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A magnetic fabric study of the Shap region in the English Lake District

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Abstract—The magnetic susceptibility anisotropy technique was applied to 50 sites, comprising 280 core samples from the Shap Granite and the surrounding country rocks from both within and outside the thermal aureole. The magnetic fabrics of individual cores from the granite pluton indicate preferred orientations of non-equi-dimensional magnetite grains. This fabric developed during the slow ascent and consequent cooling of the magma. The sites from the metamorphic rocks from the immediate contact with the Shap Granite show weak axial shortening directions which are subnormal to the granite contact. Core samples from the surrounding Ordovician and Silurian rocks within the thermal metamorphic aureole but further from the granite have oblate magnetic-fabric ellipsoids with subvertical magnetic foliations trending approximately NE–SW, parallel to the regional Caledonian cleavage planes. This suggests that the magnetic fabric observed in the granite is primary with respect to the time of emplacement of the magma, and that this emplacement post-dates the main compressive phase of the Caledonian Orogeny. The effect of the granite on the country rock is mainly thermal metamorphism with mechanical deformation limited to a very narrow strip around the granite.

INTRODUCTION

A CLOSE association between the magnetic fabrics and petrofabrics of rock samples has been known for some time (Graham 1954) and the use of the magnetic susceptibility (MSA) method for structural studies has been proposed often (see the comprehensive bibliography given by Hrouda 1982). Magnetic fabrics of many rock types have been examined and comparative petrofabric studies have demonstrated the general co-axiality of the two fabric ellipsoids. Research on sedimentary rocks has shown that the plane of maximum/intermediate susceptibility axes lies in the bedding plane of the undeformed consolidated sediments and this reflects the observed primary geological fabric (Granar 1958, Girdler 1961, Fuller 1964, Rees 1964, Graham 1966, Ab-Iorwerth 1967, Rees *et al.* 1968, Hamilton *et al.* 1968, Hamilton & Rees 1971). In studies of metamorphic rock fabrics it has been shown that the degree of anisotropy is generally higher than that of sedimentary bedding fabrics, with planar orientations of magnetic foliation planes parallel to any observed cleavages (Stacey 1960, Stone 1963, Janak 1965, Hrouda & Janak 1976, Hrouda *et al.* 1971, 1973, 1978, Hrouda 1976, 1982, Kligfield *et al.* 1977, 1982). The magnetic fabrics of granitic and basaltic intrusions have been extensively studied (Balsley & Buddington 1960, Stacey 1960, Stott & Stacey 1960, Khan 1962, King 1966, Abouzakhm 1974, Chlupacova *et al.* 1975, Heller 1973, Ellwood & Whitney 1980, Guillet *et al.* 1983), and it is well established that the MSA ellipsoid shape and orientations accurately reflect the grain structure of rocks. In general the maximum susceptibility axes trend parallel to any observed lineations and the minimum susceptibility axes trend perpendicular to any observed foliations.

The applicability of the MSA technique to the study of structural trends has been demonstrated in a variety of environments, large and small, uniform and complex (Fuller 1960, Girdler 1961, Heller 1973, Hrouda *et al.* 1971, Henry 1975, Kligfield *et al.* 1977, 1981, Rathore *et al.* 1977, 1983, Rathore & Heinz 1979, 1980, Rathore & Becke 1980, 1983, Rathore & Mauritsch 1983, and many others, see bibliography of Hrouda 1982). This paper reports on a further applicability test of the MSA method where the overprinting of an existing fabric due to a granite intrusion is studied.

A magnetic fabric study of the Shap Granite region in the English Lake District was carried out in order (1) to determine the nature and the mode of emplacement of the granite, (2) to show independently that the granite intrusion postdates the Caledonian deformations of the region which are seen in the surrounding country rock and (3) to determine the effect of the granite intrusion on the country rock. It was hoped to use the observed fabric picture, together with the knowledge of the thermal metamorphic aureole, to deduce the extent of temperature and mechanical fabric overprinting which may have affected the ferromagnetic grains in the host and granitic rocks.

An earlier magnetic fabric study in the English Lake District (Rathore 1980a) has shown that the magnetic fabric is a very good indicator of the strain fabric for the region. The magnetic fabric foliations strike parallel to the regional structural trends (Rathore 1980a, fig. 1). Detailed cross-correlations of magnetic and strain fabrics showed excellent agreements between the principal axes of the two fabric ellipsoids (Rathore 1980a, fig. 4). Furthermore, the anisotropy parameters for the two fabric ellipsoids were found to be analytically comparable (Rathore 1980a, fig. 5).

