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Comparison of strain and magnetic fabrics in Dalradian rocks from the southwest Highlands of Scotland

JASWANT SINGH RATHORE*

Department of Geophysics and Planetary Physics, School of Physics, The University, Newcastle upon Tyne, U.K.

and

BERNARD HENRY

Laboratoire de tectonophysique et Laboratoire de géomagnetisme, Université P. et M. Curie, 4 Place Jusieu, 75230 Paris Cedex 05, France

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Abstract—The magnetic fabrics of 235 samples from 31 localities in Argyllshire, Scotland were determined to study the development of the Caledonian tectonic fabric in the southwest Highlands of Scotland. The regional fabric indicates a strong NE–SW compressional foliation due to the primary deformational phases, which in parts has been overprinted by secondary deformations. A detailed comparison of the anisotropy data and the available strain data shows that the two fabric ellipsoids are co-axial, and that their axial mean ratios seem to be related by an empirical power relationship of the type:

$$\left(\frac{\chi_i}{\chi_j}\right) = \left(\frac{l_i}{l_j}\right)^a$$

(for $i = 1, 2, 3$; $j = 1, 2, 3$ and $i \neq j$) where χ_i and χ_j are orthogonal principal axes and l_i and l_j are the corresponding orthogonal principal strain axes. The exponent a for the sites from Scotland is 0.088 ± 0.017 compared with 0.142 ± 0.001 and 0.145 ± 0.005 found in the Caledonian slates of the English Lake District and the Welsh slate belt.

INTRODUCTION

MAGNETIC and petrofabric comparisons in slates from the Cambrian slate belt of North Wales and the English Lake District (both regions have undergone Caledonian deformation) have shown that the total strain ellipsoids are closely reflected by the magnetic susceptibility anisotropy ellipsoids (Rathore 1979, 1980). The orientations of the corresponding principal axes within the two ellipsoids are found to be parallel and the axial ratios of the two ellipsoids within the same rock are empirically related by a power-law of the type:

$$\left(\frac{\chi_i}{\chi_j}\right) = \left(\frac{l_i}{l_j}\right)^a \qquad (1)$$

(for $i = 1, 2, 3$; $j = 1, 2, 3$ and $i \neq j$), where χ_i and χ_j are orthogonal principal magnetic axes and l_i and l_j are the corresponding orthogonal principal strain axes. The exponent a is the correlation exponent, and in the Welsh and the Lake District slates, it was found to be remarkably similar (0.145 ± 0.005 and 0.142 ± 0.001, respectively). The question arises as to the universal validity of the relationship (1) since it is most desirable to establish an independent method of predicting strain in rocks where no strain markers are present. Before such claims can be made, however, it is necessary to accumulate further evidence in lithologies where strain data are available. In the context of tectonic history, a most suitable region for study is the Dalradian sequence of Argyllshire in the southwest Highlands of Scotland since this region also has undergone Caledonian deformation. The aims of this study were:

(i) to conduct a detailed magnetic fabric to strain orientation correlation;

(ii) to determine the regional deformation pattern of the region using magnetic fabrics;

(iii) to test for the power-law relationship between the anisotropy and the strain axial ratios and

(iv) to test the consistency of the magnetic fabric results from two susceptibility instruments of the same type.

GEOLOGY OF THE STUDY REGION AND SAMPLING

The Dalradian rocks form a thick sequence of sediments from Late Precambrian to possibly Lower Ordovician (Downie *et al.* 1971). Their deposition was occasionally accompanied by volcanic activity or by the intrusion of dolerite dykes and sills. The lower Dalradian

* Now at The Norwegian Institute of Technology, Division of Petroleum Engineering and Applied Geophysics, NTH-7034 Trondheim, Norway.

