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Correlating magnetic fabrics with finite strain: Comparing results from mudrocks in the Variscan and Appalachian Orogens

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ABSTRACT

New magnetic anisotropy data from Variscan mudstones collected in the Cantabrian Arc, N Spain constrain the corresponding strain (shortening). The results are based on our previous study of mudrocks from the Valley and Ridge Province (Appalachians) where independent strain quantification of pencil structures permitted a correlation between magnetic fabric and tectonic strain. An exponential relationship between the AMS shape parameter T and tectonic shortening was found for the interval of 10-25% shortening: shortening (%)=17*exp(T), relationship that appears to be supported by tectonic strains up to 40%. The T parameter describes the shape of the magnetic susceptibility ellipsoid, which in pelitic rocks appears more sensitive to strain than the degree of anisotropy parameter P (or P'). In mudrocks from the Cantabrian Arc a positive correlation between T parameter and deformation intensity, reflected by cleavage domains spacing, is observed. Using the above relationship, we estimate the range of tectonic shortening for the Cantabrian mudstones. The correlation between strain and AMS offers a robust estimate of strain magnitude of 10-40% in weakly to moderately deformed clay-rich rocks, where other strain indicators are often lacking or are poorly preserved..

KEYWORDS **Anisotropy of Magnetic Susceptibility. Finite strain. Cantabrian Arc. Valley and Ridge Province.**

INTRODUCTION

Understanding strain in rocks is a critical requirement for the determination and characterization of processes that are responsible for the formation of geological structures. Strain describes the distortional component of deformation, which is commonly due to grain reorientation in the uppermost crust. Measuring the preferred orientation of grains in rocks, therefore, provides a means of quantifying the finite strain ellipsoid. X-ray, electron microbeam or neutron diffraction methods have been used to determine the preferred orientation fabric of small volumes of rock (e.g., Ho et al., 1999). In addition, the Anisotropy of Magnetic Susceptibility (AMS) is capable of measuring grain preferred orientation of relatively large volumes of rock (~11 cc). AMS has been used since Ising (1942) as a reliable, rapid and sensitive method to characterize fabric in rocks. Whereas qualitative relationships between AMS and strain are well established (see discussion below), quantitative correlations are poorly understood (Singh et al., 1975; Coward and Whalley, 1979; Goldstein, 1980; Kligfield et al., 1981; Hrouda, 1982; Rathore et al., 1983; Siddans et al., 1984; Kissel et al., 1986; Borradaile, 1987, 1988, 1991; Cogne and Perroud, 1988; Aubourg et al., 1991; Housen and van der Pluijm, 1991; Hirt et al., 1993; Tarling and Hrouda, 1993;

Sagnotti and Speranza, 1993; Parés and Dinarès-Turell, 1993; Sagnotti et al., 1994; Averbuch et al., 1995; Housen et al., 1995; Aranguren et al., 1996; Saint Blanquat and Tikoff, 1997; Borradaile and Henry, 1997; Lüneburg et al., 1999; Parés et al., 1999; Parés and van der Pluijm, 2002). In a previous paper we studied AMS pattern in sediments with known finite strain to formulate a quantitative approach to determine strain from magnetic fabrics in rocks (Parés and van der Pluijm, 2003), resulting in a new correlation of fabric shape (as opposed to fabric intensity) with strain. In this paper we investigate the magnetic ellipsoid from mudrocks collected in the Cantabrian Arc, N Spain (Fig. 1) and compare the AMS properties with the already reported results from similar mudrocks in the Knobs Formation, Appalachians.

AMS-STRAIN CORRELATIONS

The Low Field Magnetic Susceptibility of a rock (the ratio of magnetization to the applied field, or K = M/H) is given by the total contribution of its bulk mineralogy, including paramagnetic (e.g., phyllosilicates, iron-bearing feldspars), diamagnetic (e.g., quartz, calcite) and ferromagnetic *sensu lato* (e.g., magnetite, goethite, hematite) grains. An intrinsic property of most rock-forming minerals is that magnetic susceptibility is anisotropic (Nye, 1957); i.e., $K_{ij} = M_i / H_j$. (where M- magnetization, H- applied field). The Anisotropy of Magnetic Susceptibility (AMS) in rocks depends mostly on crystallographic preferred orientation, shape fabric of grains, composition, and to lesser extent on distribution and size of microfractures. AMS defines a symmetric, second-rank tensor that has six independent matrix elements. These elements trace an ellipsoid that is called the magnitude ellipsoid (Nye, 1957), whose semi-axes are the three principal susceptibilities (maximum, intermediate and minimum susceptibility axes, or $K_{max} \geq K_{int} \geq K_{min}$).

