfabric and magnetic fabric in black shales from the Appalachian plateau (western Pennsylvania, USA). Tectonophysics, 765: 161-171. https://doi.org/10.1016/j.tecto.2019.04.013

Kusbach, V.K., Machek, M., Roxerová, Z., Racek, M., Silva, P.F., 2019. Localization effect on AMS fabric revealed by microstructural evidence across small-scale shear zone in marble. Scientific reports, 9(1): 1-14. https://doi.org/10.1038/s41598-019-53794-y

Larrasoaña, J.C., Pueyo, E.L. Parés, J.M., 2004. An integrated AMS, structural, palaeo- and rock-magnetic study of Eocene marine marls from Jaca-Pamplona basin (Pyrenees, N Spain): new insights into the timing of magnetic fabric acquisition in weakly deformed mudrocks. In: Magnetic fabric: Methods and Applications, Geological Society Special Publications 238, (F. Martín-Hernandez, C.M. Lueneburg, C. Aubourg, M. Jackson, Eds). Geological Society of London, London, 127-

143. https://doi.org/10.1144/GSL.SP.2004.238.01.10

Larrasoaña, J.C., Gómez-Paccard, M., Giralt, S. Roberts, A.P., 2011. Rapid locking of tectonic magnetic fabrics in weakly deformed mudrock. Tectonophysics, 507: 16-25. https://doi.org/10.1016/j.tecto.2011.05.003

Lee, T.Q., Kissel, C., Laj, C., Horng, C.S., Lue, Y.T., 1990. Magnetic fabric analysis of the Plio-Pleistocene sedimentary formations of the Coastal Range of Taiwan. Earth and Planetary Science Letters, 98(1): 23-32. https://doi.org/10.1016/0012-821X(90)90085-C

Lüneburg, C.M., Lampert, S.A., Hermann, I., Lebit, D., Hirt, A.M., Casey, M. Lowrie, W., 1999. Magnetic anisotropy, rock fabrics and finite strain in deformed sediments of SW Sardinia (Italy). Tectonophysics, 307: 51-74. https://doi.org/10.1016/S0040-1951(99)00118-3

Mamtani, M.A., Reznik, B., Kontny, A., 2020. Intracrystalline deformation and nanotectonic processes in magnetite from a naturally deformed rock. Journal of Structural Geology, 135: 104045. https://doi.org/10.1016/j.jsg.2020.104045

Marcén, M., Román-Berdiel, T., Casas, A., Calvín-Ballester, P., Oliva-Urcia, B., García-Lasanta, C., 2015. Kinematics of long lived faults in intraplate settings: case study of the Río Grío Fault (Iberian Range). European Geosciences Union General Assembly. Geophysical Research Abstracts: 5165.

Marcén, M., Casas-Sainz, A.M., Román-Berdiel, T., Oliva-Urcia, B., Soto, R., Aldega, L., 2018. Kinematics and strain distribution in an orogen-scale shear zone: Insights from structural analyses and magnetic fabrics in the Gavarnie thrust, Pyrenees. Journal of Structural Geology, 117: 105-123. https://doi.org/10.1016/j.jsg.2018.09.008

Marcén, M., Román-Berdiel, T., Casas-Sainz, A. M., Soto, R., Oliva-Urcia, B., Castro, J., 2019. Strain variations in a seismogenic normal fault (Baza Sub-basin, Betic Chain): Insights from magnetic fabrics (AMS). Tectonophysics, 765: 64-82. https://doi.org/10.1016/j.tecto.2019.05.014

Martín-Hernández, F., Hirt, A.M., 2004. A method for the separation of paramagnetic, ferrimagnetic and haematite magnetic subfabrics using high-field torque magnetometry. Geophysical Journal International, 157 (1): 117-127. https://doi.org/10.1111/j.1365-246X.2004.02225.x