was deposited on a tectonically stable continental shelf, on which differential subsidence accounts for lateral thickness and facies variations (Borradaile 1979a). Later sediments were deposited in a deep water sedimentary trough (Harris & Pitcher 1975, Roberts & Treagus 1977), and are commonly dominated by turbidite sands and muds. Syndepositional faults probably had a major effect on these sedimentation conditions (Anderton 1979). Hence, the Dalradian series is a lithologically diverse sequence of shales, limestones, dolomites, sandstones and conglomerates with some volcanic horizons and doleritic intrusions. This series of rocks was deformed during the Caledonian orogeny, probably at an early stage in the orogeny, at the end of the Cambrian to the beginning of Ordovician times. In Argyllshire, they have a regional 'mushroom'-like structure (Bailey 1922, Rast 1963), similar to the Briançonnaise zone in the Alps. Johnson *et al.* (1979), moreover, suggest a plate tectonic interpretation of the Scottish Highlands as a metamorphic Alpine-type orogen, dating from the Caledonian orogeny, and undergoing uplift during Orodovician and later times.

The deformations in the Dalradian rocks can be separated into four main periods, and in parts of the SW Highlands there may be eight phases of folding developed locally (Roberts 1974). The polyphase character was demonstrated by Clough, using cleavage analysis, as far back as 1897. The first period of deformation was responsible for the major folding. Main structures such as the Islay anticline, the Loch Awe syncline and the Tay nappe (Ardrishaig–Aberfoyle anticline) were formed during this period. Strain in the Dalradian rocks is clearly related to the slaty cleavage and stretching lineation from this first period (Borradaile 1979b, fig. 1). This mineral lineation is seen in the phyllitic minerals and is often overgrown by mimetic pyrite or fibrous quartz. The lineation is often at high angles to the major fold axes but varies throughout the region. Minor fold axes are often rotated towards sub-parallelism with the lineation (Borradaile 1972). Roberts & Sanderson (1974) used these fold axes' rotations for strain measurements. However, they assumed plane strain ($Y = 1$) and thereby estimated an X/Y ratio. Full three-dimensional strain determinations in the region have been performed on deformed vesicles or pebbles (Borradaile 1973) and on breccia fragments (Roberts & Sanderson 1974).

In Argyllshire, metamorphism during the Caledonian orogeny corresponds to the Barrovian zones (Barrow 1912) from chlorite to garnet with a temperature range from 300 to 550°C with limited oxidation (Atherton 1977), and to a depth in the order of 10–20 km.

Figure 1 shows the major fold axial traces in the studied area. The main folds of the primary deformation are, from NW to SE, the Loch Awe syncline (zone VI, in which the Tayvallich and Kilmory Bay synclines can be distinguished), the Ardrishaig anticline (separating zones V and IV) and the Aberfoyle anticline (separating zones II and I). In fact, the Ardrishaig and Aberfoyle anticlines are the same large fold which forms the Tay nappe. Erosion has removed the central part of the nappe and only the root zone (Knapdale Steep zone) is now exposed. This zone between the Ardrishaig and Aberfoyle anticlines is affected by two folds formed during the secondary deformation: the Tarbert monoform (separating zones IV and III) and the Ben Ledi monoform (separating zones III and II). These fold axes only give an indication of limits of structures. The division of the study area into zones I to VII with these fold axes was made purely to compare the magnetic fabrics within the zones. A total of 203 oriented cores (Tarling 1971) of 2.5 cm diameter and *c.* 8 cm length were collected from 31 localities of various rock types (Table 1) from within the 7 described zones (Fig. 1). From these cores, 235 samples of 2.2 cm length were derived for the study of the magnetic fabric.

THE MAGNETIC FABRIC

The intensity of magnetisation (J) produced in a substance is linearly proportional to the intensity of an applied magnetic field (H), provided this applied field is weak (i.e. less than 100 Oe). The intrinsic magnetic susceptibility $\chi = J/H$, which is a second-rank tensor, can be represented as an ellipsoid of three orthogonal principal axes $\chi_{maximum}$, $\chi_{intermediate}$ and $\chi_{minimum}$. The magnitudes of these three axes, together with their orientations with respect to a fiducial mark on a rock sample, constitute the magnetic fabric of the rock. Anisotropy of the magnetic susceptibility in rocks can arise due to one or both of two effects. 'Shape effect' anisotropy can arise due either to the alignment of elongate primary magnetite grains during deformation of the rock, or to anisotropic growth of secondary magnetite within a deformed non-magnetic matrix. Low susceptibility, low crystalline symmetry minerals, such as hematite and pyrrhotite, tend to align their crystalline axes to give a 'magneto-crystalline' anisotropy.