From a qualitative point of view, AMS has been used to characterize finite strain in a variety of tectonic settings, in low to very high strain rocks, as well as mostly undeformed rocks (Goldstein, 1980, Kligfield et al., 1981; Rathore, 1980; Rathore et al., 1983; Siddans et al., 1984; Cogne and Perroud, 1988; Aubourg et al., 1991; Housen and van der Pluijm, 1991; Hirt et al., 1993; Sagnotti and Speranza, 1993; Averbuch et al., 1995; Housen et al., 1995; Aranguren et al., 1996; Borradaile and Henry, 1997; Saint Blanquat and Tikoff, 1997; Lüneburg et al., 1999; Parés and van der Pluijm, 2002). In most deformation environments, the AMS axes show a good correlation with the orientation of the principal strain directions (see

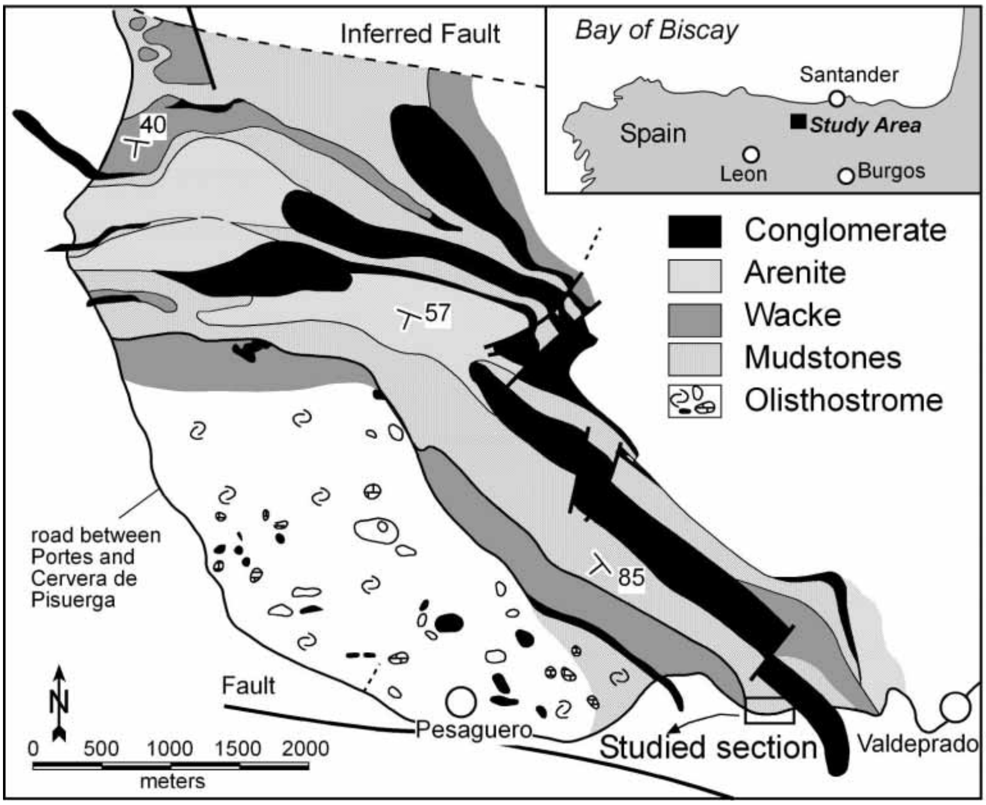

FIGURE 1 **Simplified geologic map with location of the study area. Modified from Rupke (1977).**

