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Magnetic fabrics and strain in pencil structures of the Knobs Formation, Valley and Ridge Province, US Appalachians

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Abstract

Pencil structures, which are found in weakly deformed mudrocks, reflect the bedding–cleavage intersection in weak- to moderately-cleaved rocks. Their presence indicates conditions where bedding and cleavage fabrics are approximately equal in intensity. We have determined the anisotropy of magnetic susceptibility (AMS) in pencil structures from a sequence of mudstones of the Ordovician Knobs Formation in the Valley and Ridge Province of the US Appalachians. Magnetic mineralogy was determined by X-ray analysis and low-temperature susceptibility measurements. Distribution of the magnetic ellipsoid axes is consistent with the incipient tectonic fabric of the pencil mudstones. The maximum susceptibility axes parallel the pencils' long axes, while the minimum axes of susceptibility are normal to the primary sedimentary fabric. Independent strain quantification permits a correlation between magnetic fabric and tectonic strain. An exponential relationship between the AMS shape parameter T and tectonic shortening has been found for the interval of 10–25% shortening: shortening(%) $= 17 * \exp(T)$. This relationship appears to be supported by tectonic strains up to 40%. The T parameter ($T = [\ln F - \ln L]/[\ln L + \ln F]$; where L, lineation is K_{max}/K_{int} and F, foliation is K_{int}/K_{min}) describes the shape of the magnetic susceptibility ellipsoid, which appears more sensitive to strain than past correlation attempts with the magnetic intensity parameter P (or P'). Whereas this correlation between strain and AMS is only valid within a restricted window of strain (10–40% shortening), it establishes the magnitude and directions of tectonic strain in weakly deformed clay-rich rocks, where strain indicators are otherwise lacking or are poorly developed.

Keywords: Pencil structures; Magnetic fabrics; Anisotropy of magnetic susceptibility (AMS); Appalachian Fold-and-Thrust Belt

1. Introduction

The potential of magnetic anisotropy as a strain gage in deformed rocks has been recognized for many years. Increasingly detailed studies that investigate the link between strain and magnetic fabrics reflect both a better understanding of the origin of magnetic anisotropy in rocks and using more versatile and sensitive instrumentation and approaches (such as high-field and low-temperature analysis; McCabe et al., 1985; Jackson, 1991; Richter and van der Pluijm, 1994; Borradaile and Henry, 1997; Parés and van der Pluijm, 2003). Anisotropy of remanence and anisotropy of susceptibility have both been used to characterize strain in rocks; the latter is most suitable for sensing preferred orientation of iron sheet silicates, in addition to ferromagnetic grains. Deformation environments from low to very high strain have been studied, as well as seemingly undeformed rocks (Goldstein, 1980; Kligfield et al., 1981; Rathore et al., 1983; Siddans et al., 1984; Cogné and Perroud, 1988; Aubourg et al., 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 and references therein; Saint-Blanquat and Tikoff, 1997; Lüneburg et al., 1999; Parés and van der Pluijm, 2002). In most strain environments, the AMS axes orientation shows a good correlation with the principal strain directions (see reviews by Hrouda, 1982; Borradaile, 1987, 1988, 1991; Tarling and Hrouda, 1993; Borradaile and Henry, 1997), making magnetic anisotropy a rapid and powerful tool to structural analysis. 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 and the maximum susceptibility typically parallel to the tectonic extension direction or to the intersection of

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bedding and cleavage (Singh et al., 1975; Coward and Whalley, 1979; Kligfield et al., 1981; Hrouda, 1982; Borradaile, 1987; Borradaile and Henry, 1997; Parés and van der Pluijm, 2002). The magnitude of magnetic fabrics is more complexly related to finite strain, but information about this critical linkage improves by studying specific deformation environments. In particular the transition from compaction fabrics to tectonic fabrics shows large changes (e.g. Housen et al., 1993) and has to be understood for reliable applications of magnetic analysis to deformed rocks. This study targets mudrocks in this low-strain realm, which are characterized in the field by the occurrence of pencil structures.

Among more significant realizations has been that AMS tracks the finite-strain ellipsoid orientation in moderate to strongly deformed rocks, but also in very weakly deformed rocks, where penetrative tectonic fabrics are seemingly absent. Yet, the magnetic ellipsoid orientation parallels mesoscale structures, like regional folds axes. For example, Kissel et al. (1986) investigated marine Cenozoic clays in Greece, and observed a magnetic lineation that is characterized by a cluster of the maximum susceptibility directions K_{max} parallel to fold axes. Grouping of K_{max} under progressive deformation has been observed in following studies, and is occasionally accompanied by a girdle containing K_{min} and K_{int} axes, which is thought to be the first evidence for layer parallel shortening in sedimentary rocks, as noted by Sagnotti and Speranza (1993), Parés and Dinarès-Turell (1993), Sagnotti et al. (1994) and Parés et al. (1999) in sequences from low to moderately deformed mudstones.

Pencil structures are representative of a deformation environment where two competing anisotropies, bedding and cleavage, are approximately equal in magnitude. This represents the region of the greatest change in fabric measurements (e.g. Borradaile and Tarling, 1981; Borradaile, 1988; Housen and van der Pluijm, 1990, 1991) and therefore offer a special opportunity to understand the properties of incipient magnetic fabrics and their tectonic strain significance. This study examines the AMS of pencil structures in mudrocks of the Knobs Formation, SW Appalachians, which were previously studied by Reks and Gray (1982), and offers a correlation with strain in this low deformation regime.

