PAGEOPH, Vol. 135, No. 1 (1991) 0033–4553/91/010015–15$1.50 + 0.20/0

Correlation of Strain with Anisotropy of Magnetic Susceptibility (AMS)

GRAHAM J. BORRADAILE[1]

Abstract—Existing correlations between strain and anisotropy of low-field magnetic susceptibility (AMS) have been re-assessed using a single parameter to express both anisotropies. The P' parameter (HROUDA, 1982) shows potential as a powerful single expression of the intensity of strain and of AMS. Previous correlations are improved by use of this parameter. Cautious optimism is justified for correlations between strain and susceptibility in a certain strain window between a lower limit (excluding the incomplete overprint of predeformation anisotropy) and an upper limit (excluding the effects of saturation anisotropy). For successful correlations the influence of stress-controlled recrystallisation should be minimal and the mineralogical sources of susceptibility must predate deformation.

Key words: Magnetic susceptibility, strain, anisotropy, magnetic fabric.

Introduction

The principal susceptibilities or axes of the susceptibility ellipsoid have axes defined as $k_1 \geq k_2 \geq k_3$. Initially, AMS ellipsoid shapes were plotted on the Flinn diagram of structural geologists in which k_1/k_2 was plotted against k_2/k_3. Although it is familiar to structural geologists, it is disadvantageous that the axes neither represent shape nor "ellipticity" (intensity of AMS fabric or, where appropriate, strain). However, HROUDA (1982) introduced a superior plot using expressions derived from JELINEK (1981).

On this new plot the eccentricity of the susceptibility ellipsoid is plotted as P' on the horizontal axis ($1 \leq P' \leq \infty$) and T records symmetry of shape on the vertical axis ($-1 \leq T \leq 1$). $T > 0$ for disc shapes and $T < 0$ for rod shapes. P' has an advantage over the simple anisotropy parameter P or P_2 ($= k_1/k_3$) in that it includes some reference to the intermediate principal value. For neutral ellipsoids, called plane strain ellipsoids by the structural geologist, $T = 0$.

[1] Department of Geology, Lakehead University, Thunder Bay, Ontario P7B 5E1, Canada.

From HROUDA (1982), the definitions of P' and T are

$$T = \frac{2(\ln k_2 - \ln k_3)}{\ln k_1 - \ln k_3} - 1$$

(N.B. there was a misprint in the above formula in BORRADAILE, 1988.)

$$P' = \exp\sqrt{\{2(a_1^2 + a_2^2 + a_3^2)\}}$$

where $a_i = \ln(k_i/kb)$ for $i = 1$ to 3 and $kb = (k_1 \cdot k_2 \cdot k_3)^{1/3}$ or $kb = (k_1 + k_2 + k_3)/3$ (for the usual range of k, the different definitions of kb make little difference).

P' includes a reference to all three principal values and provides a useful parameter for representation of both strain *and* susceptibility ellipsoids. For strain ellipsoids, the principal strains $X \geq Y \geq Z$ are substituted in the above formulae for k_1, k_2 and k_3. Later in this paper use will also be made of principal ratios. These are $a = X/Y$, $b = Y/Z$ for strain and $L = k_1/k_2$, $F = k_2/k_3$ for AMS.

As the popularity of low-field AMS studies grew, there was a natural attempt to extend its uses to quantify strain, rather than merely determining fabric directions or potential principal strain axes. The difficulties of this procedure are now easier to see with the benefit of hindsight. Strain can increase indefinitely but AMS has a definite upper limit which cannot be greater than the most anisotropic mineral in the rock when all grains of that mineral are perfectly aligned. Thus we recognise that a saturation AMS may be quickly reached when, for example, all the magnetite grains are strongly aligned. Alternatively, it could occur with little strain at all: It could be influenced primarily by stress during recrystallisation, causing a perfect alignment of chlorite or mica. Thus at best we should not expect a straightforward power law correlation of strain ratios and principal susceptibility ratios over the complete range of strains possible. Moreover, at low strains say, $<20\%$ shortening in pure shear (the exact value would be dependent on lithology and other factors), the initial fabric might not be completely overprinted. At the other extreme, at high strains say, $>75\%$ shortening in pure shear, saturation alignments of the most susceptible minerals might be expected to occur. It is only in the window between these two limits, the exact position of which would depend on lithology, metamorphism, mineralogy and deformation mechanisms, that one might reasonably expect a correlation of strain ratios and principal susceptibility ratios. Fortunately, several such studies have already been made in rocks which appear to fall in this window of opportunity: the Welsh Slates (WOOD *et al.*, 1976; RATHORE, 1979), the Chelmsford Sandstone of Ontario (KLIGFIELD *et al.*, 1977; CLENDENEN *et al.*, 1988), the Dalradian Slates of SW Scotland (RATHORE and HENRY, 1982), and the Borrowdale Volcanic Slates of England (RATHORE, 1980; BORRADAILE and MOTHERSILL, 1984). All of these rocks would be classified, texturally, as possessing slaty cleavage or very low-grade continuous schistosity.

The parameters for correlation of principal strain with AMS should be chosen with care. The most logical choice is to use ratios, but several workers have used normalised logarithmic parameters derived from the ratios. Some workers plot information concerning *all three principal values* on the one graph. As BORRADAILE and MOTHERSILL (1984) have shown this has lead to fictitious correlations being generated in some instances. However, CLENDENEN *et al.* and RATHORE and HENRY, did establish weak correlations in a valid manner, and inspection of the data of WOOD *et al.* (1976) shows that their data contains a good correlation between magnitudes of minimum strain axis value and minimum susceptibility value.