Martín-Hernández, F., Ferré, E.C., 2007. Separation of paramagnetic and ferrimagnetic anisotropies: A review. Journal of Geophysical Research: Solid Earth, 112(B3). https://doi.org/10.1029/2006JB004340

Martín-Hernandez, F., Guerrero-Suárez, S., 2012. Magnetic anisotropy of hematite natural crystals: high field experiments. International Journal of Earth Sciences, 101(3): 637-647. https://doi.org/10.1007/s00531-011-0665-z

Mattei, M., Sagnotti, L., Faccenna, C., Funiciello, R., 1997. Magnetic fabric of weakly deformed clay-rich sediments in the Italian peninsula: relationship with compressional and extensional tectonics. Tectonophysics, 271: 107-122. https://doi.org/10.1016/S0040-1951(96)00244-2

Mattei, M., Speranza, F., Argentieri, A., Rossetti, F., Sagnotti, L., Funiciello, R., 1999. Extensional tectonics in the Amantea basin (Calabria, Italy): a comparison between structural and magnetic anisotropy data. Tectonophysics, 307(1-2): 33-49. https://doi.org/10.1016/S0040-1951(99)00117-1

Mattsson, T., Petri, B., Almqvist, B., McCarthy, W., Burchardt, S., Palma, J. O., Galland, O., 2021. Decrypting magnetic fabrics (AMS, AARM, AIRM) through the analysis of mineral shape fabrics and distribution anisotropy. Journal of Geophysical Research: Solid Earth, e2021JB021895. https://doi.org/10.1029/2021JB021895

Mertanen, S., Karell, F., 2012. Palaeomagnetic and AMS studies on Satulinmaki and Koijarvi fault and shear zones. Geological Survey of Finland Special Paper, 52: 195-226.

Merz, L., Almqvist, B.S., Grimmer, J.C., Kontny, A., 2019. Magnetic fabric development in the Lower Seve thrust from the COSC-1 drilling, Swedish Caledonides. Tectonophysics, 751: 212-228. https://doi.org/10.1016/j.tecto.2018.12.018

Mochales, T., Pueyo, E. L., Casas, A.M., Barnolas, A., Oliva-Urcia, B., 2010. Anisotropic magnetic susceptibility record of the kinematics of the Boltaña Anticline (Southern Pyrenees). Geological Journal, 45(5-6): 562-581. https://doi.org/10.1002/gj.1207

Mondal, T.K., Mamtani, M.A., 2014. Fabric analysis in rocks of the Gadag region (southern India)-implications for time relationship between regional deformation and gold mineralization. Tectonophysics, 629: 238-249. https://doi.org/10.1016/j.tecto.2013.09.021

Morrish, A.H., 1994. Canted antiferromagnetism: hematite. World Scientific Publishing C. Pte Ltd, Singapore. https://doi.org/10.1142/2518

Nagaraju, E., Parashuramulu, V., 2019. AMS studies on a 450 km long 2216 Ma dyke from Dharwar craton, India: implications to magma flow. Geoscience Frontiers, 10(5): 1931-1939. https://doi.org/10.1016/j.gsf.2018.12.003

Nédélec, A. Bouchez, J.L., 2015. Granites: petrology, structure, geological setting and metallogeny. Oxford University Press, 335 p. https://doi.org/10.1093/acprof:oso/9780198705611.001.0001

Nye, J.F., 1951. Physical properties of crystals. Clarendon Press. Oxford.