2. Pencil structures

Weakly deformed mudrocks can break into long narrow strips that are rhombohedral in cross-sections. The pencil structures, as originally described by Cloos (1957), are enhanced by weathering and typically reflects a bedding–cleavage intersection fabric. Durney and Kisch (1994) recognize two different types of pencil structures, depending on their long axes orientation relative to the strain axes. Pencils can develop parallel to the extension direction of the finite strain ellipsoid, as described by Ramsay (1981) in the Swiss Alps, where they also coincide with the bedding and cleavage intersection (see also Ramsay and Huber, 1983). A second type of pencils are described by Engelder and Geiser (1979), Reks and Gray (1982) and Nickelsen (1986), as elongated rock fragments defined by intersecting fracture sets subparallel to pre-existing bedding fissility and cleavage, and to the inferred *Y*-axis of the strain ellipsoid. In all cases the pencil structure is related to weak strain and, in a sequence of fabric development in mudrocks, pencil structures represent the 'early deformation stage' that predates the 'embryonic cleavage stage' of Ramsay and Huber (1983). A corollary is that pencil structure represents a stage where mineral reorientation or new mineral growth is sufficient to produce a second mechanical anisotropy to the rock, yet maintaining a primary fabric, so that the rock will tend to break into elongate fragments.

3. Geologic setting

The western portion of the Appalachian orogen in the Valley and Ridge Province constitutes the southern Appalachian foreland fold-and-thrust belt (Wood and Bergin, 1970; Kulander and Dean, 1986; Hatcher et al., 1989). The Pulaski thrust sheet of southwestern Virginia is one of the major thrusts in the area and comprises northeast-trending folds and faults (Fig. 1). To the southeast it is bounded by the Blue Ridge Province. Folds are symmetric to slightly overturned and have strike lengths of 6–30 km and half wavelengths of 1–3 km (Reks, 1981). Exposed formations in the study area include the Early Cambrian to Middle Ordovician Knobs Formation that is made up of weakly deformed mudstones and siltstones. Most of the sampled outcrops exhibit well developed pencil-like fragments, characterized by two sets of parallel surfaces that intersect at high angles, corresponding to bedding and cleavage (Reks and Gray, 1982) (Fig. 2). A subhorizontal set is parallel to bedding, and a second, steeply-dipping set, which is less well visible, is parallel to regional cleavage. Pencil structures vary in shape, producing a spectrum of pencil types ranging in length from 20 to 140 mm (Reks, 1981). Reks and Gray (1982) showed that with increasing strain, as determined from pressure fringes, fabric changes in the mudrock produce higher length/width ratios, meaning that pencil geometry is strain dependent. Pencil shape is specified by the length (l) and width (w) ratios of fragments measured in the bedding plane. On the basis of this scheme, the intensity of pencil structure has been subdivided as weak ($l/w < 13$), moderate ($13 < l/w < 19$) and strong ($l/w > 19$) (Reks and Gray, 1982).

4. Methods

We sampled mudrocks of the Knobs formation at 20 different localities, of which 18 gave consistent results (Table 1), matching as many sites as possible to the same

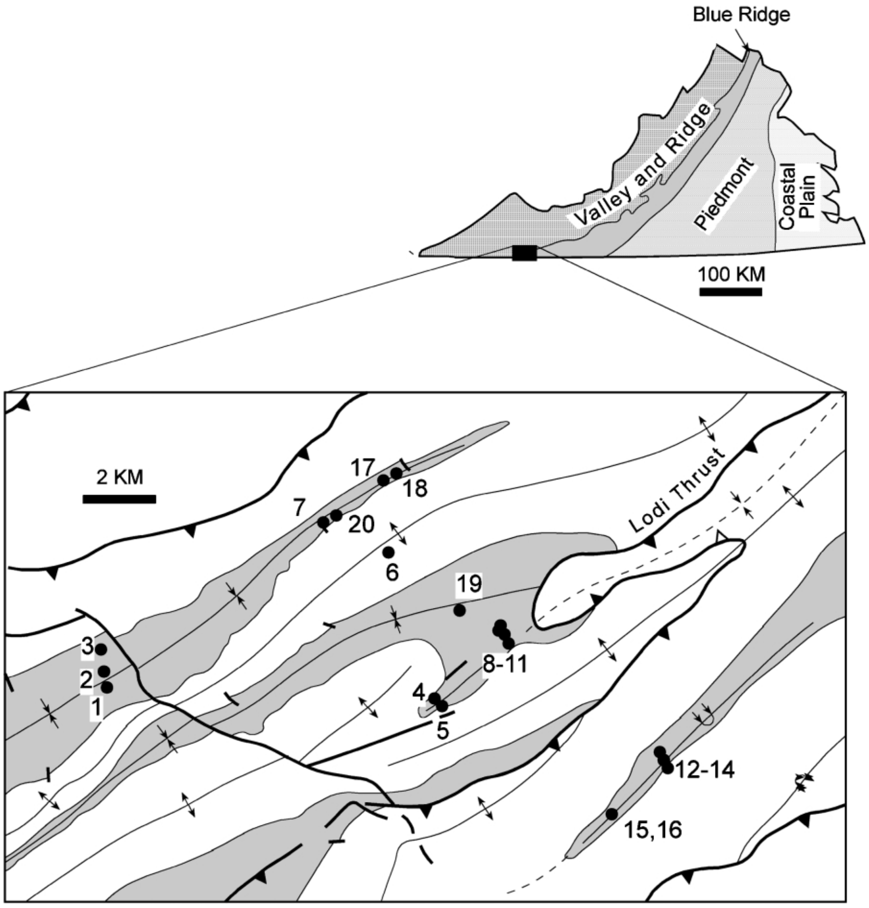


Fig. 1. Geological setting (modified from Reks and Gray, 1982) showing sampling localities for this study.