The value of the few proven positive power-law correlations lies in the fact that it may become possible to predict finite strain from the considerably easier to determine AMS within the "20% to 75% strain-window" postulated above. There is no suggestion that there might be a universal law, valid under all conditions and for all rock types. Indeed, even simple theoretical models indicate a nonlinear relationship between log(strain) and log (AMS) (HROUDA, 1987; ROCHETTE, 1988). However, in a given area, where correlations have been established with observed strain markers, it may be possible to extrapolate the power law with some confidence to outlying regions where strain markers are absent. The success of the studies on the Welsh slates, the Dalradian slates and the Chelmsford sandstone suggest that these three areas may be suitable for further study in this way.

The writer has re-assessed the published information concerning strain-susceptibility correlations below. When correlations are performed in a valid manner there appears to be reason for cautious optimism, as many of the previous studies do show some satisfactory correlation.

Laboratory experiments provide limited support for some power law relating magnitudes of strain and AMS. This has been attempted by BORRADAILE and ALFORD (1987, 1988) using magnetite-bearing sands bonded with Portland cement. High pressure triaxial deformation succeeded in changing the predeformation AMS fabrics in a fashion that was kinematically consistent with the imposed strain histories (pure shear and transpressional shear). The initial fabrics were not easily overprinted at the range of strains that were possible ($<40\%$ shortening in pure shear). For example, an AMS ellipsoid with its long axis parallel to the shortening axis would change its anisotropy very slowly, first becoming spherical, and then finally elongating in the maximum extension direction. I shall term this "flipping". In this sense the AMS fabric "deforms" somewhat like a passive ellipsoidal marker according to the Rf/ϕ theory of structural geology (see RAMSAY, 1967; pp. 202–209; BORRADAILE, 1987b). However, for the purposes of statistical correlation of strain with anisotropy, BORRADAILE and ALFORD excluded unsuitably oriented ellipsoids that generated "flipped" fabrics. In this way a strong power law correlation was established between intensity of AMS (expressed as P') and strain ratio (b) (see Fig. 1). Although natural deformation mechanisms were not reproduced in the experiments, the good correlation may encourage one to establish similar relationships for specific rock types in individual areas.

Review of Previously Established Correlations of Strain and AMS Magnitudes

Previously published correlations of susceptibility and strain are reviewed. In many cases the original data was given in print, in other cases only site-mean values were given and in still other cases data had to be deduced from enlargements of the published graphs. In two instances the published data were insufficient to re-evaluate the work. Most previous attempts to correlate magnitudes of strain and susceptibility have used plots on which all three principal values are plotted and correlated simultaneously. This is clearly invalid (BORRADAILE and MOTHERSILL, 1984). In one instance both principal ratios (i.e., a and b; L and F) were plotted simultaneously, leading to similar spurious correlations. Since only ratios of strain are determined directly, it seems logical to correlate shape ratios such as L with a (max/int ratios for susceptibility and strain, respectively) and F with b (int/min ratios). However, a single anisotropy parameter, P' (calculated for both strain and susceptibility), is found to give the strongest correlations with the existing data base.

In each case the magnetic anisotropy parameter L, F or P' (k) has been treated as the dependent variable and the corresponding strain parameter a, b or P' (e) is taken as the independent variable. Even this much is not beyond dispute. The measurement of strain may be regarded as straightforward by some workers with a geophysical background. For example, let us consider the numerous studies which use reduction spots as strain markers in slates. Some authors simply record the deformed shapes of these objects which is only adequate if the spots were initially spherical. Otherwise a complex procedure using an analysis of the Rf/ϕ family (BORRADAILE, 1987b) would be necessary to deduce the strain. Moreover, consideration is not always given to the question of the age of the reduction spots. Are they pre-deformation in age, or could they be post-deformational? In the latter case the spots would accurately reflect the preferred orientation fabric which was controlled by diffusion during the reduction process. Nevertheless, in the analyses below the strain data are taken at face value.

Similarly we should examine the way in which the susceptibility has been determined. Although all the methods concern low-field susceptibility, different instruments and different field strengths have been used in each case. This is not expected to significantly change the *ratios* of the anisotropies. Moreover, some earlier data was subject to a computer-program error supplied with the Digico instrument (HROUDA *et al.*, 1983). RATHORE (1988) re-evaluated such data and found that the magnetic anisotropy ratios (L and F) were only slightly affected ($<5\%$ error) for typical values, However, in attempting to re-establish correlations for previous work he plotted both ratios simultaneously (i.e., $\log_{10}$ of the following parameters: L against a, and F against b) so that the results are subject to the same criticism raised by BORRADAILE and MOTHERSILL (1984). The study by RATHORE and HENRY (1982) is not subject to this criticism because only the ratios a and L were determined.

In the correlations special consideration is given to three items. *Firstly*, it is not sufficient to quote a Pearson-correlation coefficient to establish a linear relationship. It is also necessary to evaluate the significance of the result by testing the hypothesis that the regression line does possess a nonzero slope. This is a function of the number of data points and the actual characteristics of the spatial distribution on the scatter diagram, both of which should be examined when evaluating the correlations. Significance is expressed by a probability p ($0 \le p \le 1$) that the same distribution could not be generated by a random process. A very significant result has a low p-value. Conventionally, a p-value of 0.05 is accepted as the maximum permissible value. (However, it is worth pondering that this only means that an equally strong distribution could be generated randomly once out of twenty times.) Again, it is emphasized that the p-value alone does not signify a good correlation. It merely indicates the degree of confidence one may place in the correlation coefficient, r. For example Figure 4a and Figure 1b have the same p-value. This indicates that we can be equally confident that Figure 1b shows a strong correlation and Figure 4a has a weak correlation. We must evaluate p, r, the number of data (n) and the actual graph distribution simultaneously to establish if there is a sensible correlation.