Oliva-Urcia, B., Larrasoaña, J.C., Pueyo, E.L., Gil, A., Mata, P., Parés, J.M., Schleicher, A.M., Pueyo, O., 2009. Disentangling magnetic subfabrics and their link to deformation processes in cleaved sedimentary rocks from the Internal Sierras (west central Pyrenees, Spain). Journal of Structural Geology, 31: 163-176. https://doi.org/10.1016/j.jsg.2008.11.002

Oliva-Urcia, B., Casas, A.M., Soto, R., Villalaín, J.J. Kodama, K., 2010. A transtensional basin model for the Organyà basin (central southern Pyrenees) based on magnetic fabric and brittle structures. Geophysical Journal International, 184 (1): 111-130. https://doi.org/10.1111/j.1365-246X.2010.04865.x

Oliva-Urcia, B., Román-Berdiel, T., Casas, A.M., Bogalo, M.F., Osácar, M.C. García-Lasanta, C., 2013. Transition from extensional to compressional magnetic fabrics in the cretaceous Cabuérniga basin (North Spain). Journal of Structural Geology, 46: 220-234. https://doi.org/10.1016/j.jsg.2012.09.001

Oliva-Urcia, B., Casas, A.M., Moussaid, B., Villalaín, J.J., El Ouardi, H., Soto, R., Torres-López, S., Román-Berdiel, T., 2016. Tectonic fabrics vs. mineralogical artifacts in AMS analysis: a case study of the Western Morocco extensional Triassic basins. Journal of Geodynamics, 94-95: 13-33. https://doi.org/10.1016/j.jog.2016.01.004

Ort, M.H., Porreca, M., Geissman, J.W., 2015. The use of palaeomagnetism and rock magnetism to understand volcanic processes: introduction. In: The Use of Palaeomagnetism and Rock Magnetism to Understand Volcanic Processes, Geological Society Special Publications 396, (M.H. Ort, M. Porreca, J.W. Geissman, Eds). Geological Society of London, London, 1-11. https://doi.org/10.1144/SP396.17

Parés, J.M., 2004. How deformed are weakly deformed mudrocks? Insights from magnetic anisotropy. In: Magnetic fabric: Methods and Applications, Geological Society Special Publications 238, (F. Martín-Hernandez, C.M. Lueneburg, C. Aubourg, M. Jackson, Eds). Geological Society of London, London, 191-203. https://doi.org/10.1144/GSL.SP.2004.238.01.13

Parés, J.M., 2015. Sixty years of anisotropy of magnetic susceptibility in deformed sedimentary rock. Frontiers in Earth Science, 3(4): 1-13. https://doi.org/10.3389/feart.2015.00004

Parés, J.M., Anastasio, D., 2018. The extent of penetrative Pyrenean deformation in the Ebro foreland Basin: Magnetic fabric data from the eastern sector. Geologica Acta, 16(4): 375-390.

Parés, J.M., van der Pluijm, B.A., 2002a. Phyllosilicate fabric characterization by low-temperature anisotropy of magnetic susceptibility (LT-AMS). Geophysical Research Letters, 29(24): 68-1. https://doi.org/10.1029/2002GL015459

Parés, J.M., van Der Pluijm, B.A., 2002b. Evaluating magnetic lineations (AMS) in deformed rocks. Tectonophysics, 350(4): 283-298. https://doi.org/10.1016/S0040-1951(02)00119-1

Parés, J.M., van der Pluijm, B.A., 2014. Low-temperature AMS and the quantification of subfabrics in deformed rocks. Tectonophysics, 629: 55-62. https://doi.org/10.1016/j.tecto.2014.03.005

Parés, J.M., van der Pluijm, B.A., Dinarès-Turell, J., 1999. Evolution of magnetic fabrics during incipient deformation of mudrocks (Pyrenees, northern Spain). Tectonophysics, 307: 1-14. https://doi.org/10.1016/S0040-1951(99)00115-8

Pocoví, J.A., Anchuela, Ó.P., Pueyo, E.L., Casas-Sainz, A.M., Berdiel, M.R., Imaz, A. G., Villalaín, J.J., 2014. Magnetic fabrics in the Western Central-Pyrenees: an overview. Tectonophysics, 629: 303-318. https://doi.org/10.1016/j.tecto.2014.03.027