reviews by Hrouda, 1982; Borradaile, 1987; 1988; 1991; Tarling and Hrouda, 1993 and Borradaile and Henry, 1997). When a tectonic foliation is present, the principal magnetic susceptibility directions parallel the flattening plane of the finite-strain ellipsoid, with the minimum susceptibility perpendicular to foliation whereas the maximum susceptibility or magnetic lineation typically parallels either the tectonic extension direction or the intersection of bedding and cleavage (Singh et al., 1975; Kligfield et al. 1981; Coward and Whalley, 1979; Hrouda, 1982; Borradaile, 1987; Borradaile and Henry, 1997; Parés et al., 2001; Parés and van der Pluijm, 2002). A unique advantage of AMS over other techniques is that the magnetic ellipsoid orientation also reflects strain in very weakly deformed rocks, where penetrative fabrics are often absent in hand specimen or outcrop (Kissel et al., 1986; Sagnotti and Speranza, 1993; Parés and Dinarès-Turell, 1993; Sagnotti et al., 1994 and Parés et al., 1999).

There has been considerable debate about the quantitative relationship between AMS and strain, as the magnitudes of magnetic fabrics and strain are more complexly related. Among the studies focusing on AMS-strain correlation, there are two main approaches. One is numerical modeling that simulates magnetic fabric development (Owens, 1974; Richter, 1992; Benn, 1994), and second are empirical correlations between strain markers and the susceptibility ellipsoid (e.g., Borradaile, 1991). Despite the abundant literature, no unifying quantitative model has been put forward. Difficulties in correlation models between AMS and strain arise from: a) an incomplete understanding of the relationship between the sources of susceptibility and the AMS ellipsoid, b) recrystallization of AMS-carriers and c) an improper use of the magnetic parameters. In that sense, our previous work indicates that the shape parameter (T= [lnF-lnL]/[lnL+lnF]; where L, lineation is K_{max}/K_{int} and F, foliation is K_{int}/K_{min}) is a more reliable gauge than intensity parameters (e.g., P'), which have been typically considered.

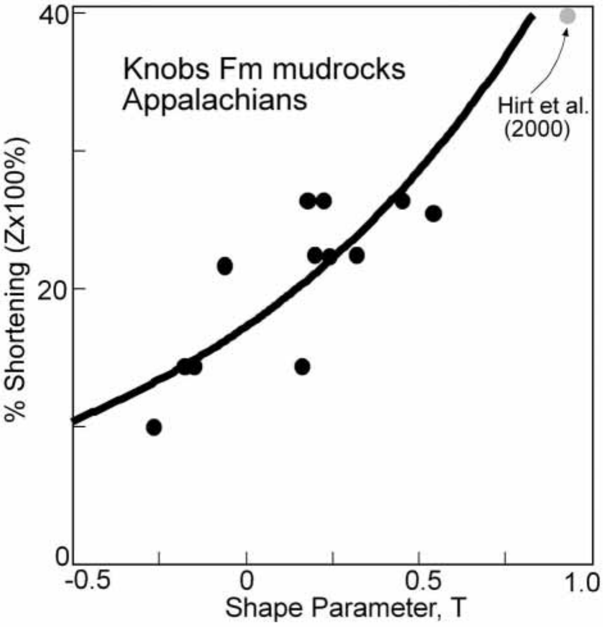

FIGURE 2 **Plot of shape parameter T (T= [lnF-lnL]/[lnL+lnF]; where L, lineation is Kmax/Kint and F, foliation is K_{int}/K_{min}) versus % shortening in pencil structures from Knobs Formation (Parés and van der Pluijm, 2003).**

A sequence of mudrocks form the Knobs Formation (Appalachians) that develop pencil structures of variable intensity allowed us to determine the magnetic fabrics (AMS) and compare it with shortening values (Parés and van der Pluijm, 2003). In their originial study, Reks and Gray (1982) showed a correlation between pencil factor and shortening in the Knobs Fm., as deduced from pressure-fingers. We determined a quantitative relationship between shortening and AMS. A correlation was found between the T parameter and strain [shortening (%) = 17*exp(T)] for a window of ~10 to 25% shortening (Fig. 2). Whereas this AMS-Strain relationship for mudrocks can not be a priori extrapolated to other rock types, because a variety of factors can modulate the qualitative