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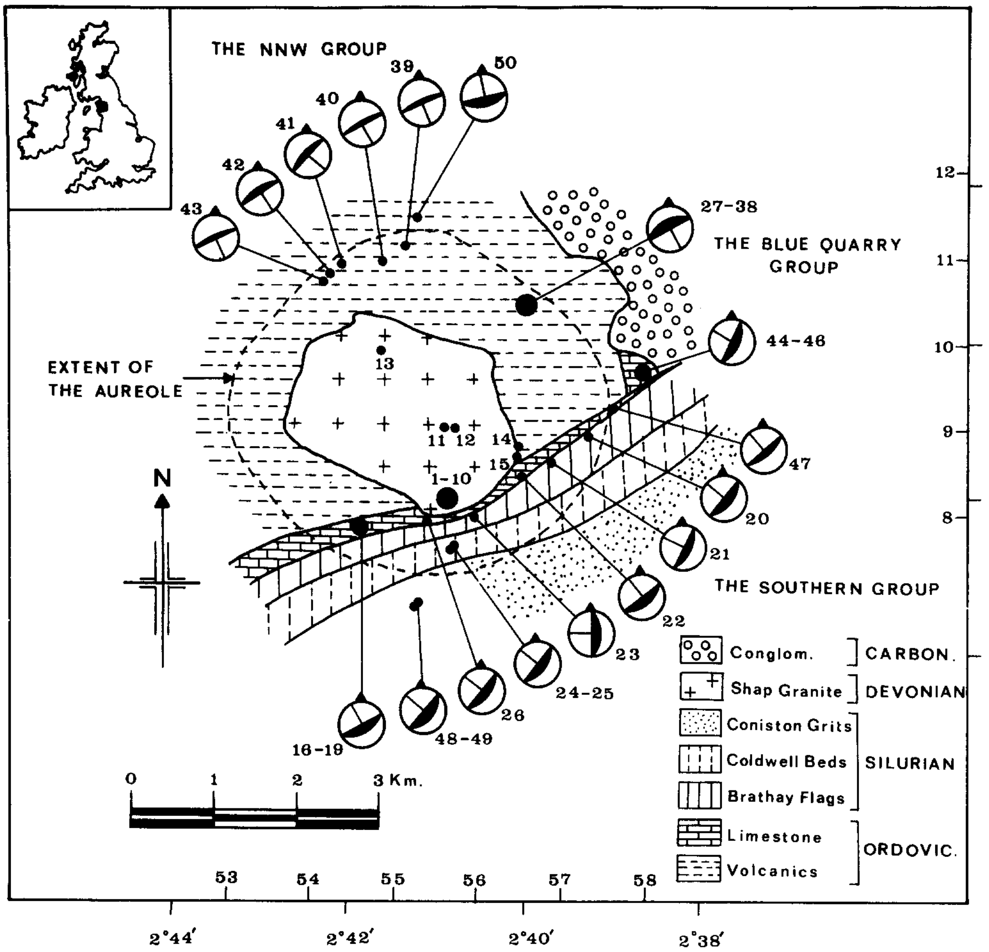

Fig. 1. A map of the Shap region studied, showing site locations and their magnetic fabric orientation data on lower-hemisphere equal angle stereographic projections. The magnetic foliation planes (planes containing maximum and intermediate susceptibility axes) and their corresponding azimuth declinations are shown schematically.

Geology and sampling

The Shap Granite crops out over 5 km^2 of moorland in the eastern Lake District, forming an irregular oval, having a longer diameter from east to west (Fig. 1). It is best exposed in large quarries on its southwestern slopes. The shape of the intrusion has been suggested by Locke & Brown (1978) to be a steep-sided cone with its central axis dispiaced about ½ km south of the outcrop centre. It is mainly a porphyritic adamellite (Grantham 1928), dated at 394 ± 3 Ma (Wadge *et al.* 1978), and thus belongs to the Devonian group of the Lake District granites. The Shap Granite is a composite intrusion with several stages of intrusion in which magmas became progressively more acidic (Grantham 1928).

The metamorphic aureole consists essentially of the Lower Ordovician Borrowdale Volcanic Group, lava types ranging from basic andesite to rhyolite and pyroclastic rocks, and the Coniston Limestone Group consisting of metamorphosed impure limestone and rhyolite and Silurian greywackes (Harker & Marr 1891, 1893, Marr 1916, Hollingworth 1955, Boulter & Soper 1973, Firman 1972, 1978). Near the granite contact temperatures were locally high enough to form sillimanite (Harker & Marr 1891, 1893).

The Lake District underwent Caledonian orogenesis during the late Ordovician and Silurian which imparted NE–SW striking structures in the region (Wood 1971, Soper & Numan, 1974). However, the observed growths of metamorphic minerals across the regional cleavage in the Shap aureole (Boulter & Soper 1973) suggest a late to post-Caledonian date for the intrusion of the granite.

Two hundred and eighty core samples from 50 sites were collected from the Shap Granite and the surrounding country rocks (Borrowdale Volcanic Group, the Coniston Limestone Group and the Silurian sediments) surrounding the intrusion. Thirty of these sites are located within the mapped borders of the thermal aureole (Fig. 1) and are treated as three sub-groups: the southern group, which contains sites from the metamorphosed sediments, the Blue Quarry group (sites 27–31) and the NNW-group (sites 39–43). The sampled sites were all in fresh, undisturbed exposures. Three to six separately oriented cores, 2.5 cm in diameter and about 8 cm long, were taken from each site (Tarling 1971). A single specimen, 2.15 cm high, was cut from each of the 280 cores for magnetic susceptibility anisotropy determinations on the Digico Complete Result Anisotropy Delineator (Rathore 1979, Rathore & Henry 1982). For reference, it should be noted that