Table 1
Summary of the anisotropy of magnetic susceptibility results. Symbols: τ—eigenvalues, σ—standard deviation, Dec/Inc—declination/inclination

Site	Eigenvector 1				Eigenvector 2				Eigenvector 3			
	τ	σ	Dec	Inc	τ	σ	Dec	Inc	τ	σ	Dec	Inc
VA1	0.34405	0.00092	250.9	15.4	0.34022	0.00086	351.9	34.6	0.31573	0.0017	140.9	51.1
VA2	0.34404	0.00039	85	5.1	0.33552	0.00037	178.7	36.3	0.32043	0.00052	348.1	53.2
VA3	0.34127	0.00047	249	4	0.33731	0.00037	157.3	23.1	0.32141	0.0003	348.2	66.5
VA4	0.34263	0.00081	65.4	6	0.33046	0.00043	163.5	53.1	0.32691	0.00099	331	36.2
VA5	0.34603	0.00022	240.1	7.8	0.33193	0.00041	64	82.1	0.32204	0.00041	330.1	0.5
VA7	0.34548	0.00023	71.9	13.1	0.34049	0.00017	174.2	42.6	0.31403	0.00039	328.7	44.5
VA8	0.34402	0.00079	58	1.4	0.33948	0.00057	149.1	37.7	0.3165	0.00059	326.2	52.3
VA9	0.34562	0.00082	61.1	14.3	0.33498	0.00071	163.8	40.7	0.3194	0.00136	315.9	45.8
VA10	0.34595	0.00105	57.8	13.1	0.33519	0.00091	294.6	67	0.31887	0.00196	152.2	18.6
VA11	0.34653	0.00087	57.8	18.7	0.33189	0.0011	317.5	27.9	0.32158	0.00194	177.3	55.4
VA12	0.34418	0.00037	57.4	10	0.3323	0.00021	174.1	68.5	0.32352	0.00041	324	18.8
VA13	0.34752	0.00024	61.2	6.3	0.33523	0.00043	155.3	33.1	0.31725	0.00065	321.7	56.2
VA14	0.34419	0.00062	244.5	6.4	0.33283	0.00105	359.7	75.3	0.32298	0.00164	153	13.2
VA15	0.34809	0.00062	54.3	2.9	0.33543	0.00041	150.5	64.7	0.31648	0.00103	322.9	25.2
VA16	0.34503	0.00065	66.2	5	0.33658	0.00084	159.1	30.7	0.31839	0.00149	327.9	58.8
VA17	0.34388	0.00066	255.4	25.3	0.33873	0.00031	22	51.6	0.31739	0.00093	151.6	26.8
VA18	0.34087	0.00138	59.5	18.2	0.33491	0.00057	283.8	65.4	0.32422	0.00101	154.9	16.1
VA20	0.34795	0.00043	235.5	8.4	0.33874	0.00037	330.7	31.7	0.31332	0.00068	132.4	57

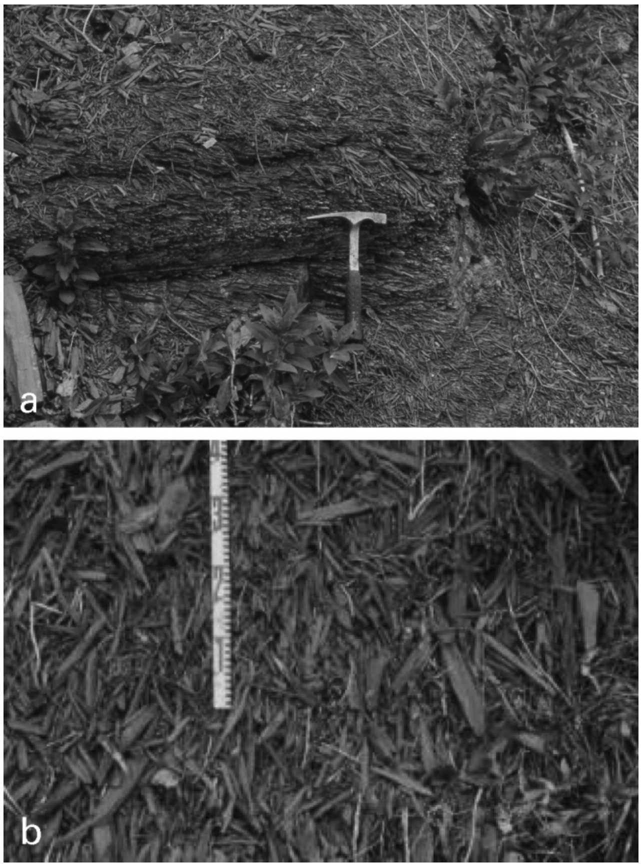


Fig. 2. Outcrop morphology of pencils in the Knobs Formation, SW Virginia. (a) Photograph approximately perpendicular to bedding showing two sets of intersecting surfaces. (b) Outcrop showing pencil development of moderate intensity.

localities studied by Reks and Gray (1982). Oriented hand samples were collected in the field at each locality, producing 5–12 specimens per site. Because of their fissility, hand samples were impregnated in the laboratory with resin before drilling cores for magnetic analysis.