TABLE 1 **Summary of the Anisotropy of Magnetic Susceptibility results.**

Site	Eigenvector 1				Eigenvector 2				Eigenvector 3			
	τ	σ	Dec	Inc	τ	σ	Dec	Inc	τ	σ	Dec	Inc
S971	0.34372	0.00094	296.4	19.1	0.34302	0.00125	49.1	48.0	0.31325	0.00183	192.0	35.6
S973	0.34369	0.00031	320.7	50.5	0.34094	0.00044	53.6	2.4	0.31538	0.00055	145.5	39.4
S976	0.34548	0.00088	148.2	61.6	0.33065	0.00058	51.8	3.5	0.32387	0.00072	319.9	28.2
S977	0.34087	0.00091	139.0	67.6	0.33275	0.0003	41.8	3.0	0.32638	0.00111	310.6	22.0
S978	0.34175	0.00036	167.7	65.1	0.33480	0.00034	30.8	18.7	0.32346	0.00022	295.3	15.8
S979	0.34157	0.00022	205.8	74.5	0.33428	0.00020	41.6	14.9	0.32415	0.00027	310.5	4.0

Symbols: τ : Eigenvalues; σ : standard deviation; Dec/Inc – Declination / Inclination of the eigenvectors.

magnetic parameter (such as mineralogy and recrystallization), our work shows that magnetic anisotropy can be a proxy of shortening in low strain environments, where grain reorientation is the main deformational mechanism. In this paper we use the obtained AMS-strain gauge in order to determine the strain range in a sequence of variably cleaved mudstones from the Cantabrian Arc.

METHODS

Oriented hand samples were collected in the field at each locality, producing three to six specimens per site. Because of their fissility, hand samples were impregnated in the laboratory with resin before drilling cores or cutting cubes for magnetic analysis. The used resin has a very low diamagnetic susceptibility and could be neglected in our measurements. All AMS measurements were carried out with a Kappabridge KLY-2.03 susceptibility bridge (Geofyzika Brno) at the University of Michigan, using the fifteen directional susceptibilities scheme by Jelinek (1978), on a frequency of 920 Hz (sensitivity of the coil is ~ 5x10-7 SI). AMS data analysis has been performed by linear perturbation analysis (Jelinek, 1978, 1981; Tauxe, 1998) and the confidence ellipses obtained by the method developed by Constable and Tauxe (1990) for statistical bootstrap for anisotropy data. First, the matrix elements and residual errors for each individual sample are calculated using fifteen measurements. Then, the bootstrap statistics for the matrix elements are calculated. Rather than a one-to-one comparison of the magnetic ellipsoid mean axes with structural elements, it is more meaningful to use the orientation distributions (e.g., Borradaile, 2001). Instead of plotting the 95% confidence ellipses to visualize the orientation distributions, which also all require unnecessary parametric assumptions (Tauxe, 1998), we display the bootstrap eigenvectors on a stereonet as a smear of points around the eigenparameters. Confidence regions for the bootstrapped distributions can be drawn as a contour line enclosing 95% of the bootstrapped eigenvectors. Details on the statistical method can be found in Tauxe (1998). The data for individual sites are listed in Table 1, including the values for the major, intermediate and minor eigenvectors.

Representative samples have been analyzed by X-ray diffraction and demonstrate that phyllosilicates are present in these mudrocks, with chlorite and illite as the major components, and some traces of kaolinite. Together, our results suggest that magnetic susceptibility resides dominantly in phyllosilicates and specifically in chlorite and illite. The pattern of AMS axes can hence be interpreted as a preferred orientation fabric of these iron sheet silicates.