A *second item* that we must consider is the possibility that some component of original fabric remains. Strain analyses have been designed to allow for this, so that that strain ratios are not affected in this way. However, it is not yet possible to determine the nature of the pre-deformational susceptibility fabric. With very high strains, the interfering effect may become less significant but for most of the data reviewed below it could present a problem. One experimental study (Figures 1a,b) did avoid this because AMS was known before and after deformation. Moreover, the strain was known very precisely ($\pm 0.01\%$) because the deformation was produced in a triaxial rig. In Figure 1 the P' values for susceptibility ($P'(k)$) are plotted against the same value for strain ($P'(e)$). This produces a significant regression line with $p = 0.002$. Note, however, that for no strain ($P'(e) = 1$) there is an appreciable anisotropy—the intrinsic initial AMS of these experimentally prepared samples. Subsequently we shall see similar indications that there may be initial AMS components in most previous studies of natural deformation (Figures 2–5). However, other explanations are possible.

One special feature of experimentally produced AMS fabrics is that the initial AMS can be measured. Since this is known it is possible to correct for the initial anisotropy: The simple method chosen here is to plot the change in P', $(P' - P_0')$ for AMS against the natural logarithm of the strain ratio ($\ln(Y/Z)$ or $\ln b$). A well defined regression line is produced (Figure 1b) which is highly significant ($p < 0.001$). This experimental example serves to emphasize the importance of the initial AMS fabric. It is just as important in AMS studies as is the initial fabric or strain marker initial shape in studies of finite strain.

The *third item* to which attention is drawn concerns the interrelationship of ratios of principal (strain and susceptibility) axes. The parameter P' summarises the

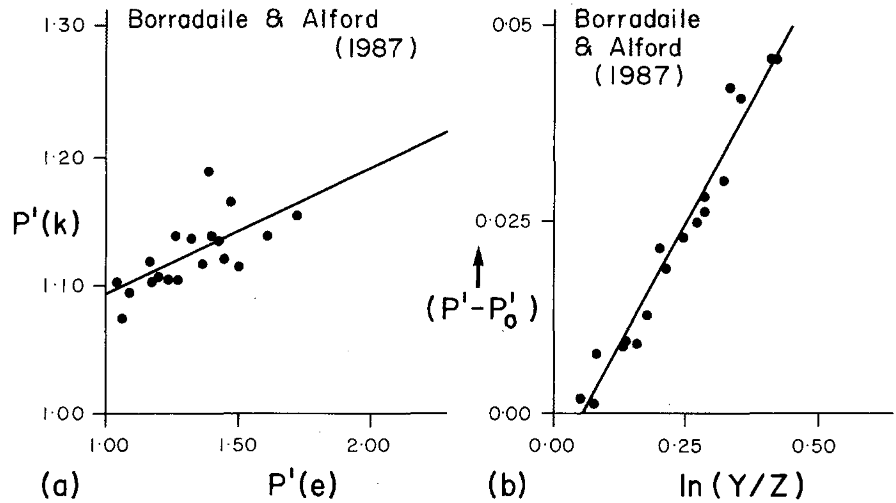

Figure 1
(a) Regression line for anisotropy degree of low-field susceptibility $P'(k)$ versus anisotropy degree for strain P' (e), for experimentally deformed synthetic "sandstones" (Table 3 for data). (b) Correlation of *change* of degree of AMS versus ln(strain ratio). These data are only available because the pre-deformation AMS is known. Data from Table 2.

influences of all three principal values. In this regard it is a superior parameter: It has produced the most successful correlation of strain and susceptibility magnitudes in this review. However, the ratios L of F, a or b which have been used hitherto, express only one aspect of the shape of the appropriate ellipsoid. For example, most of the papers present studies of slates, phyllites or schists. Since these usually have flattened or oblate fabrics, a and L are automatically close to unity. This makes it very difficult to establish a correlation between a and L, even though one probably exists. As a result most studies yield no correlations between $\ln(a)$ and $\ln(L)$ (see Table 1). This unnecessary pessimism is an artefact because previous studies have concentrated on flattened rather than constricted fabrics. Also, the nature of any correlation that exists between a and L is unlikely to be equal to that between b and F (except, perhaps in some cases of plane strain) so that it is inappropriate to plot both sets of ratios on one diagram. Thus in this study separate plots were made of $\ln(a)$ against $\ln(L)$; $\ln(b)$ against $\ln(F)$ and $P'(k)$ against $P'(e)$. The results are given in Tables 1, 2 and 3. Correlations using logarithms of the principal ratios were slightly higher than correlations of the ratios directly so that only the statistics for logarithmic correlations are tabulated.

In almost all cases, because most of the rocks are slates with oblate petrofabrics, the ranges of values for b and F ratios are greater. Consequently, it is easier to establish power-law correlations for these parameters (Table 2). However, in most