All AMS measurements were carried out with a Kappabridge KLY-2.03 susceptibility bridge (Geofyzika Brno), using the 15 directional susceptibilities scheme by Jelinek (1978), on a frequency of 920 Hz (sensitivity of the coil is $\sim 5 \times 10^{-7}$ SI). AMS data analysis is performed by linear perturbation analysis (LPA, Tauxe, 1998), following the method initially developed by Constable and Tauxe (1990) for statistical bootstrapping of anisotropy data in order to obtain the confidence ellipses. First, the matrix elements and residual errors for each individual sample are calculated using 15 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 (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 principal, major and minor eigenvectors.

Critical for AMS analysis is determination of the magnetic carrier that is responsible for magnetic susceptibility, and specifically to determine whether the AMS tensor is due to paramagnetic phases (mostly phyllosilicates in mudrocks) or to ferromagnetic minerals (mostly magnetite). To determine the dominant phase for magnetic susceptibility, we apply a modified approach outlined by Richter and van der Pluijm (1994), which allows the distinguishing of the ferromagnetic and paramagnetic susceptibility contributions. A representative result is shown in Fig. 3a. The steady increase in magnetic susceptibility from low (77 K) to room temperature is indicative of paramagnetic dominance of the bulk susceptibility. A set of samples has also been

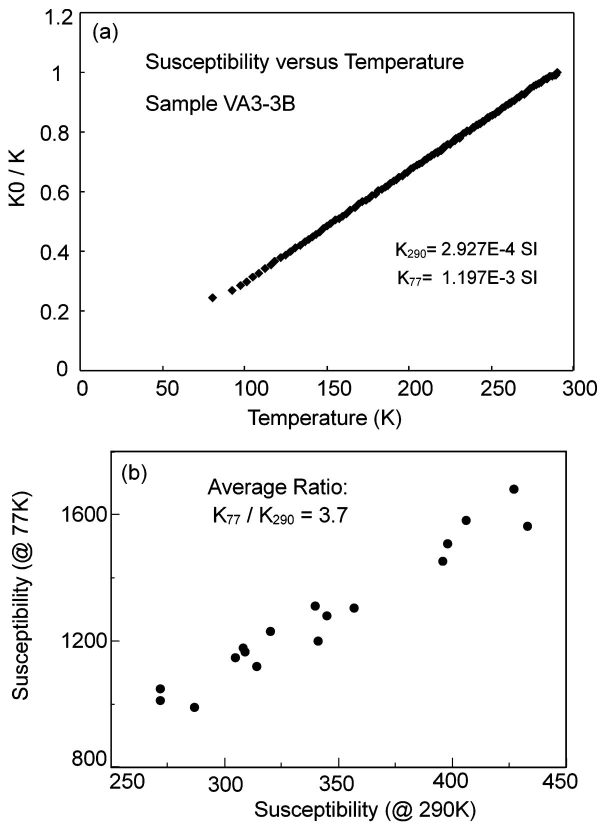


Fig. 3. (a) Temperature dependence of low-field susceptibility for a representative sample of Knobs Formation, based on the procedure of Richter and van der Pluijm (1994). K_0/K is the normalized reciprocal magnetic susceptibility (reading temperature during warming up versus ambient temperature, 290 K). The increase of the reciprocal susceptibility between 90 and 290 K indicates that samples are dominated by paramagnetic minerals. (b) Comparison of magnetic susceptibility measured at 77 and 290 K temperature. The K_{77}/K_{290} ratio is 3.7, which indicates that phyllosilicates dominate the magnetic susceptibility tensor.

measured at both 290 and 77 K to determine the ratio of bulk susceptibility at room temperature and at liquid nitrogen temperature (K_{290}/K_{77}). This ratio should theoretically be around 3.7, as seen in these samples (Fig. 2b).

Representative samples have been analyzed with 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. Combined, low-temperature susceptibility analysis (Fig. 3) and XRD 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 of these iron sheet silicates.