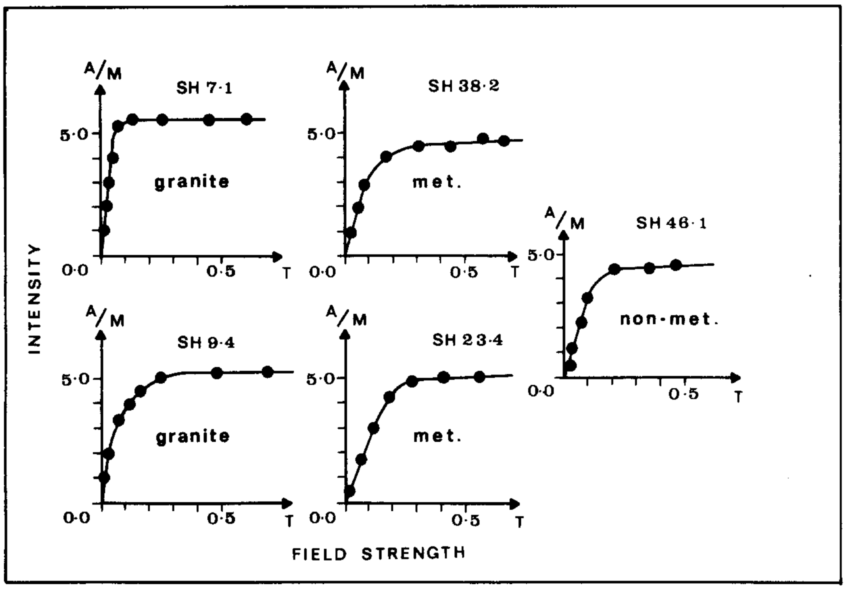

Fig. 2. Saturation magnetisation curves for five samples from the Shap suite show typically low field saturations indicating magnetite as the magnetic carrier.

the original calibration of the Digico had been incorrect (Veitch *et al.* 1983, Hrouda *et al.* 1983). The data presented here have been corrected for this error.

The magnetic fabric parameters and analyses

The magnetic mineral responsible for the magnetic fabric in the Shap rocks was identified as magnetite by plotting IRM (isothermal remanent magnetization) curves (Fig. 2). In all cases saturation magnetization is reached rapidly between 0.1 and 0.3 Tesla with a very steep initial slope indicating the presence of magnetite as the magnetic carrier. Cubic magnetite in elongated aggregates gives rise to shape effect anisotropy in the rock. This low field anisotropic susceptibility of a rock can be represented as an oriented ellipsoid with three mutually perpendicular axes: $\chi_{maximum}$, $\chi_{intermediate}$ and $\chi_{minimum}$ (Stacey 1960). In magnetic fabric analysis the magnitude and nature of the susceptibility ellipsoid is expressed in terms of the anisotropy parameters P_1, P_2, P_3 and E, where

$$P_1 = \frac{\chi_{max}}{\chi_{int}}; \quad \text{lineation } (L)$$

$$P_2 = \frac{\chi_{max}}{\chi_{min}}; \quad \text{anisotropy factor}$$

$$P_3 = \frac{\chi_{int}}{\chi_{min}}; \quad \text{foliation } (F).$$

The ratio $P_3/P_1 = E$, is the ellipticity of the susceptibility ellipsoid, thus if $E > 1$ the ellipsoid is oblate and the foliation is more developed than the lineation, and conversely if $E < 1$ the ellipsoid is prolate and the lineation is more developed than the foliation within the rock. The site-mean susceptibilities (defined as $\chi = \sqrt[3]{\chi_{max} \cdot \chi_{int} \cdot \chi_{min}}$) and the site-mean fabric parameters for the survey are given in Table 1. The form of the fabric ellipsoid is analysed with the aid of an ellipticity histogram (Fig. 3). Rose-diagram analysis of the susceptibility minimum axes is presented in Fig. 4, and the axial orientation data are plotted on lower hemisphere stereographic projections in Fig. 5. Note that due to the high density of points not all sites are included in the stereograms. The data presented gives a representative picture of the regional fabric orientations.

MAGNETIC FABRIC RESULTS

The Shap Granite and the contact metamorphic rocks

The samples from the Shap Granite sites (1–13) have a high site-mean susceptibility χ of approximately 710 × 10^{-6} (dimensionless S.I. units) for the whole group. The mean susceptibility in sites 11 and 12 is about 115 × 10^{-6}. The mean shapes of the susceptibility ellipsoids are mixed prolate and oblate, with a dominant tendency to oblateness (Fig. 3). The degree of anisotropy in all the granite and the contact metamorphic sites is low, with mean P_2 values of 1.07 in the granite and 1.03 in the granite contact (sites 14 and 15). The orientational data from this region is rather scattered both within and between sites although there is a well-defined fabric in each core. Due to this apparent randomness of the orientations of the fabric ellipsoids, the axial data have been omitted from the fabric map (Fig. 1) and in the stereogram plots (Fig. 5). Rose-diagram analyses have been carried out at the localities for all samples (Fig. 4f). The rose diagram of the susceptibility minimum axes indicates some degree of order both within and between the localities over the granite region. The shaded sections represent minimum axes of the magnetic susceptibility ellipsoids from the granite sites and unshaded sections represent the minimum axes of the contact