GEOLOGIC SETTING

The Cantabrian Arc is the foreland fold-and-thrust belt of northern Iberia's Variscan orogen and constitutes the core of the larger Ibero-Armorican Arc (Fig. 1). There is a general absence of metamorphism and cleavage in the rocks which together with low amount of strain points to a deformation under shallow crustal conditions (Julivert and Arboleya, 1986; Pérez-Estaun et al., 1988). Several major allochthonous units can be distinguished. A dominantly shaly Precambrian sequence is overlain by a Paleozoic sequence that comprises a Cambro-Ordovician, a Siluro-Devonian and a well developed Carboniferous sequence. The Pisuerga-Carrión Unit or Palentine Unit (Julivert, 1971) formed as a relatively autochthonous part of the Asturian Arc in the southwestern sector of the Cantabrian zone. It has been overthrust by three separate units coming from the south, west and north (Esla Unit, Ponga Unit and Picos de Europa Unit,

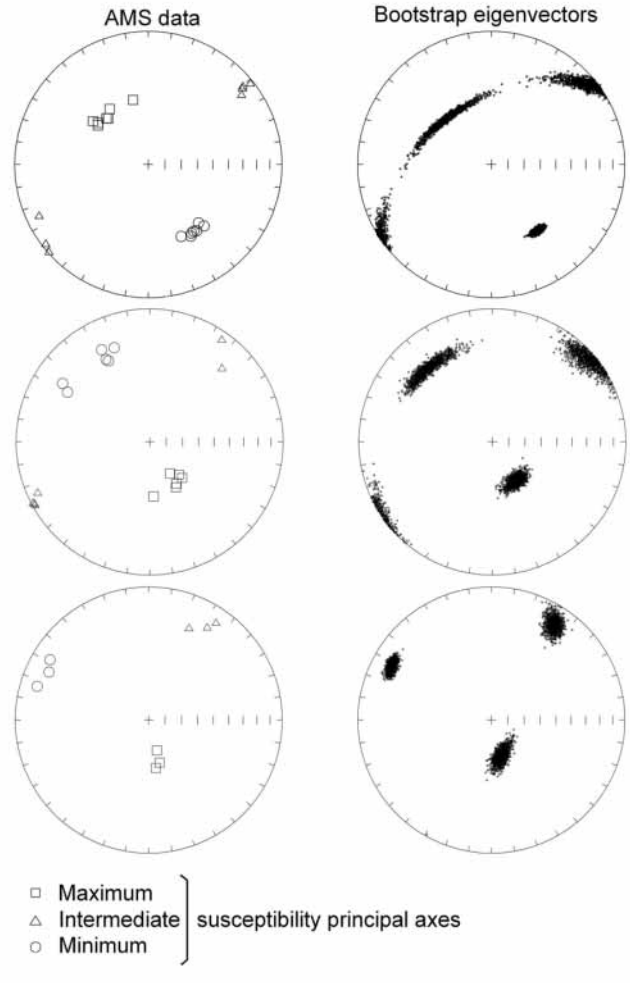

FIGURE 3| **Anisotropy of Magnetic Susceptibility data of three representative sites (see Table 1). For each site, the equal area lower hemisphere projections of the principal (squares), major (triangles) and minor (circles) eigenvectors is shown on the left. To the right are corresponding bootstrapped eigenvectors.**