5. Relation of magnetic fabrics to pencil structures

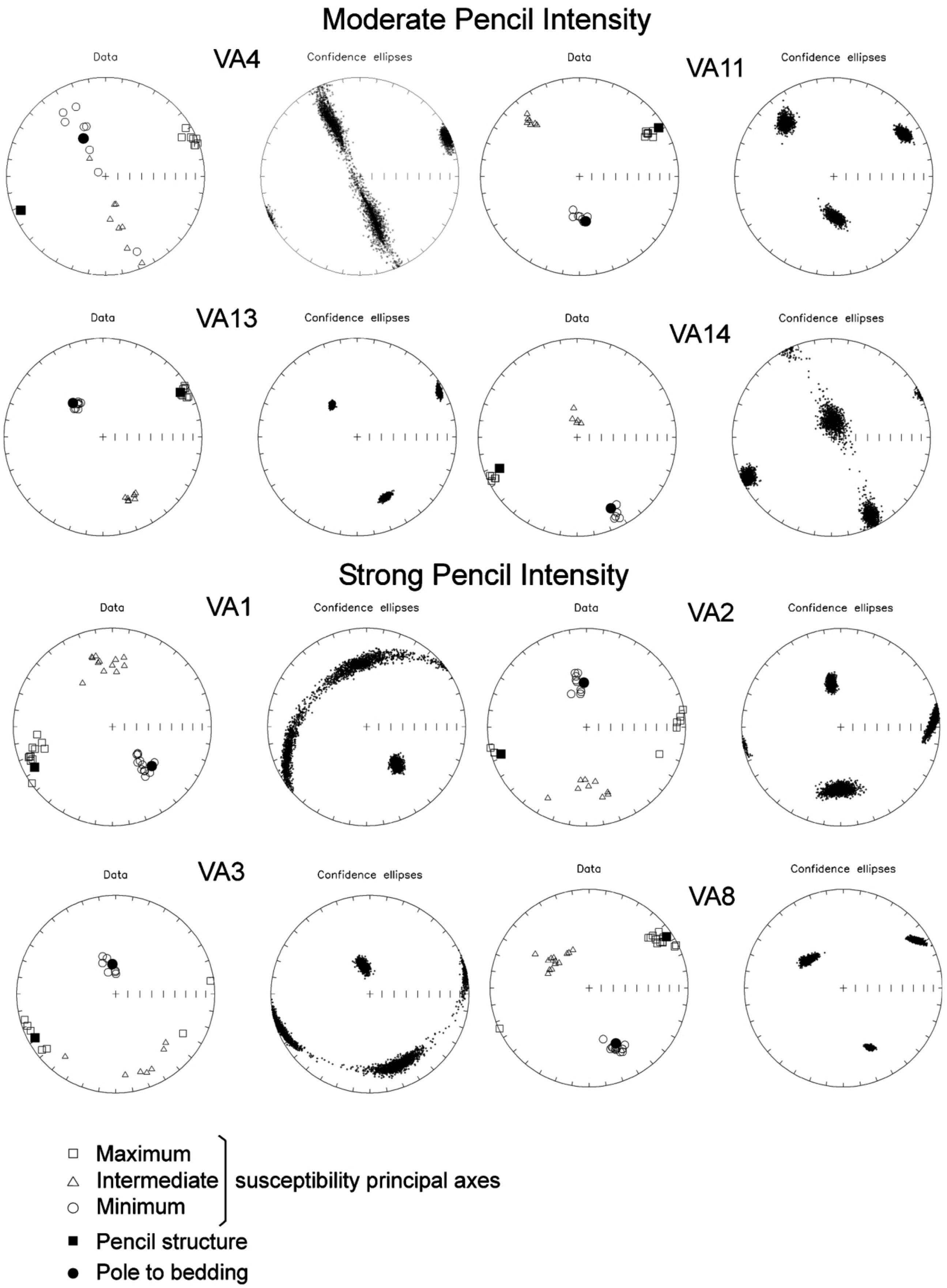
Fig. 4 summarizes the orientation data of some representative sites of the Knobs Fm. in the study area. The maximum axis of the magnetic ellipsoid is parallel to the orientation of the pencil structures' long axes in the mudrocks. Specifically, pencil structures in all studied sites determine the orientation of the maximum susceptibility axes by a K_{max} cluster (magnetic lineation) whose mean direction coincides with the orientation of the long axes of the pencil fragments. Magnetic lineations and pencil structures both trend NE–SW and are horizontal to very shallowly plunging. An additional feature of the axes distribution is the relation of bedding to the magnetic fabric. In all studied cases, the minimum axes of susceptibility, K_{min}, coincide with the pole to local bedding. The magnetic ellipsoid orientation hence reflects a composite fabric where traces of bedding are present (K_{min} perpendicular to bedding), but a tectonic imprint is also evident (K_{max} parallel to pencil long axis). Distribution of K_{min} axes perpendicular to bedding in slightly deformed rocks has previously been observed in other weakly deformed mudstones (e.g. Kissel et al., 1986; Sagnotti and Speranza, 1993; Sagnotti et al., 1994; Parés et al., 1999). All these studies highlight that the first evidence for layer parallel shortening in mudrocks is recognized in the grouping of K_{max} axes perpendicular to the tectonic shortening direction while maintaining K_{min} axes perpendicular to bedding (see Fig. 4). Further, models by Housen et al. (1993) illustrate that when two planar mineral fabrics contribute to the mean AMS tensor, the intersection of these two sub-fabrics will control the orientation of the K_{max} direction in agreement with naturally deformed rocks (e.g. Borradaile and Tarling, 1981).