Table 1

$\ln(k_1/k_2)$ versus $\ln(a)$ correlations

	r	c	m	P	
WOOD *et al.*, 1976	0.268	0.0317	0.0451	0.144	0.144$n = 31$, reduction spots in slates
KNEEN, 1976	0.815	−0.0003	0.056	*0.048*	$n = 6$, reduction spots in slates
RATHORE *et al.*, 1983	0.379	0.0286	0.068	*0.012*	$n = 43$, mica fabric in slates
RATHORE & HUGON, 1987	0.247	0.0347	0.0253	0.324	$n = 18$, mica fabric in slates
RATHORE, 1980	−0.724	0.121	−0.149	0.103	$n = 6$ lapilli in slaty tuff (site means only)
BORRADAILE & MOTHERSILL, 1984	0.189	0.008	0.0359	0.468	$n = 17$ lapilli (rims) in slaty tuff
KLIGFIELD *et al.*, 1981	0.619	0.005	0.0209	0.190	$n = 6$ reduction spots in slates (site means only)
COGNÉ & PERROUD, 1988	0.484	0.047	0.053	0.224	$n = 8$, xenoliths in intrusion (site means only)
KLIGFIELD *et al.*, 1982	−0.006	0.035	−0.0001	0.988	$n = 9$, oolites with oxide coating in limestone
HIRT *et al.*, 1988	0.682	0.006	0.032	*0.03*	$n = 10$, concretions in sandstone (site means only)
RATHORE & HUGON, 1987	−0.239	0.0342	−0.017	0.648	$n = 6$, reduction spots in slate

r = Pearson's correlation coefficient
c = constant; m = slope of regression line
if $p < 0.05$ value of r is significant at 95% level

cases it was much simpler to identify correlations using P' as the parameter. For example, the studies using reduction spots in the Welsh slates (KNEEN, 1976; WOOD *et al.*, 1976) have correlations (Figure 2) with p-values of 0.005 and 0.026, respectively.

In other studies using ooids with an iron oxide coating in limestones (KLIGFIELD *et al.*, 1982), concretions in sandstones (HIRT *et al.*, 1988) and xenoliths in igneous rock (COGNÉ and PERROUD, 1988) good power-law correlations are discerned (Figures 3a,c,d). Similar results should be expected from the study by KLIGFIELD *et al.* (1981), but only site-mean data were available to the writer and this may be detrimental to the correlation given here.

Further studies, by RATHORE *et al.* (1983) and RATHORE and HUGON (1987) used intensity of strong mica fabrics in slates to infer strain, rather than a direct strain measurement, although reduction spots were noted at a few localities in the latter paper. As a result, the values plotted as ($P'(e)$) are extremely large. It is difficult to use the correlation in the context of strain because the mica fabrics must, in turn, be evaluated to yield a strain estimate (OERTEL, 1983). However, the

Table 2

$\ln(k_2/k_3)$ *versus* $\ln(b)$ *correlations*

	r	c	m	P	
Wood *et al.*, 1976	0.595	−0.149	0.313	*<0.001*	$n = 31$, reduction spots in slate
Kneen, 1976	0.729	−0.052	0.0911	0.100	$n = 6$, reduction spots in slate
Rathore *et al.*, 1983	0.501	−0.121	0.315	*0.001*	$n = 43$, mica fabric in slate
Rathore & Hugon, 1987	0.4779	0.0148	0.0695	*0.045*	$n = 18$, mica fabric in slate
Rathore, 1980	0.180	0.144	0.033	0.733	$n = 6$, lapilli in slaty tuff (site means only)
Borradaile & Mothersill, 1984	−0.492	0.151	−0.077	*0.045*	$n = 17$, lapilli (rims) in slaty tuff
Kligfield *et al.*, 1981	0.831	0.019	0.036	*0.040*	$n = 6$, reduction spots in slate
Cogné & Perroud, 1988	0.825	0.0359	0.127	*0.012*	$n = 8$, xenoliths in intrusion (site means only)
Kligfield *et al.*, 1982	0.894	−0.081	0.313	*0.001*	$n = 9$, oolites with oxide cooling in limestone
Hirt *et al.*, 1988	0.533	0.003	0.044	0.113	$n = 10$, concretions in sandstone (site means only)
Rathore & Hugon, 1987	0.780	−0.059	0.106	0.067	$n = 6$, reduction spots in slate
Borradaile & Alford, 1988	0.577	0.032	0.0139	*0.01*	$n = 19$, experimental deformation of sand – Portland cement aggregate

r = Pearson's correlation coefficient
c = constant; m = slope of regression line
if $p < 0.05$ value of r is significant at 95% level

correlations established (Figures 4a,b) could still be used as a predictive tool to infer the intensity of mica fabrics without recourse to time-consuming and complex texture-goniometer studies.

One group of rocks has yielded no significant correlation, or negative correlations between susceptibility and strain. The Borrowdale volcanic slates of N. England are weakly metamorphosed and cleaved tuffs that contain accretionary lapilli as strain markers. Rathore's original data (actually site means only) yield a poor correlation. Also the susceptibility values were not determined from the same specimens which were used to determine the strain—instead previously published strain values were used, and some of those previous studies did not take into account the original shapes of the lapilli. A repeat study, using a new method of analysing the strain without dependence on the original fabric was performed by Borradaile and Mothersill (1984). They also determined the AMS and found no significant correlations with strain. Indeed, as recommended here, the use of P'

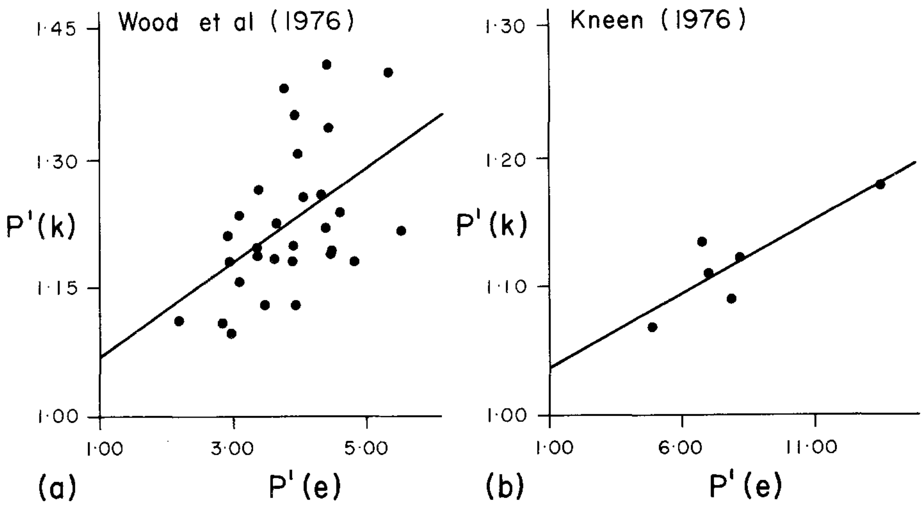

Figure 2

Low-field AMS data for Welsh slates in which hematite is considered to be responsible for most of the susceptibility. The strain markers are reduction spots. Data from Table 3.