Table 1. Mean susceptibility and anisotropy parameters

Site no.	χ_{mean}	Mean P_1	Mean P_2	Mean P_3	E Mean
	Sites within the Shap Granite				
1	1115.2	1.035	1.069	1.033	.998
2	639.1	1.013	1.058	1.044	1.030
3	726.0	1.029	1.088	1.057	1.027
4	987.1	1.011	1.074	1.063	1.051
5	392.9	1.020	1.040	1.020	1.000
6	966.4	1.037	1.065	1.027	.990
7	771.2	1.063	1.099	1.034	.973
8	525.6	1.033	1.074	1.041	1.009
9	314.1	1.026	1.051	1.024	.998
10	569.3	1.049	1.086	1.035	.986
11	766.8	1.021	1.086	1.064	1.042
12	721.3	1.011	1.064	1.052	1.041
13	735.5	1.018	1.074	1.056	1.039
	Contact Hornfels Sites				
14	90.6	1.011	1.031	1.020	1.009
15	139.8	1.020	1.032	1.012	.993
	Metamorphosed Coniston Limestone Sites				
16	1.1	1.034	1.070	1.035	1.001
17	3.7	1.019	1.048	1.020	1.010
18	3.2	1.015	1.059	1.044	1.029
19	3.3	1.025	1.060	1.035	1.010
	Coniston Limestone—Shap Wells Hotel Group				
44	121.2	1.026	1.118	1.090	1.063
45	107.4	1.023	1.083	1.059	1.036
46	218.9	1.025	1.185	1.154	1.126
	Borrowdale Volcanics—Blue Quarry Group				
27	11796.0	1.129	1.253	1.110	.984
28	707.7	1.130	1.198	1.059	.939
29	141.6	1.187	1.242	1.047	.883
30	3334.8	1.078	1.108	1.027	.953
31	288.9	1.141	1.204	1.053	.924
32	2876.0	1.105	1.182	1.069	.968
33	1009.0	1.191	1.232	1.034	.871
34	48.9	1.023	1.037	1.014	.991
35	39.9	1.039	1.052	1.013	.975
36	1328.2	1.223	1.580	1.293	1.060
37	4944.7	1.166	1.233	1.059	.908
38	1.1	1.034	1.070	1.035	1.001
	Borrowdale Volcanics—NNW Group				
39	24.7	1.039	1.116	1.075	1.035
40	41.2	1.013	1.035	1.021	1.008
41	23.1	1.018	1.081	1.061	1.042
42	45.1	1.003	1.015	1.011	1.008
43	157.8	1.016	1.164	1.146	1.128
	Silurian sediments within the thermal aureole				
20	156.9	1.029	1.218	1.184	1.151
21	155.3	1.092	1.240	1.136	1.040
22	26.8	1.027	1.089	1.060	1.032
23	225.0	1.019	1.104	1.083	1.063
24	283.9	1.097	1.217	1.108	1.011
25	332.6	1.024	1.107	1.081	1.056
26	19.1	1.013	1.104	1.089	1.075
	Sites beyond the thermal aureole				
47	17.9	1.014	1.087	1.072	1.057
48	14.8	1.027	1.065	1.037	1.010
49	28.8	1.017	1.066	1.048	1.031
50	27.9	1.011	1.051	1.040	1.029

$\chi_{mean} = \sqrt[3]{\chi_{max} \cdot \chi_{int} \cdot \chi_{min}}$
$P_1 = \chi_{max}/\chi_{int}$
$P_2 = \chi_{max}/\chi_{min}$
$P_3 = \chi_{int}/\chi_{min}$
$E = P_3/P_1$

hornfels sites. In this multi-petalled rose there is a distinct maximum alignment of the axes in an approximate N–S direction indicating a regional influence on the minimum axes within the granite samples. If this influence is taken as a stress episode then the direction of the principal compressive stress is the same, i.e. dominantly N–S. The fabric directions of the contact hornfels indicate clearly the effect of the granite intrusion on these sites.

The thermally metamorphosed rocks

The metamorphic rocks in the southern group, within the thermal aureole, have relatively high magnetic susceptibilities. Furthermore, there is an increase in the susceptibility on approaching the granite from the aureole limits. In sites 20 and 21 the mean susceptibility is 155×10^{-6}, in sites 23, 24, 25 it is 275×10^{-6}. Sites 22 and 26 have much lower susceptibilities, around 23×10^{-6}, and the metamorphosed limestone sites (sites 16–19) have the lowest susceptibilities of all, 3×10^{-6} (Table 1). The susceptibility ellipsoid is oblate in all these sites and the degree of anisotropy is much higher than in the granite sites (Table 1). The P_2 parameter ranges from 1.06 to 1.18 with a mean value of 1.11. These parameter values indicate a well-developed magnetic fabric having subvertical foliation planes which strike approximately NE–SW with a steep dip to the SE (Figs. 1, 4d and 5b). This foliation strike is uniform except in site 23 in which the foliation planes are rotated to strike approximately N–S (Fig. 1). Sites 39–43 from localities to the N and NW of the Shap Granite have much weaker susceptibilities than those in the south: typically around 35×10^{-6}, with the exception of site 43 which has a susceptibility value of 157×10^{-6}. All ellipsoids in this region are weakly oblate with a mean ellipticity $E = 1.04$ (site 43 is exceptional with $E = 1.13$). The anisotropy factors are also low: typical P_2 values lie between 1.01 and 1.12 (site 48 has $P_2 = 1.16$). The trend of the subhorizontal minimum axes in sites 39, 40, 41, 42 and 43 is approximately NW–SE and the maximum and intermediate axes are scattered in the foliation planes striking approximately NE–SW. When these minimum axes directions are plotted in a rose diagram (Fig. 4c) they show that the strongest trend is the NW–SE direction.