Pencil intensity in the Knobs Fm. was established on the basis of the pencil shape factor, l/w, where l and w are the length and width of the pencil fragment, respectively (Reks and Gray, 1982). For convenience, we follow the same classification scheme as those authors, who distinguish weak ($l/w < 13$), moderate ($13 < l/w < 19$) and strong ($l/w > 19$) pencil intensity in the Knobs Fm. mudrocks. We have plotted the magnetic parameter results (lineation $L = K_{max}/K_{int}$ and, foliation $F = K_{int}/K_{min}$) on a Flinn type diagram (Fig. 5) and grouped them following the associated pencil intensity. The distribution of magnetic lineation and foliation shows an excellent correlation with pencil intensity. Generally, high values of magnetic foliation fall in the region of strong pencil intensity, whereas sites with low magnetic foliation and rather constant lineation lie in the moderate pencil intensity domain. Moderate pencil structures are generally confined to the constrictional field of the Flinn diagram ($k \geqq 1$). Also, we note that on average, magnetic lineation in the strong pencil intensity domain is slightly lower than in the moderate domain, reflecting a stronger magnetic foliation in the latter ($k < 1$). Pencil development seems therefore more efficient in changing the oblateness rather than prolateness of the magnetic ellipsoid. Two sites were collected in a region without pencils, which show low values in magnetic lineation and a moderate magnetic foliation, similar to samples from other environments with little or no tectonic strain fabrics.

A more complete documentation of changes in the magnetic ellipsoids is given by the distribution of the principal eigenvectors of the magnetic tensor (Fig. 6). Histograms of bootstrapped eigenvalues provide an approach 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 a moderate pencil intensity display a relatively distinct τ_1 distribution, with τ_2 and τ_3 close but not overlapping. Note that in this situation, the corresponding K_{max} directions are well defined on a stereographic projection, but K_{int} and K_{min} directions are variably distributed in a girdle (Fig. 4). In contrast, sites in the strong pencil domain have all three eigenvalues 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 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 and susceptibility tensor in the studied rocks as discussed below.

6. Discussion

The potential of magnetic anisotropy as a strain gage has received a lot of attention, and several quantitative relationship have been reported from studies on slates (e.g. Wood et al., 1976; Rathore, 1979, 1980; Lüneburg et al., 1999) and in oolitic limestones (e.g. Kligfield et al., 1982). Yet, it is evident from the extensive literature that there is a gap in the transition field from compaction to tectonic fabric, which is examined by our results from the


Moderate Pencil Intensity
Data
VA4
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VA11
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VA13
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Strong Pencil Intensity
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VA1
Confidence ellipses
Data
VA2
Confidence ellipses
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VA3
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VA8
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Maximum
Intermediate
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susceptibility principal axes
Pencil structure
Pole to bedding

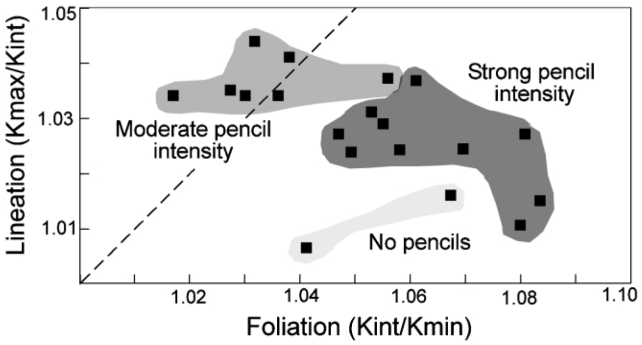

Fig. 5. Flinn-type diagram (foliation versus lineation) showing the shape of the AMS ellipsoids of the individual sites in the mudrocks from the Knobs Formation. The ellipsoid shape changes from prolate (above the neutral line) for moderate pencil development, to oblate (below the neutral line) for strong pencil development.

Knobs Fm. pencils. In their previous study, Reks and Gray (1982) made strain determinations using pressure-fringes adjacent to pyrite concretions. The association of pressure-fringes with pencil development provided an opportunity to derive a relationship between pencil shape and bulk strain. The length/width ratio turns to be a measure of strain, with $(Y/Z) = 0.913 + 0.019(l/w)$ (Reks and Gray, 1982). This relation for the mudstones of the Knobs Fm. allows us to estimate the shortening for sites whose magnetic anisotropy have been determined in this study. The approach chosen is to plot the symmetry of shape parameter T for anisotropy of magnetic susceptibility ($T = [\ln F - \ln L]/[\ln L + \ln F]$; Jelinek, 1981, where L and F is lineation and foliation, respectively) against shortening as determined from pressure fringes by Reks and Gray (1982) (Fig. 7a). In their original paper, these authors determine the stretches ($1 + e_1$ and $1 + e_3$), from which we recalculated the corresponding shortening (%shortening $= [1 - e_3] * 100$). In Fig. 7a we plot data only from sites for which both strain and magnetic results are available. Also for comparison, we included a recent result 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. As opposed to previous attempts of correlating AMS with strain, here we use the magnetic shape parameter T, which by definition has values of $-1 < T \leq 1$. The correlation between T and shortening cannot then be just linear: a typical sedimentary fabric, with K_{max} distributed within the depositional plane, and K_{min} 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 $+1$. Previous studies in low-strain mudrocks in the Pyrenean Foreland Basin (Parés et al., 1999) and in Southern Italy (Sagnotti and Speranza, 1993) offer good examples of sequences from undeformed to slightly deformed rocks that document a trend of T from the prolate field ($T < 1$) (for very weak deformation) to progressively higher and positive T values in more deformed mudstones. Overprinting of magnetic fabrics by small strains has also been investigated in granites (e.g. Bouchez et al., 1990; Benn et al., 1998), as well as with numerical simulations of fabric imprinting by strain in sedimentary rocks (e.g. Hrouda, 1991). 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 in our natural study 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 $+1$.