Porquet, M., Pueyo, E.L., Román-Berdiel, T., Olivier, P., Longares, L.A., Cuevas, J., Ramajo, J., the Geokin3DPyr working group by alphabetical order, Antolín, B., Aranguren, A., Auréjac, J.B., Bouchez, J.-L., M. Casas, A.M., Denèle, Y., Gleizes, G., Hilario, A., Izquierdo-Llavall, E., Leblanc, D., Oliva-Urcia, B., Santana,V., Tubía, J.M., Vegas, N., 2017. Anisotropy of magnetic susceptibility of the Pyrenean granites. Journal of Maps, 13(2): 438-448. https://doi.org/10.1080/17445647.2017.1302364

Prior, D. J., Boyle, A.P., Brenker, F., Cheadle, M.C., Day, A., López, G., Peruzzi, L., Potts, G., Reddy, S., Spiess, R., Timms, N.E., Trimby, P., Wheeler, J., Zetterstrom, L., 1999. The application of electron backscatter diffraction and orientation contrast imaging in the SEM to textural problems in rocks. American Mineralogist, 84: 1741-1759. https://doi.org/10.2138/am-1999-11-1204

Pueyo-Anchuela, Ó., Gil Imaz, A., Pocoví Juan, A., 2010. Tectonic imprint in magnetic fabrics in foreland basins: a case study from the Ebro Basin, N Spain. Tectonophysics, 492(1-4): 150-163. https://doi.org/10.1016/j.tecto.2010.06.016

Pueyo-Anchuela, O., Pueyo, E.L., Juan, A.P., Imaz, A.G., 2012. Vertical axis rotations in fold and thrust belts: comparison of AMS and paleomagnetic data in the Western External Sierras (Southern Pyrenees). Tectonophysics, 532: 119-133. https://doi.org/10.1016/j.tecto.2012.01.023

Ramsay, J.G., 1967. Folding and fracturing of rocks. Mc Graw Hill Book Company, 568 pp.

Ramsay, J.G., Graham, R.H., 1970. Strain variation in shear belts. Canadian Journal of Earth Sciences, 7(3): 786-813. https://doi.org/10.1139/e70-078

Ramsay, J.G., Huber, M.I., 1983. The techniques of modern structural geology: strain analysis. Academic press.

Ramsay, J.G., Huber, M.I., Lisle, R.J., 1983. The techniques of modern structural geology: Folds and fractures (Vol. 2). Academic press.

Rees, A.I., 1965. The use of anisotropy of magnetic susceptibility in the estimation of sedimentary fabric 1. Sedimentology, 4(4): 257-271. https://doi.org/10.1111/j.1365-3091.1965.tb01550.x

Richter, C., Ratschbacher, L., Frisch, W., 1993. Magnetic fabrics, crystallographic preferred orientation, and strain of progressively metamorphosed pelites in the Helvetic Zone of the Central Alps (Qartenschifer Formation). Journal of Geophysical Research, 98: 9557-9570. https://doi.org/10.1029/93JB00554

Roberts, A.P., 2015. Magnetic mineral diagenesis. Earth-Science Reviews, 151: 1-47. https://doi.org/10.1016/j.earscirev.2015.09.010

Robion, P., David, C., Dautriat, J., Colombier, J.C., Zinsmeister, L., Collin, P.Y., 2014. Pore fabric geometry inferred from magnetic and acoustic anisotropies in rocks with various mineralogy, permeability and porosity. Tectonophysics, 629: 109-122. https://doi.org/10.1016/j.tecto.2014.03.029

Rochette, P., 1988. Inverse magnetic fabric in carbonate-bearing rocks. Earth and Planetary Science Letters, 90(2): 229-237. https://doi.org/10.1016/0012-821X(88)90103-3

Román-Berdiel, T., Pueyo-Morer, E.L., Casas-Sainz, A.M., 1995. Granite emplacement during contemporary shortening and normal faulting: structural and magmatic study of the Veiga Massif (NW Sapin). Journal of Structural Geology, 17: 1689-1706. https://doi.org/10.1016/0191-8141(95)00062-I

Román-Berdiel, T., Casas-Sainz, A.M., Oliva-Urcia, B., Calvín, P., Villalaín, J.J., 2019. On the influence of magnetic mineralogy in the tectonic interpretation of anisotropy of magnetic susceptibility in cataclastic fault zones. Geophysical Journal International, 216(2): 1043-1061. https://doi.org/10.1093/gji/ggy481

Sagnotti, L., 2007. Iron sulfides. In: Encyclopedia of geomagnetism and paleomagnetism. Springer.