The Shap Blue quarry area to the NE of the granite also lies within the metamorphic aureole, yet here the magnetic fabric is distinctly different from other thermally metamorphosed sites. Twelve sites (27–38) were collected from this quarry region. These sites have the strongest and the most widely variable susceptibilities, ranging from 1 to 11796×10^{-6}. These susceptibility changes are sometimes within a few meters. The very high susceptibilities encountered here are to be expected because of the existence of a magnetite vein in the quarry (R. J. Firman, private communications). There is a further anomaly in that only one site (site 36) has an oblate ellipsoid (E mean = 1.06, Table 1). The P_2

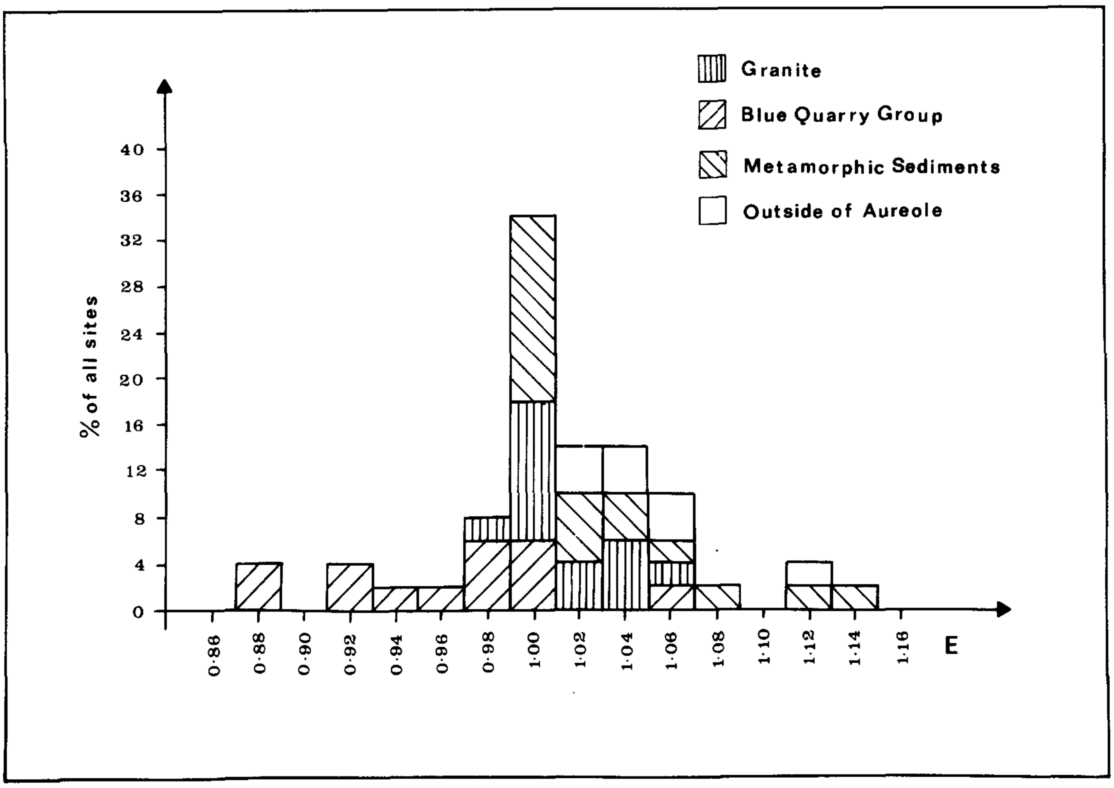

Fig. 3. Histogram of ellipticity values showing the variation of the ellipsoid shape over the region. $E < 1$ indicates prolateness and $E > 1$ indicates oblateness.

parameter in these rocks is also inhomogeneous ranging from 1.04 to 1.58 with a regional mean of 1.20. This region has the most strongly developed magnetic fabric in the whole study area. The lineations, without exception, are subvertical (Fig. 5c), but the minimum axes are diffusely grouped along a SE–NW direction (Fig. 4e). The only oblate site in this region (site 36) has low ellipticity ($E = 1.06$, $P_2 = 1.58$) and its steeply dipping foliation plane strikes approximately E–W, (Fig. 4e). Despite the oblateness in this site the best grouping within the axes is along the maximum susceptibility direction (subvertical) in agreement with the remaining sites from this region.