Curie point determinations on the samples investigated here indicated that the probable primary carrier of the fabric was either pyrrhotite or a mixture of pyrrhotite and magnetite (Fig. 2). In sample AS86 (Fig. 2a) the magnetic intensity falls steadily with increase in temperature and the Curie point is reached at around 375°C. The cooling curve shows the buildup of a ferromagnetic component starting around 400°C. In sample AS243 (Fig. 2b), a similar heating curve is obtained whereby a Curie point is reached around 360°C. On further heating the magnetisation begins to increase around 500°C. This was believed to be the onset of the production of magnetite and hence cooling was commenced immediately so that the cooling curve of the initial magnetic fraction could be observed. On the cooling curve, the magnetite gains paramagnetic component and at *c.* 320°C, there is a second increase in the intensity representing the original magnetic fraction passing its Curie point. In sample AS194 (Fig. 2c), similar de-magnetising curve is observed, only this time oxidation is allowed to continue, and the consequent magnetite produced goes through the Curie point at *c.* 580°C. The cooling curve again shows an increase in magnetisation starting at around 400°C. In samples AS133, AS96 and

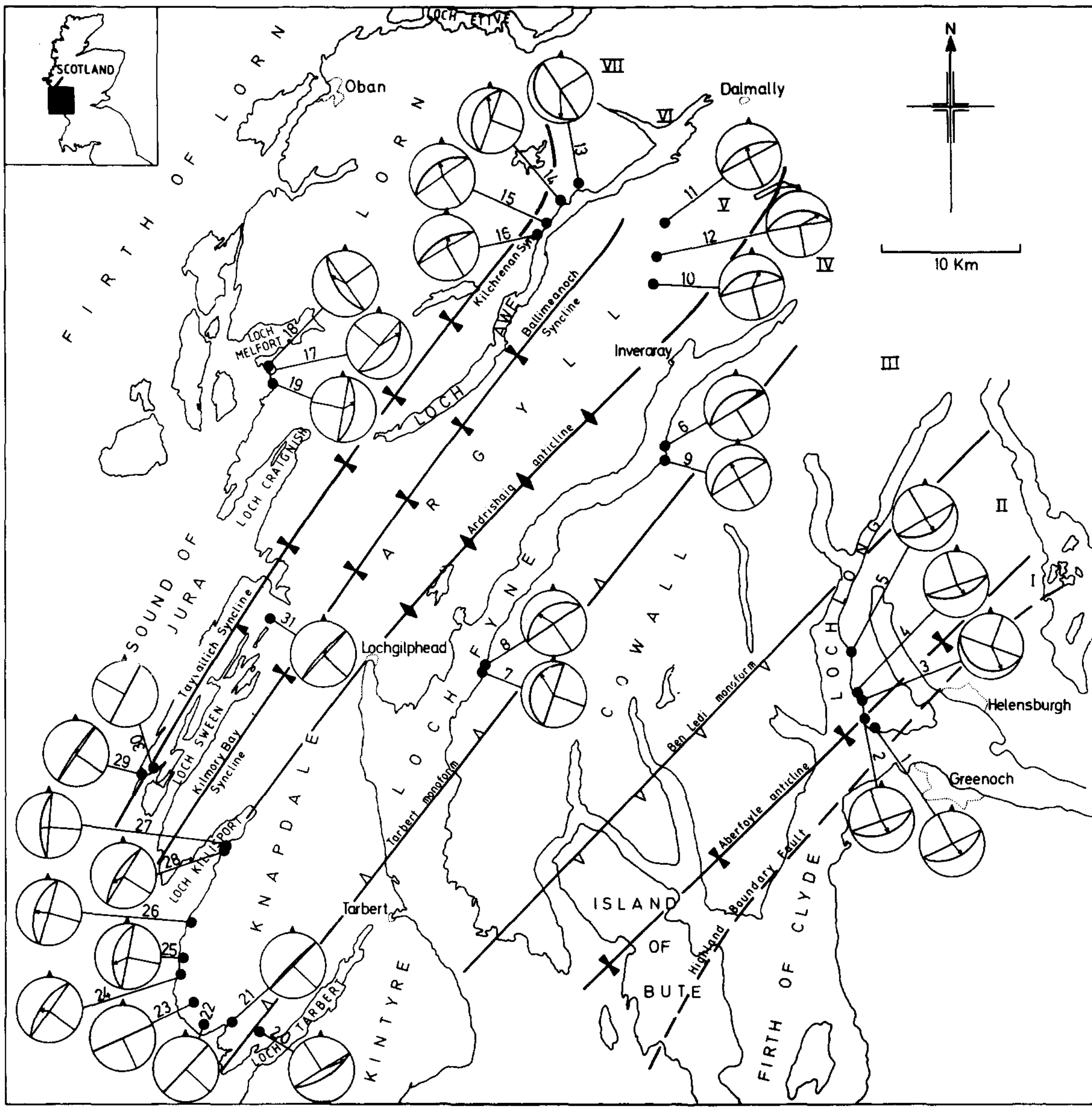

Fig. 1. A map of the study region, showing the site locations and their magnetic fabric orientation data on lower-hemisphere equal angle stereographic projections. The magnetic foliation planes (planes containing maximum and intermediate susceptibility axes) and the corresponding azimuth declinations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

AS293 (Figs. 2d–f), it is evident that the magnetic fractions are mixed with a distinct dominance of probably magnetite, Curie point *c.* 580°C. The other magnetic fraction once again has Curie points around 350–400°C. This mineral is believed to be pyrrhotite despite the Curie points being slightly higher than those commonly reported for pyrrhotite *c.* 320°C. The phyllitic minerals overgrown by mimetic pyrite suggest that the rocks were metamorphosed in a reducing milieu, and thus it would be expected to find pyrrhotite as a magnetic constituent which, when heated in air, oxidises to magnetite.