Table 3

P′ (susceptibility) versus P′ (strain) correlations

	r	*c*	*m*	*P*	
Wood *et al.*, 1976	0.495	1.012	0.0548	*0.005*	$n = 30$, one outlier deleted, reduction spots in slates
Kneen, 1976	0.866	1.025	0.0114	*0.026*	$n = 6$, reduction spots in slates
Rathore *et al.*, 1983	0.472	1.107	0.0557	*0.002*	$n = 42$, mica fabric by *texture goniometry* in slate
Rathore & Hugon, 1987	0.5618	1.065	0.0151	*0.015*	$n = 18$, mica fabric
Rathore, 1980	0.777	1.111	0.0293	0.069	$n = 6$, lapilli shapes in slaty tuff (site means only)
Borradaile & Morthersill, 1984	−0.511	1.179	−1.504	0.036	$n = 17$, lapilli (rims) in slaty volcanic ash
Kligfield *et al.*, 1982	0.582	1.045	0.0047	0.225	$n = 6$, reduction spots in slate (site means only)
Cogné and Perroud, 1988	0.876	1.035	0.062	*0.004*	$n = 8$, xenoliths in intrusion (site means only)
Kligfield *et al.*, 1982	0.755	0.959	0.080	*0.019*	$n = 9$, oolites with oxide coating in limestone
Hirt *et al.*, 1988	0.677	0.986	0.0248	*0.032*	$n = 10$, concretions in sandstone (site means only)
Rathore & Hugon, 1987	0.6974	1.062	0.0102	0.124	$n = 6$, reduction spots in slates
Borradaile & Alford, 1987	0.670	0.993	0.098	*0.002*	$n = 19$, experimental deformation of sand—Portland cement aggregate

r = Pearson's correlation coefficient

c = constant; m = slope of regression line

if $p < 0.05$ value of r is significant at 95% level suggests a negative correlation (Figure 5b: Table 3). The lack of correlation in this study is probably due to the fact that this rock contains multiple mineralogical sources of susceptibility (BORRADAILE *et al.*, 1986; Henry, 1990). These have different intrinsic AMS, so that small interspecimen variations in mineral content cause large changes in the AMS of the specimen in the manner shown by BORRADAILE (1987a). These override any effect due to strain.

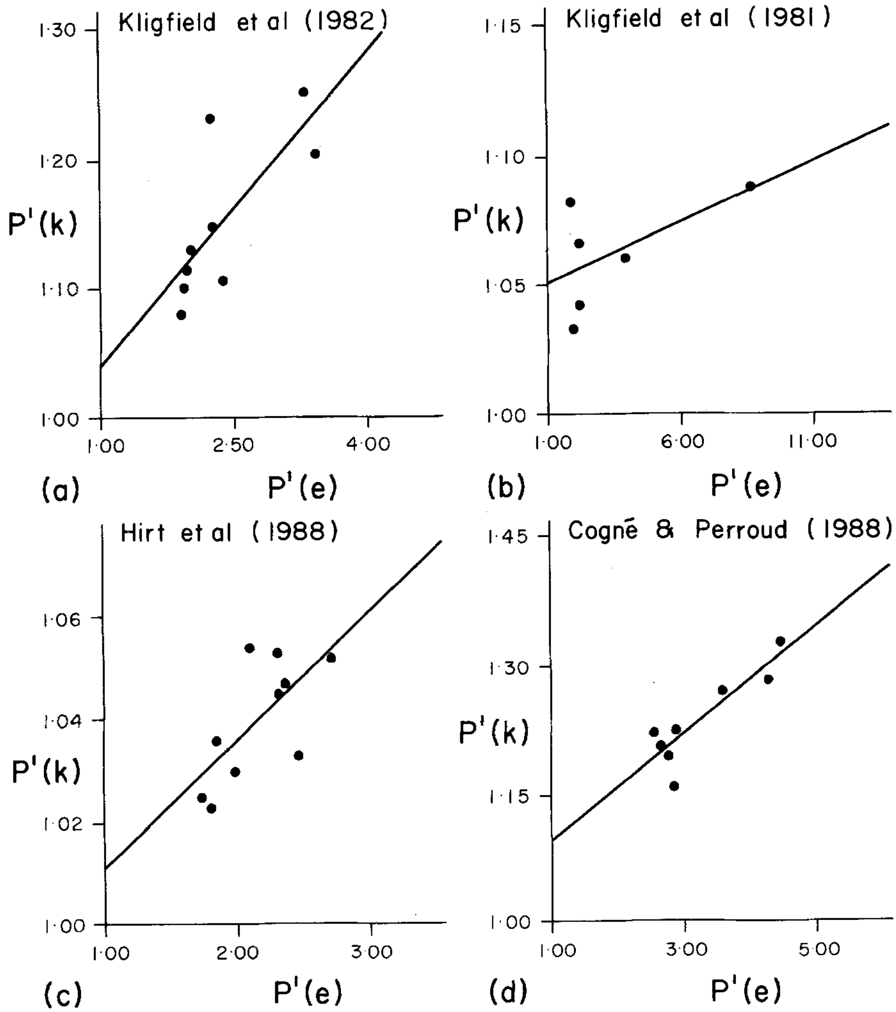

Figure 3

Correlations of low-field AMS data (k) versus strain data (e) using the P', anisotropy degree, parameter. Strain markers used were: (a) ooids in limestone, (b) reduction spots in slates, (c) concretions in sandstone, (d) xenoliths in granite. Data from Table 3.