We favor an exponential correlation to fit the relationship between the observed T and strain values, as shown in Fig. 7a. Hence, for strain values higher than ~25%, the T values trend progressively towards unity. The result by Hirt et al. (2000) in the region of ~40% shortening supports the exponential correlation used. Borradaile (1991) suggested that until ~20% shortening the initial (sedimentary) magnetic fabric of a rock may not have been completely overprinted, whereas above 75% shortening one expects saturation of the magnetic fabric. There are, however, no conclusive data that offer a lower bound of shortening that produces magnetic fabric in deformed rocks. Reks and Gray's (1982) study of the Knobs Fm. concludes that pencil structure development requires that two fabric anisotropies, bedding and cleavage, are approximately equal in magnitude (see also Durney and Kisch, 1994). This balance, where neither of the two fabrics dominate, occurs in a relatively narrow strain range. Strain state of pencils from syntectonic crystal-fibers in pressure fringes adjacent to pyrite concretions (Durney and Ramsay, 1973) show that incipient cleavage development in these mudrocks occurs with strain after 9% shortening (Reks and Gray, 1982). Particulate flow, mostly by intergranular slip and kinking is considered to be the dominant mechanism for reorienting phyllosilicate grains in the earliest stages of deformation (Borradaile, 1981; Oertel, 1983; Hounslow, 1990; Bhatia and Soliman, 1991; Owens, 1993; van der Pluijm et al., 1998). Deformation experiments on sediments indeed support a dominant role of grain rotation in low-strain environments (as low as 12% shortening), especially when water is present (e.g. Carson and Berglund, 1986). At higher strains, greater than 25% shortening, cleavage is well developed in the

Fig. 4. Anisotropy of magnetic susceptibility data of Knobs Formation mudrocks (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 and major structural elements (poles to bedding and orientation of long axes of pencil structure).