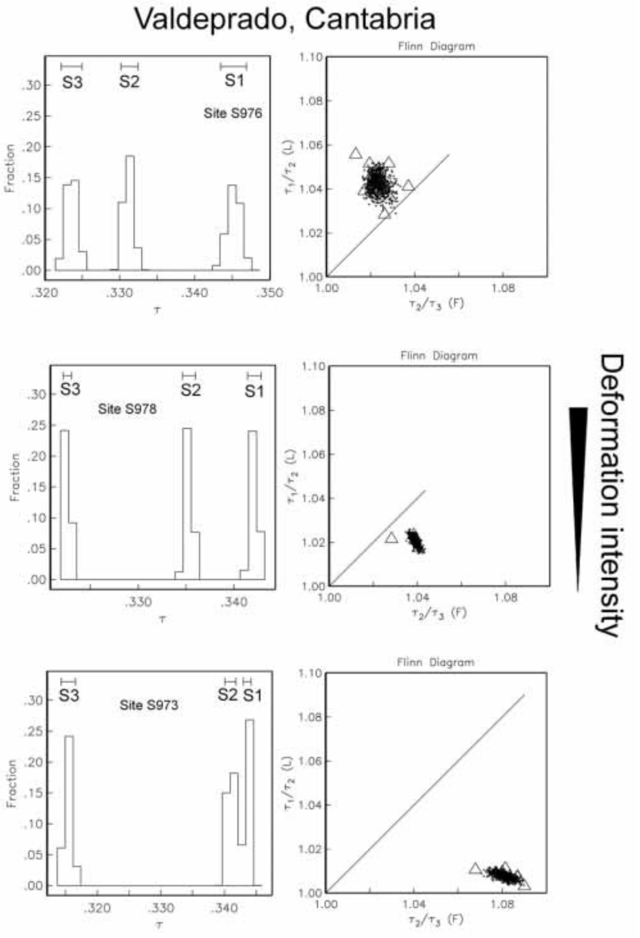

FIGURE 4 **Histograms of the bootstrapped eigenvalues associated with the eigenvectors (Table 1). Each diagram includes Cartesian coordinates S1, S2, and S3 and the associated bounds containing 95% of each eigenvalue. In the corresponding Flinn-type diagrams, data from individual samples are shown as triangles, dots are average values for bootstrapped para-data sets.**

respectively). The section that we has studied is located in the central part of the Pisuerga-Carrión Unit, near the locality of Valdeprado, and has been described in detail by Norris and Rupke (1986). The rocks are Carboniferous in age and comprise a 200 m succession of mudstones that shows a progressive development of slaty cleavage towards its base. Microstructural and mineralogical data through the mudstone are documented in Norris and Rupke (1986). The mudstone sequence unit coarsens appreciably upwards from clay to very coarse siltstone in average grain-size. Cleavage is prominent in the lower half of the section and in the basal 50 m can be designated as slates. In a general way the increase in cleavage intensity coincides with a decrease in average grain size and an increase in the proportion of phyllosilicates. Cleavage domains become more closely spaced and continuous downwards, which can be used as a proxy of deformation intensity, as examined below.

RELATION OF MAGNETIC FABRIC TO STRAIN

The studied mudstones from the Cantabrian Arc do not show pencil structures, as the Knobs Fm does, and only a weak cleavage is present in the lower part of the stratigraphic section. Principal susceptibility axes distribution is consistent with a very weak fabric (Fig. 3). Typically Kmax axes cluster, defining a magnetic lineation that might indicate an extension direction, although there is no independent evidence for a tectonic stretching.

Changes in the magnetic ellipsoid with strain can be documented by the distribution of the principal eigenvalues of the magnetic tensor (Fig 4). We have used histograms of bootstrapped eigenvalues to qualitatively compare magnetic ellipsoids, by inspecting the grouping or dispersion of the corresponding eigenvalues. This is achieved by comparing the confidence intervals or bounds of the eigenvalues. Sites having lower deformation intensity display a distinct ô1 distribution, with ô2 and ô3 close but not overlapping. In contrast, in sites having higher deformation intensity all three eigenvalues are distinct and equally well defined, more typical for a triaxial ellipsoid. It can be seen that there is a gradation from the most prolate to the most oblate magnetic ellipsoid as indicated by the histograms of the principal eigenvectors distribution. Such a distribution of magnetic data resembles the deformation path already noticed by Housen et al. (1993); Sagnotti et al. (1994) and Parés et al. (1999) among others, suggesting that it may be possible to compare the magnitudes of strain with the susceptibility tensor in the studied rocks as discussed below.

The fact that we observe a progressive change of AMS properties with strain allows us to apply the AMS-strain relationship obtained in the Knobs Fm. mudrocks