Conclusions

Improved correlations between strain and AMS are recognised using the P' parameter for both strain and AMS. It is invalid to plot individual ratios L versus a and F versus b on the same graph as these are quite unrelated (see Figure 6) and lead to spurious correlations. Correlations of L versus a; or of F versus b are valid but yield poorly defined regression slopes (see Tables 1, 2 and Figure 7). The most

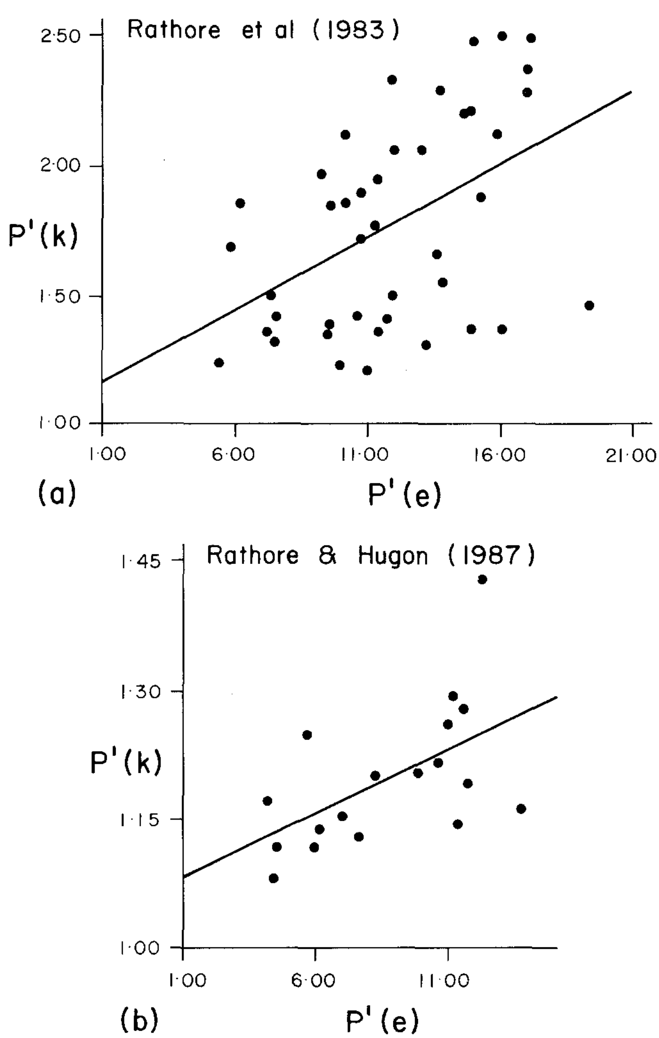

Figure 4
Correlations of P' for low field AMS versus P' calculated from the anisotropy of the preferred orientation of the mica subfabric in slates. the latter is not a strain parameter and as such the P' values are very high. Data from Table 3.

significant regressions are for $P'(k)$ versus $P'(e)$ (Table 3). The slopes are generally in the range

$$m = 0.005 \quad \text{to} \quad 0.1$$

where $P'(k) = m \cdot (P'(e)) + \text{constant}$.

The constant is usually substantial and positive (see Figures 1–5) which may indicate appreciable pre-deformation susceptibility fabric that should not be neglected. As an anonymous reviewer pointed out, it could also indicate some nonlinear behaviour at low strains.

Unfortunately, the emphasis of previous studies on flattened fabrics reduces the range of available data for detecting correlations. Nevertheless, there are some indications that within limits, some rocks do show a correlation between strain and AMS. The limits imposed are that the strains should not be too low (interference of pretectonic magnetic fabric components) and not too high (where saturation of AMS may occur). Moreover, to assess the significance of the AMS fabric and whether it is reasonable or not to expect a correlation with strain, one should have knowledge of the mineralogical sources of low-field AMS. The latter does not necessarily need very sophisticated equipment. Simple microscopic analysis, perhaps backed up by mineral separation work, is usually sufficient to assess the contribution of different minerals to AMS in conjunction with published information on susceptibility anisotropies of individual minerals (BORRADAILE 1988). Simple leaching tests can also be instructive (BORRADAILE *et al.*, 1990).

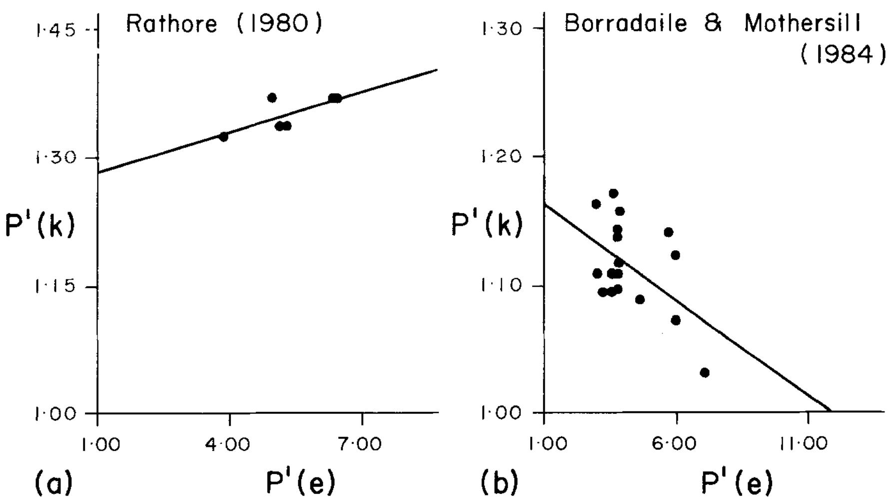

Figure 5
Correlations of P' for AMS (k) versus P' for strain (e) for the Borrowdale slaty tuffs. The strain markers are accretionary lapilli. RATHORE used their outlines as markers whereas BORRADAILE and MOTHERSILL used the rim-thickness variations. Data from Table 3.