Sagnotti, L., Faccenna, C., Funiciello, R. Mattei, M., 1994. Magnetic fabric and structural setting of Plio-Pleistocene clayey units in an extensional regime: the Tyrrhenian margin of Central Italy. Journal of Structural Geology, 16: 1243-1257. https://doi.org/10.1016/0191-8141(94)90067-1

Sagnotti, L., Speranza, F., Winkler, A., Mattei, M., Funiciello, R., 1998. Magnetic fabric of clay sediments from the external northern Apennines (Italy). Physics of the Earth and Planetary Interiors, 105(1-2): 73-93. https://doi.org/10.1016/S0031-9201(97)00071-X

Sagnotti, L., Winkler, A., Montone, P., Di Bella, L., Florindo, F., Mariucci, M. T., Marra, F., Alfonsi, L., Frepoli, A., 1999. Magnetic anisotropy of Plio-Pleistocene sediments from the Adriatic margin of the northern Apennines (Italy): implications for the time-space evolution of the stress field. Tectonophysics, 311: 139-153. https://doi.org/10.1016/S0040-1951(99)00159-6

Santolaria, P., Casas, A. M., Soto, R., 2015. Anisotropy of magnetic susceptibility as a proxy to assess internal deformation in diapirs: case study of the Naval salt wall (Southern Pyrenees). Geophysical Journal International, 202(2): 1207-1222. https://doi.org/10.1093/gji/ggv231

Schöfisch, T., Koyi, H., Almqvist, B., 2021. Influence of décollement friction on anisotropy of magnetic susceptibility in a fold-and-thrust belt model. Journal of Structural Geology, 144: 104274. https://doi.org/10.1016/j.jsg.2020.104274

Schöpa, A., Floess, D., de Saint Blanquat, M., Annen, C., Launeau, P., 2015. The relation between magnetite and silicate fabric in granitoids of the Adamello Batholith. Tectonophysics, 642: 1-15. https://doi.org/10.1016/j.tecto.2014.11.022

Silva, P.F., Marques, F.O., Henry, B., Madureira, P., Hirt, A.M., Font, E., Lourenço, N., 2010. Thick dyke emplacement and internal flow: A structural and magnetic fabric study of the deep-seated dolerite dyke of Foum Zguid (southern Morocco). Journal of Geophysical Research: Solid Earth, 115(B12). https://doi.org/10.1029/2010JB007638

Soto, R., Casas-Sainz, A.M., Villalaín, J.J., Oliva-Urcia, B., 2007. Mesozoic extension in the Basque-Cantabrian basin (N Spain). Contributions from AMS and brittle mesostructures. Tectonophysics, 445: 373-394. https://doi.org/10.1016/j.tecto.2007.09.007

Soto, R., Casas-Sainz, A.M., Villalaín, J.J., Gil-Imaz, A., Fernández-González, G., Del Río, P., Calvo, M., Mochales, T., 2008. Characterizing the Mesozoic extension direction in the northern Iberian plate margin by anisotropy of magnetic susceptibility (AMS). Journal of the Geological Society, 165: 1007-1018. https://doi.org/10.1144/0016-76492007-163

Soto, R., Larrasoaña, J.C., Arlegui, L.E., Beamud, E., Oliva-Urcia, B., Simón, J.L., 2009. Reliability of magnetic fabric of weakly deformed mudrocks as a palaeostress indicator in compressive settings. Journal of Structural Geology, 31(5): 512-522. https://doi.org/10.1016/j.jsg.2009.03.006