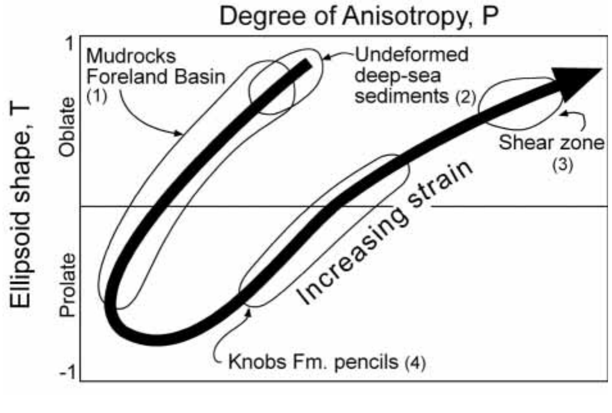

FIGURE 5 **Evolution of magnetic parameters T and P with strain in mudrocks, from compaction to well-developed tectonite. Circled areas show segments that we have already documented: (1) Parés et al. (1999); (2) Joseph et al., 1998; (3) Parés et al., 2001; (4) Parés and van der Pluijm (2003).**

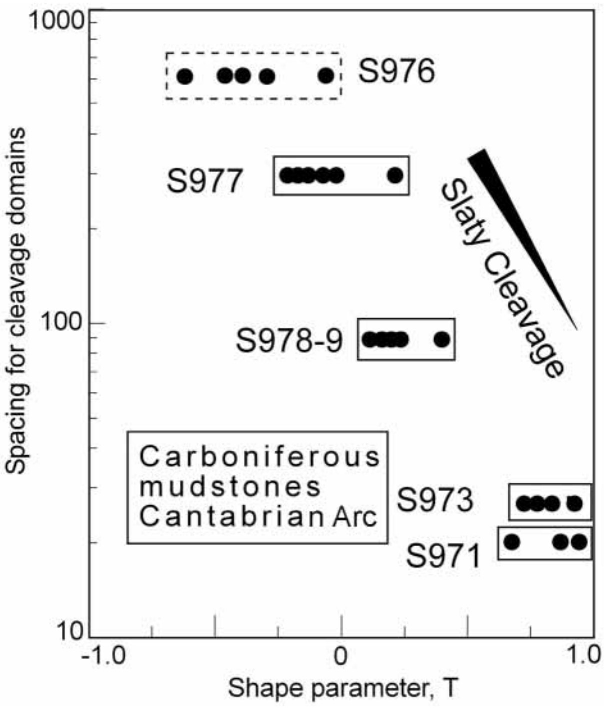

FIGURE 6 | **Changes of the T value as a function of the spacing for cleavage domains (data from Norris and Rupke, 1986).**

to the studied Cantabrian Arc shales. As discussed in the above section, Parés and van der Pluijm (2003) based the AMS-strain function on the symmetry of shape parameter T (Jelinek, 1981) against shortening. The length/width ratio of the Knobs Fm. pencils turns to be a measure of strain, with (Y/Z) = 0.913+0.019(l/w) (Reks and Gray, 1982). We used such a relationship to calibrate magnetic anisotropy with shortening (Parés and van der Pluijm, 2003). In their original paper, Reks and Gray (1982) determine the stretches ($1+e_1$ and $1+e_3$), from which we recalculated the corresponding shortening (% shortening = $[1-e_3] * 100$). Also we included results by Hirt et al. (2000) for slates from the Cantabrian Arc which have higher shortening (~40%) than mudstones from the Knobs Fm. and hence better constrain the AMS-strain correlation in pelitic rocks. It is important to note that the correlation between T and shortening cannot then be simply linear. A typical sedimentary fabric, with K_{max} axes contained within the depositional plane, and K_{min} axes normal to it, has a T that is close to +1. Strongly cleaved sedimentary rocks (e.g., slates), with no traces of the primary foliation, also have T values close to +1. Some previous studies in low-strain mudrocks from the Pyrenean Foreland Basin (Parés et al., 1999) and from Southern Italy (Sagnotti and Speranza, 1993) offer good examples of sequences from undeformed to slightly deformed rocks that document such a trend of T. Hence, the parameter T changes from the oblate to the prolate field (T<1) (for very weak deformation) and then back progressively to the oblate field with higher values in stronger deformed mudstones. The conceptual sequence of evolution of the magnetic fabrics with progressive strain in pelitic rocks in shown in Fig. 5. Overprinting of magnetic fabrics by small strains has also been investigated with numerical simulation. Notably, Benn (1994) developed numerical models to investigate the effects of small superimposed strain on the shape and magnitude of pre-existing AMS fabric in granites. The path of the T parameter suggested by our own observations is remarkably similar to the prediction of the numerical simulation by Benn (1994), in that during progressive strain the shape parameter T increases into the prolate field and beyond a strain of ~20% the parameter returns to the oblate field and approaches +1.