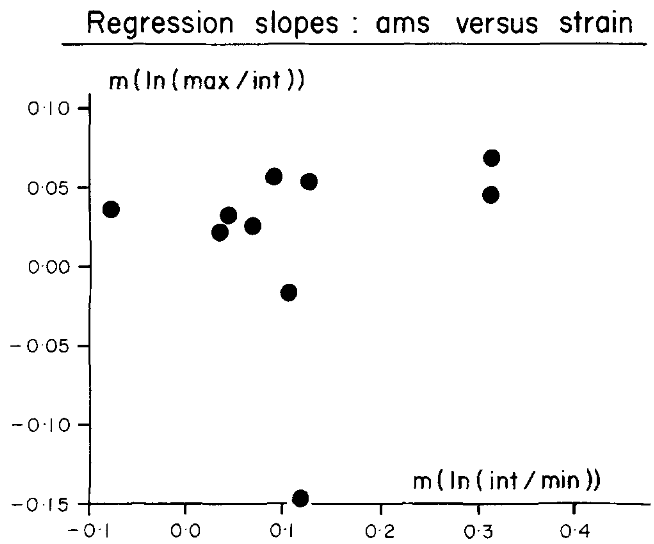

Figure 6
Review of correlations from previous literature for m (slope of regression line) between AMS and strain. There is no relation between the (max/int) data and the (int/min) data, indicating that such data groups should be correlated separately. Data from Tables 1 and 2.

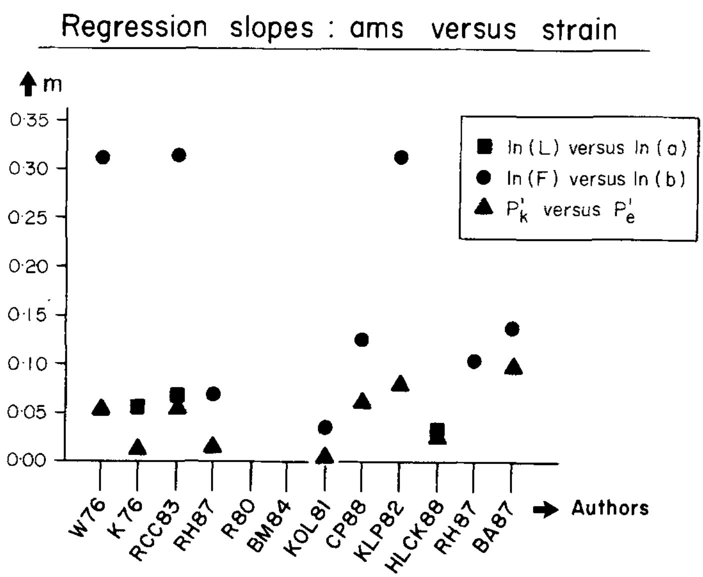

Figure 7
Review of regression slopes (m) from previous literature. Authors' initials and year of publication are indicated. Data from Tables 1, 2 and 3.

Lastly, the author would like to emphasize that the greatest use of AMS in structural studies is as a petrofabric tool, not as a strain sensor. Undue emphasis has been placed on the determination of strain magnitudes through AMS. The speed, sensitivity and the fact that AMS gives an integrated, bulk measure of fabric make it superior to any method yet devised in structural geology for estimating preferred alignments of mineral fabrics. With care such measures of fabric can be used as powerful indicators of kinematic history of rocks. Moreover, the principal directions defined through AMS are very often principal strain directions. That item alone justifies an expanded role for AMS in tectonic studies.

Acknowledgement

I thank NSERC Canada for operating grant # A6861. Bruce Luyendyk and an anonymous reviewer are gratefully acknowledged for constructive criticism.

Appendix

The programs for plotting HROUDA ($P' - T$) diagrams and Flinn diagrams, together with data storage and recall routines are available for IBM compatible personal computers. Also available are a group of strain analysis methods (BORRADAILE, 1987b) for elliptical markers including modelling routines for synthetic data, plotting Rf/ϕ graphs, etc. If you wish to use a copy, send a formatted 5.25" or 3.5" disc to the author in a sturdy, reusable mailer.

REFERENCES

BORRADAILE, G. J. (1987a), *Anisotropy of Magnetic Susceptibility: Rock Composition versus Strain*, Tectonophysics *138*, 327–329.

BORRADAILE, G. J. (1987b), *Analysis of Strained Sedimentary Fabrics: Review and Tests*. Can. J. Earth Sci. *24*, 442–455.

BORRADAILE, G. J. (1988), *Magnetic Susceptibility, Petrofabrics and Strain*, Tectonophysics *156*, 1–20.

BORRADAILE, G. J., MACKENZIE, A., and JENSEN, E. (1990), Silicate versus Trace Mineral Susceptibility in Metamorphic Rocks, J. Geophys. Res. *95*, 8447–8451.