The unmetamorphosed country rock

Seven sites (44–50) were sampled from the Borrowdale Volcanics and the Coniston Limestones from outside the mapped thermal aureole (Fig. 1). In terms of susceptibility, these sites formed two groups: the one of the Coniston Limestone from the Shap Wells locality (sites 44, 45 and 46) has high susceptibilities with a mean value of 150×10^{-6}, and the other from the volcanic series has a mean value of 22×10^{-6}. Although all ellipsoids are oblate, the fabric development in the Shap Wells group of sites is the strongest (Table 1). The E and P_2 parameters in the limestone are higher than those in the volcanics by about 5% on average (in contrast to the metamorphic limestones). The orientation data show no distinction (Fig. 5d). The foliation planes strike approximately NE–SW and dip steeply to the SE (Fig. 1). The minimum axes align along a single direction approximately NW–SE (Fig. 4b). This fabric appears to be uniformly distributed to the S, E and N of the thermal aureole.

The regional magnetic fabric

There is a large variation of mean susceptibilities in the region. However, on removal of the two extreme groups, the Blue Quarry Borrowdale Volcanics and the Coniston Limestones, a definite trend emerges (Table 1). As is expected the magmatic granite has a high quantity of magnetite and correspondingly high susceptibilities, $\chi = 710 \times 10^{-6}$. Then in decreasing order come the metamorphosed sediments with $\chi = 171 \times 10^{-6}$, the contact hornfels with $\chi = 115 \times 10^{-6}$, the Borrowdale Volcanics to the north of the granite with $\chi = 58 \times 10^{-6}$ and finally the unmetamorphosed rocks other than the Coniston Limestone with $\chi = 22 \times 10^{-6}$. This susceptibility fall-off in the country rocks may possibly be linked with the radial thermal gradient whereby greater quantities of new magnetite were formed in the rocks nearer the contact than in those further away. It is possible that the original quantities of magnetite in the various rock types were not the same. The ellipticity spectrum (Fig. 3) indicates that 34% of all sampled sites have plane-strain ellipsoids (i.e. $0.99 \leq E \leq 1.01$, with $E \simeq 1.00$), 46% of the sites have dominant oblate ellipsoids ($E > 1.01$) and the remaining 20% of the sites have prolate

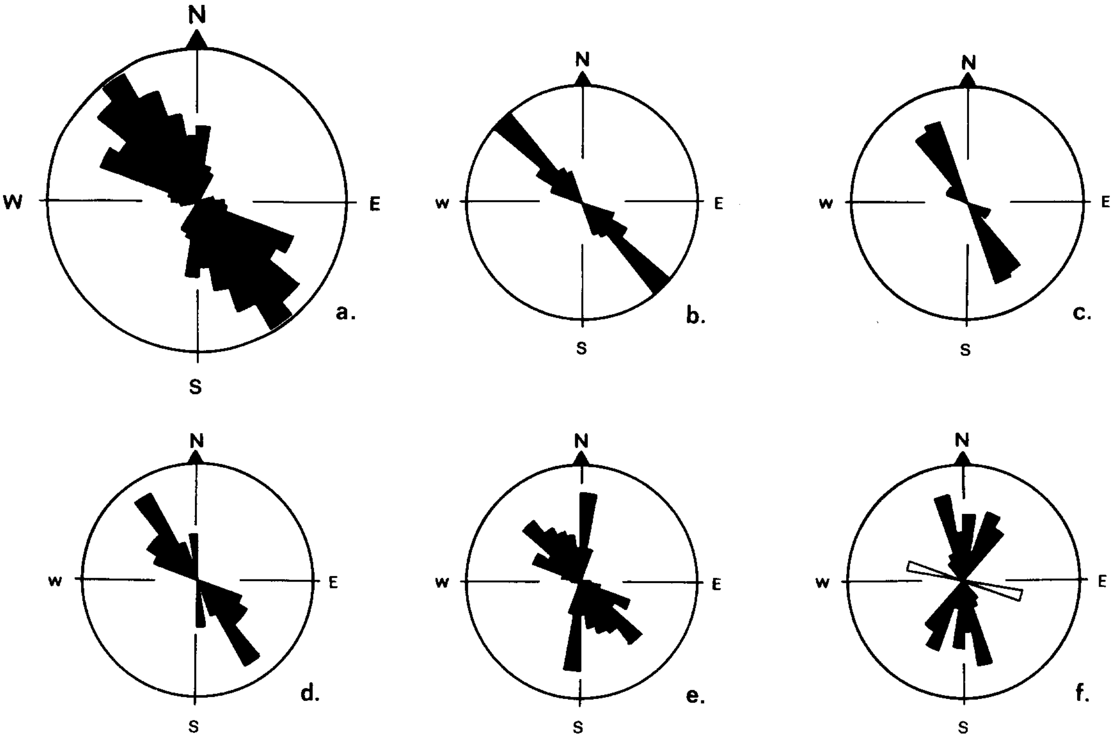

Fig. 4. Rose diagrams of the magnetic minimum axes declinations for (a) all sites, (b) non-metamorphosed sites, (c) Borrowdale volcanics to the north of the granite within the aureole, (d) metamorphosed sediments, (e) the Blue Quarry group and (f) sites from the Shap Granite. The unshaded directions in (f) are from the contact aureole hornfels.

ellipsoids ($E < 0.99$). These prolate sites are mainly from the Blue Quarry.