There is no strain marker for mudstones of the studied locality in the Cantabrian Arc. However, spacing between cleavage domains, as determined by Norris and Rupke (1986), can be used as a qualitative gauge of deformation intensity. Their results show is a systematic reduction of cleavage domains spacing downwards in the stratigraphic section, corresponding with the mesoscopic increase in cleavage intensity and appearance of slaty cleavage. We have used the cleavage domains spacing to qualitatively compare our magnetic results with deformation intensity (Fig. 6). We observe a correspondence between cleavage spacing and T. Values of T for the Cantabrian Arc mudstones range from +0.9 (highly oblate) to –0.4 (moderate prolate) and show a positive correspondence with defor-

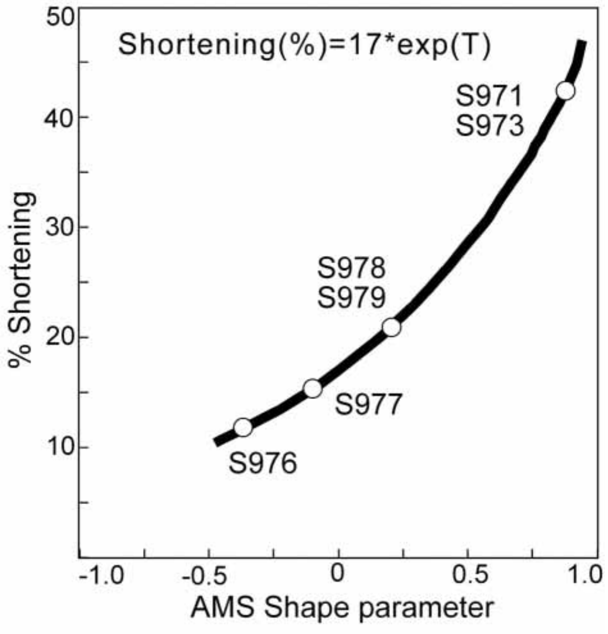

FIGURE 7 | **Value of tectonic shortening obtained for the shales and slates. Curve is given by the relationship [shortening (%) = 17*exp(T)] (from Parés and van der Pluijm, 2003).**

mation intensity as indicated by the spacing between cleavage domains. Samples from slates (stratigraphically downwards) have high positive T values and a close spacing between cleavage domains.

Supported by this correlation between AMS and deformation intensity, we use the relationship found in the Knobs Fm. shales to constrain shortening in the mudstones from the Cantabrian Arc, where no quantitative strain marker is present. Figure 7 shows the function shortening (%) = 17*exp(T) and the corresponding values of shortening for the Cantabrian Arc mudstones. Obtained shortening values range from ~11% in the shales to ~40% in moderately developed slates at the bottom of the stratigraphic sequence. Overall, the lower shortening values have the same range as those found in the Knobs Fm, whereas high values are consistent with results from other slate belts where strain markers permitted deformation intensity determination (e.g., Ramsay and Huber, 1983).

CONCLUSIONS

We have determined the magnetic fabrics (AMS) for mudrocks with weak to moderately well-developed slaty cleavage in mudrocks of the Cantabrian Arc. The magnetic shape parameter T shows a consistent progression with shortening strain as indicated by the spacing for cleavage domains, which suggest the application of the relation ship shortening (%) = 17*exp (T) (Parés and van der Pluijm, 2003) to quantifying the amount of shortening based on magnetic fabrics.

Whereas we exercise some caution until more data are available, our correlation between AMS and strain seems to suggest a rapid and robust approach for clay-rich rocks that otherwise lack strain markers, and where progressive mineral reorientation is the principal mechanism for deformation. However, this AMS-strain relationship for mudrocks cannot be directly applied to other rock types, because a variety of factors affects rock magnetic properties (such as mineralogy and recrystallization).

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