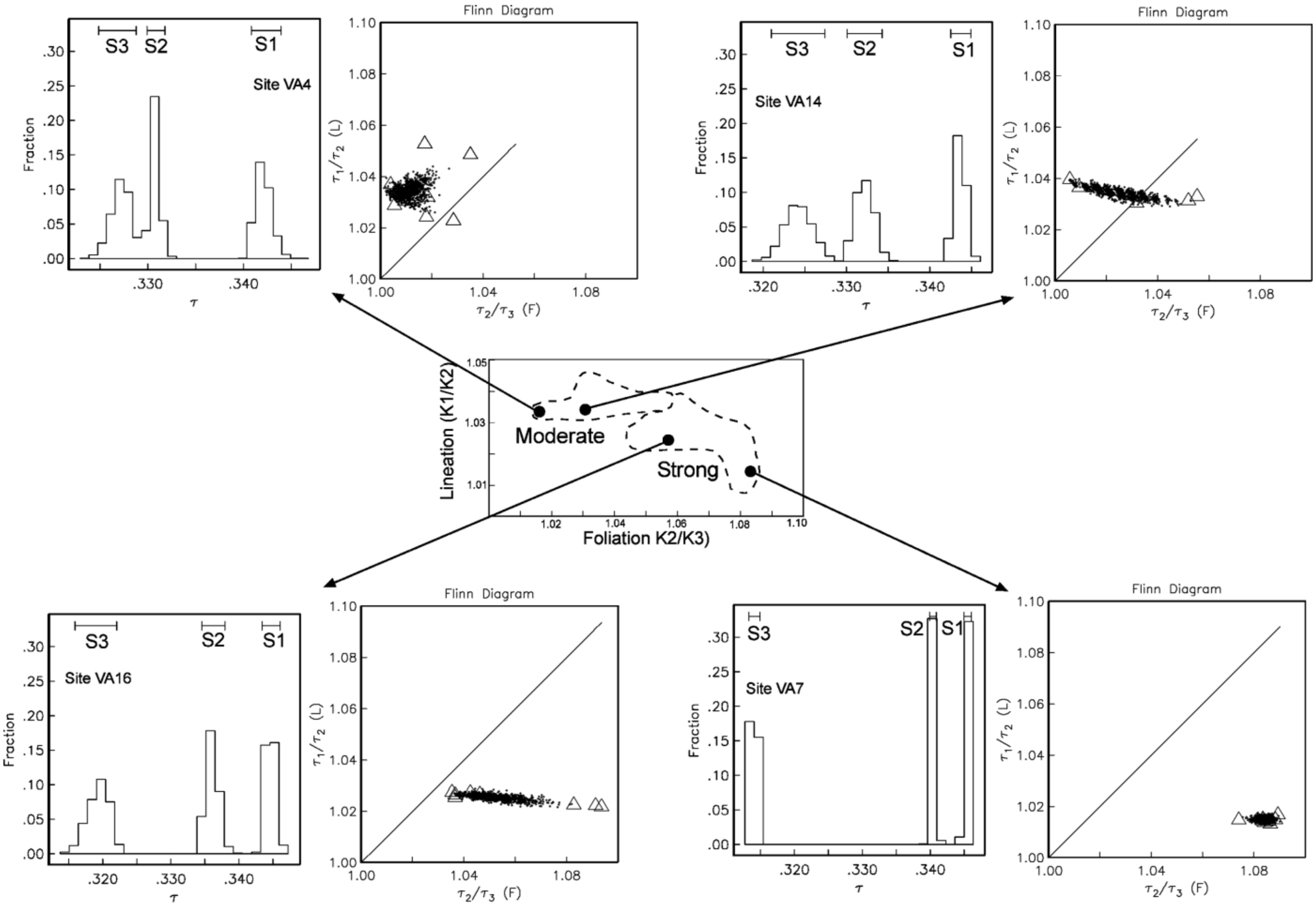

Fig. 6. Magnetic fabric and pencil intensity development. For each site, a histogram (left) and a Flinn-type diagram (right) are shown. Histogram includes Cartesian coordinates S_1, S_2, and S_3 of the bootstrapped principal eigenvectors. Notice the 95% confidence bounds drawn above the histograms. In the Flinn-type diagrams, data from individual samples are shown as triangles, dots are average values for bootstrapped para-data sets (Tauxe, 1998).

Knobs Fm. mudrocks and overwhelms the bedding anisotropy, preventing pencil structure development. The window of strain values that represent a balance between bedding and cleavage intensity corresponds to shortening strains between 10 and 25%. From a qualitative perspective, magnetic fabrics in pencil structures of Knobs Fm. for this range reveal that the magnetic lineation is parallel to the long axes of the pencil fragments. Quantitatively, the magnetic parameter T, which defines the shape of the magnetic susceptibility ellipsoid, is strain dependent as defined by the relation shortening (%) $= 17 * \exp(T)$ for the window of $\sim 10-25\%$ shortening. The earlier mentioned result by Hirt et al. (2000) for 40% shortening supports this relationship. Note that the range in which T relates to shortening strain is not sufficiently large to re-orient the direction of the principal minimum susceptibility axes, which remain normal to the bedding fabric (see Fig. 4). With increasing shortening, tectonic cleavage dominates and T approaches unity; that is, the magnetic ellipsoids become highly oblate and parallel to the flattening plane. Fig. 7b depicts the conceptual pattern of T with strain for a sedimentary rock with increasing cleavage development. The region constrained in this study is indicated as a solid line.

7. Conclusions

We have determined the magnetic fabrics (AMS) for mudrocks with pencil structures of variable intensity. Reks and Gray (1982) previously showed a correlation between pencil fabric and strain based on pressure fringes, and this study shows that AMS is at least equally sensitive as a recorder of strain state in the absence of other strain markers. The magnetic shape parameter, T, rather than magnetic intensity (such as P'), shows a consistent progression with shortening strain. A correlation between T and strain has been determined as: shortening (%) $= 17 * \exp(T)$ for a range of $\sim 10-25\%$ shortening. This AMS-strain relationship for mudrocks cannot be a priori extrapolated to other rock types, because a variety of factors affects rock magnetic properties (such as mineralogy and recrystallization). Our study shows, however, that magnetic anisotropy is a reliable proxy of shortening in low

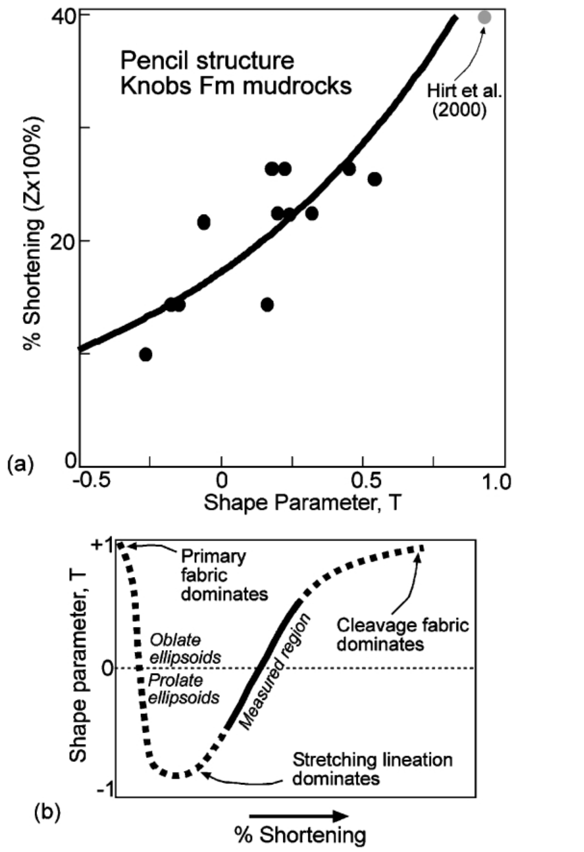

Fig. 7. (a) Graph of shape parameter T ($T = [\ln F - \ln L]/[\ln L + \ln F]$) versus %shortening in pencil structures from Knobs Formation. Data points correspond to sites where strain has been determined on the basis of pencil intensity (Reks and Gray, 1982). Also included is the result from Hirt et al. (2000) for slates from the Cantabrian belt. See text for discussion. (b) Conceptual model of changes in the shape parameter with increasing strain. Solid line represents the measured region of T and shortening.

strain mudrocks, where grain reorientation is the main deformation mechanism.

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