The regional orientation data for the susceptibility minimum axes are analysed in Fig. 4. The dominant trend for the short magnetic axes in all sites is N35°W (Fig. 4a) (i.e. perpendicular to the Caledonian strike direction), despite the fact that 86% of all sites lie within the metamorphic aureole. Sites from outside the aureole also show magnetic short-axes alignment along the N35°W direction (Fig. 4b). From within the metamorphic aureole, the Borrowdale Volcanics to the north of the granite show a slightly more dispersed direction around N30°W (Fig. 4c), whereas the metamorphosed sediments in the southern group still have the dominant short axes trends along N35°W (Fig. 4d). The dispersion of directions in the metamorphosed sediments is higher. In the Blue Quarry sites where the ellipsoids are dominantly prolate, the maximum axes group subvertically. The minimum axes have two main observable directions (Fig. 4e): a NW–SE direction (remanent of the Caledonian direction) and a strong N–S direction, with dispersion between the two directions. In the Shap Granite no trace of the NW–SE Caledonian direction is visible. There is a dispersion of minimum axes trends between NNW–SSE and NNE–SSW, indicating a mean regional N–S axial shortening over the granite (Fig. 4f). The two hornfels sites indicate axial shortening directions subnormal to the granite contact. These sites are the only sites with convincing fabric orientation changes.

INTERPRETATIONS

The Shap Granite and the contact metamorphic rocks

The magnetic susceptibility, which is a function of the quantity and the type of ferromagnetic mineral in a rock, is relatively high in the granite indicating the presence of magnetite. The fabric appears random in terms of the form of the ellipsoids and ordered in terms of their planar orientations, indicating that the magnetite is possibly present as minor inclusions within the large-sized host silicate matrix (Grantham 1928). Furthermore, since the degree of alignment reflects the degree of alignment of the host minerals, which in this case is low, it can be inferred that crystallization of the granite was a slow process in a low strain environment. The very low anisotropies and the ellipticities of the susceptibility ellipsoids are indications of the low strain environment within the Shap Granite. The Caledonian directions in the Lake District are known to be approximately NW–SE (Wood 1971, Soper & Numan 1974, Bell 1975, Rathore 1980a), yet no indication of this stress direction is found in the fabric ellipsoids (Fig. 4f). Boulter & Soper (1973) proposed that the mode of emplacement of the Shap Granite was by forceful intrusion during the waning stages of the Caledonian compressive phase, and that the intrusion was responsible for displacing the country rock in a ductile manner. However, they limit this deflection of the cleavage to the contact aureole, presumably to within a few metres of the granite contact