BORRADAILE, G. J., and MOTHERSILL, J. S. (1984), *Coaxial Deformed and Magnetic Fabrics Without Simply Correlated Magnitudes of Principal Values*, Phys. Earth and Planet. Int. *35*, 294–300.

BORRADAILE, G. J., MOTHERSILL, J. S., TARLING, D. M., and ALFORD, C. (1986), *Sources of Magnetic Susceptibility in a Slate*, Earth and Planet. Sci. Letters *76*, 336–340.

BORRADAILE, G. J., and ALFORD, C. (1987), *Relationship between Magnetic Susceptibility and Strain in Laboratory Experiments*, Tectonophysics *133*, 121–135.

BORRADAILE, G. J., and ALFORD, C. (1988), *Experimental Shear Zones and Magnetic Fabrics*, J. Struct. Geol. *10*, 895–904.

CLENDENEN, W. S., KLIGFIELD, R., HIRT, A. M., and LOWRIE, W. (1988), *Strain Studies of Cleavage Development in the Chelmsford Formation, Sudbury Basin, Ontario*, Tectonophysics *145*, 191–211.

COGNÉ, J. P., and PERROUD, H. (1988), *Anisotropy of Magnetic Susceptibility as a Strain Gauge in the Flamanville Granite, NW France*, Phys. Earth and Planet. Int. *51*, 264–270.

HENRY, B. (1990), *Magnetic Fabric Implications for the Relationships between Deformation Mode and Grain Growth in Slates from the Borrowdale Volcanic Group in the English Lake District*, Tectonophysics *178*, 225–230.

HIRT, A. M., LOWRIE, W., CLENDENEN, W. S., and KLIGFIELD, R. (1988), *The Correlation of Magnetic Anisotropy with Strain in the Chelmsford Formation of the Sudbury Basin, Ontario*, Tectonophysics *145*, 177–179.

HROUDA, F. (1987), *Mathematical Model Relationship between the Paramagnetic Anisotropy and Strain in Slates*, Tectonophysics *142*, 323–327.

HROUDA, F. (1982), *Magnetic Anisotropy and its Application in Geology and Geophysics*, Geophysical Surveys *5*, 37–82.

HROUDA, F., STEPHENSON, A., and WOLTAR, L. (1983), *On the Standardization of Measurements of the Anisotropy of Magnetic Susceptibility*, Phys. Earth and Planet. Int. *32*, 203–208.

JELINEK, V. (1981), *Characterization of the Magnetic Fabrics of Rocks*, Tectonophysics *79*, T63–T67.

KLIGFIELD, R., LOWRIE, W., and DALZIEL, I. W. D. (1977), *Magnetic Susceptibility Anisotropy as a Strain Indicator in the Sudbury Basin, Ontario*, Tectonophysics *40*, 287–308.

KLIGFIELD, R., OWENS, W. H., and LOWRIE, W. (1981), *Magnetic Susceptibility Anisotropy, Strain and Progressive Deformation in Permian Sediments from the Maritime Alps (France)*, Earth and Planet. Sci. Letters *55*, 181–189.

KLIGFIELD, R., LOWRIE, W., and PFIFFNER, O. A. (1982), *Magnetic Properties of Deformed Oolitic Limestones from the Swiss Alps: The Correlation of Magnetic Anisotropy and Strain*, Eclogae geol. Helv. *75/1*, 127–157.

KNEEN, SYLVIA J. (1976), *The Relationship between the Magnetic and Strain Fabrics of Some Haematite-bearing Welsh Slates*, Earth and Planet. Sci. Letters *31*, 413–416.

OERTEL, G. (1983), *The Relationship of Strain and Preferred Orientation of Phyllosilicate Grains in Rocks—A Review*, Tectonophysics *100*, 413–447.

RAMSAY, J. G., *Folding and Fracturing of Rocks* (McGraw-Hill, New York 1987) 568 pp.

RATHORE, J. S. (1979), *Magnetic Susceptibility Anisotropy in the Cambrian Slate Belt of N. Wales and Correlation with Strain*, Tectonophysics *53*, 83–98.

RATHORE, J. S. (1980), *The Magnetic Fabrics of Some Slates from the Borrowdale Volcanic Group in the English Lake District and their Correlations with Strains*, Tectonophysics *67*, 207–220.

RATHORE, J. S., and HENRY, B. (1982), *Comparison of Strained Magnetic Fabrics in Dalradian Rocks from the Southwest Highlands of Scotland*, J. Struct. Geol. *4*, 373–384.

RATHORE, J. S., COURRIOUX, G., and CHOUKROURE, P. (1983), *Study of Ductile Shear Zones (Galicia, Spain) using Texture Goniometry and Magnetic Fabric Methods*, Tectonophysics *98*, 87–109.

RATHORE, J. S., and HUGON, H., *Comparison of magnetic, mica and reduction spot fabrics in the Rocroi Massif, Ardenes, France*, In *The Rhenish Massif* (Vogel, A., Miller, H., and Greiling, R. eds) (F. Vieweg and Sohn., Brauschweig/Wiesbaden 1987) pp. 79–94.

RATHORE, J. S. (1988), *Strain to Anisotropy Correlations Corrected for the Digico Calibration Error*, Phys. Earth. and Planet. Int. *51*, 355–360.

ROCHETTE, P. (1988), *Mathematical Model Relationship between the Paramagnetic Anisotropy and Strain in Slates—Discussion*, Tectonophysics *156*, 313–315.

WOOD, D. S., OERTEL, G., SINGH, J., and BENNETT, H. F. (1976), *Strain and Anisotropy in Rocks*, Phil. Trans. R. Soc. Lond. *A283*, 27–42.

(Received January 29, 1990, received/accepted July 3, 1990)