Soto, R., Kullberg, J.C., Oliva-Urcia, B., Casas-Sainz, A.M., Villalaín, J.J., 2012. Switch of Mesozoic extensional tectonic style in the Lusitanian basin (Portugal): Insights from magnetic fabrics. Tectonophysics, 536-537: 122-135. https://doi.org/10.1016/j.tecto.2012.03.010

Soto, R., Beamud, E., Oliva-Urcia, B., Roca, E., Rubinat, M., Villalaín, J.J., 2014. Applicability of magnetic fabrics in rocks associated with the emplacement of salt structures (the Bicorb-Quesa and Navarrés salt walls, Prebetics, SE Spain). Tectonophysics, 629: 319-334. https://doi.org/10.1016/j.tecto.2014.07.004

Soto, R., Larrasoaña, J.C., Beamud, E., Garcés, M., 2016. Early-Middle Miocene subtle compressional deformation in the Ebro foreland basin (northern Spain); insights from magnetic fabrics. Comptes Rendus Geoscience, 348(3-4): 213-223. https://doi.org/10.1016/j.crte.2015.10.009

Soto, R., Beamud, E., Roca, E., Carola, E., Almar, Y., 2017. Distinguishing the effect of diapir growth on magnetic fabrics of syn-diapiric overburden rocks: Basque-Cantabrian basin, Northern Spain. Terra Nova, 29(3): 191-201. https://doi.org/10.1111/ter.12262

Soto, R., Casas-Sainz, A., Oliva-Urcia, B., García-Lasanta, C., Izquierdo-Llavall, E., Moussaid, B., Kullberg, J.C., Román-Berdiel, T., Sánchez-Moya, Y., Sopeña, A., Torres López, S., Villalaín, J.J., El-Ouardi, H., Gil-Peña, I., Hirt, A., Scholger, R., 2019. Triassic stretching directions in Iberia and North Africa inferred from magnetic fabrics. Terra Nova, 31: 465-478. https://doi.org/10.1111/ter.12416

Staudigel, H., Gee, J., Tauxe, L., Varga, R.J., 1992. Shallow intrusive directions of sheeted dikes in the Troodos ophiolite: anisotropy of magnetic susceptibility and structural data. Geology, 20: 841-844. https://doi.org/10.1130/0091-7613(1992)020<0841:SIDOSD>2.3.CO;2

Tarling, D.H., Hrouda, F., 1993. The magnetic anisotropy of rocks. Chapman and Hall, 212 p.

Uyeda, S., Fuller, M.D., Belshe, J. C., Girdler, R.W., 1963. Anisotropy of magnetic susceptibility of rocks and minerals. Journal of Geophysical Research, 68(1): 279-291. https://doi.org/10.1029/JZ068i001p00279

Van der Pluijm, B.A., Ho, N.C., Peacor, D., 1994. High-resolution X-ray texture goniometry. Journal of Structural Geology, 16(7): 1029-1032. https://doi.org/10.1016/0191-8141(94)90084-1

Wing-Fatt, L., Stacey, F. D., 1966. Magnetic anisotropy of laboratory materials in which magma flow is simulated. Pure and Applied Geophysics, 64(1): 78-80. https://doi.org/10.1007/BF00875533

Zhu, K.Y., Li, M.Y., Shentu, L.F., Shen, Z.Y., Yu, Y.H., 2017. Evaluation of a small-diameter sampling method in magnetic susceptibility, AMS and X-ray CT studies and its applications to mafic microgranular enclaves (MMEs) in granite. Journal of Volcanology and Geothermal Research, 341: 208-227. https://doi.org/10.1016/j.jvolgeores.2017.06.002

MANUSCRITO RECIBIDO EL: 10-12-2021
RECIBIDA LA REVISIÓN EL: 25-04-2022
ACEPTADO EL MANUSCRITO REVISADO EL: 19-05-2022