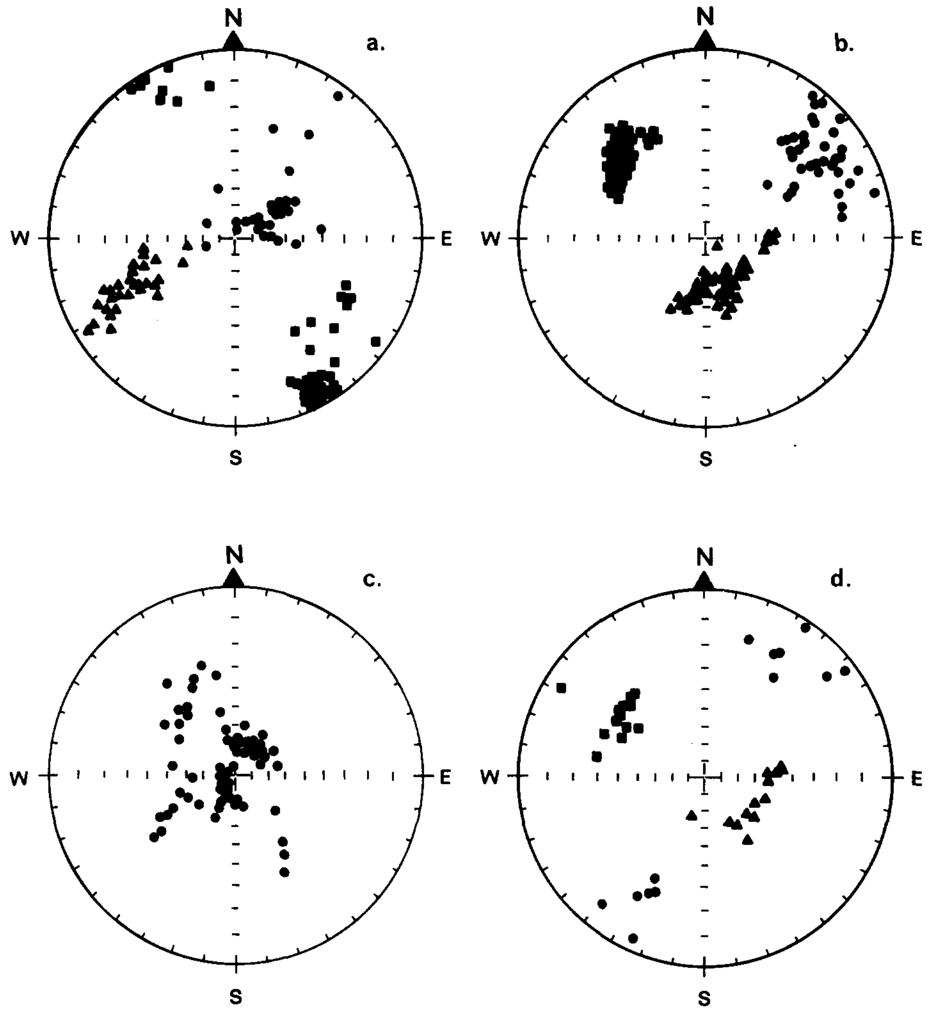

Fig. 5. Magnetic fabric axes: circles, $\chi_{maximum}$; triangles, $\chi_{intermediate}$ and squares, $\chi_{minimum}$, in lower-hemisphere equal-angle stereographic projections. (a) Sites from the NNW group, (b) sites from the southern group, (c) sites from the Blue Quarry group, (d) sites from the Shap Wells Hotel group.

(see fig. 1 of Boulter & Soper 1973). On the evidence of the magnetic fabric data, the strained zone due to the granite intrusion is small. There appears to be some evidence for very weak radial axial shortening within the marginal contact sites (Fig. 4f). Had there been a large degree of axial shortening due to a forceful intrusion, then the deflection of the Caledonian cleavage would be observed at greater distances within the metamorphic aureole (see for example Rathore 1980b, fig. 4). This seems not to be the case (Boulter & Soper 1973, fig. 1, and Fig. 1 here). In fact there are indications of a N–S axial shortening at the time of intrusion of the granite at the sites sampled (Fig. 4f).

The metamorphosed region

The susceptibility of these rocks is variable, indicating a spatially variable amount of magnetite. The quantity increases in some places near the granite which indicates that the thermal effect of the intrusion may have created new magnetite. This effect was not widespread and the response of the matrix minerals to heat in producing extra magnetite is not observed in the NW group of sites. This could be related to the relative position of the granite central axis with respect to the sampled localities (Locke & Brown 1978). The nature of the fabric ellipsoids, with the exception of the Blue Quarry group, indicates a regional Caledonian fabric (Figs. 4c & d). These fabric directions seem little disturbed by the granite intrusion. The new magnetite, which may have been produced in response to the heating within the aureole, has presumably acquired a mimetic fabric of the pre-existing deformed matrix (textural anisotropy, Heller 1973) and the magnetic mineral growths are thus within the Caledonian tectonic foliations. The implications of this pre-existing fabric not being overprinted and the granite itself not being strongly foliated are that the magmatic intrusion had very low straining effects upon the country rock and was itself not influenced by the Caledonian deformations. The intrusion was more than probably in the form of a warm plastic mass rather than a cold solidified mass (Rathore 1980b). Furthermore, this intrusion could have been during a period of relaxation after the Caledonian compression phase such that there was very little mutual straining between the granite and the country rock.

The anomalous fabrics of the Blue Quarry sites can be interpreted with the help of the N–S axial shortening directions observed in the granite (Fig. 4f). If such subhorizontal N–S axial shortening stresses were to act on a suite of rocks having the Caledonian fabric (subvertical foliations striking approximately NE–SW with subvertical magnetic lineations), then, according to Graham's model of fabric overprinting (Graham 1966), it would be expected to find composite prolate ellipsoids with vertical lineations (see also Kligfield *et al.* 1981). The fanning out of the minimum axes between NW and N, as observed in Fig. 4(e), and the subvertical lineations observed in these sites, support this fabric overprinting hypothesis. The cause of this N–S axial shortening is unknown; however it appears to be well substantiated by the magnetic fabric data.

The unmetamorphosed country rocks

The mean susceptibilities of the sites sampled outside the thermal aureole are low. These relatively low susceptibilities outside the aureole and the higher susceptibilities inside the aureole are in agreement with the hypothesis that the heating of the country rocks within the aureole increased their magnetite content. The fabric ellipsoids in all these sites unanimously reflect the Caledonian trends (Fig. 4b). There is no effect of the granite on this fabric. It can be concluded, then, that the effect of the granite intrusion was mainly a static, thermal metamorphism confined to about a kilometre from the granite contact. There appears to be no influence of the granite intrusion on this fabric.

CONCLUSIONS

The magnetic fabric of the Shap Pluton indicates that the mode of emplacement of the granite was by magma flow with subsequent cooling and crystallization with very weak N–S axial shortening. There are no indications of the Caledonian directions which confirm that the granite post-dates the Caledonian Orogeny. The effect of the granite on the country rock is thermal metamorphism over a short distance from the contact. Some heat-induced metasomatic processes resulting in the production of extra magnetite must have occurred and this is responsible for the strong magnetic susceptibilities of the rocks within the thermal aureole. The nature of the fabric ellipsoids in the country rock, except for the Blue Quarry region, indicates a regional Caledonian trend which has not been disturbed by the intrusion of the granite. The weak N–S axial shortening observed in the granite sites is supported by the fabric ellipsoids of the Blue Quarry region. However, in the majority of sites within and all sites outside the thermal aureole, there is no disturbance of the Caledonian fabric, indicating that the granite intrusion was post-Caledonian, causing very little mechanical fabric overprinting.

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