Pyrrhotite is a pseudo-hexagonal platy mineral having the magnetically hard axis parallel to the *c*-axis. Pyrrhotite platelets are believed to undergo passive rotations to align parallel to the prevailing cleavages, thus maximum/intermediate susceptibility axis planes will parallel the cleavage planes and the minimum susceptibility axis will be aligned in the direction of maximum shortening in the rock. Rocks containing magnetite or a mixture of magnetic and pyrrhotite will have a shape effect dominant magnetic fabric, and the long axes of magnetite align the long axes of the fabric elements and the minimum axes the direction of rotational compression.

MEASUREMENT AND ANALYSIS

The magnetic fabrics of the 235 samples were determined on two separate units of the modified computer-linked slow spinner magnetometer (Molyneux 1971), described as the Complete Result Anisotropy Delineator, CRAD (Rathore 1975). The purpose of measuring on two separate units was to test the consistency of the magnetic fabric results from two machines working on the same

Table 1. Site mean magnetic fabric parameters

Site No.	Max axis Dec°	Max axis Inc°	Min axis Dec°	Min axis Inc°	Mean P_1	Mean P_2	Mean P_3	Mean E	f
AS 1–S	141.9	38.6	154.7	−50.6	1.1228	1.1564	1.0298	0.9174	0.80
AS 2–S	327.6	−34.1	160.8	−54.9	1.1405	1.2683	1.1118	0.9751	0.60
AS 3–GS	333.2	−12.0	201.0	−72.9	1.0651	1.4045	1.3186	1.2380	0.33
AS 4–GS	318.8	−43.2	162.8	−45.2	1.0942	1.4138	1.2921	1.1810	0.29
AS 5–S	322.3	−52.1	329.5	38.2	1.0966	1.5169	1.3834	1.2616	0.26
AS 6–S	56.3	0.5	329.6	−47.4	1.0514	1.2645	1.2038	1.1475	0.16
AS 7–S	150.7	−13.8	289.3	−72.9	1.0301	1.6098	1.5629	1.5176	0.08
AS 8–Q	123.2	−31.6	326.4	−56.2	1.3540	6.3090	4.5161	3.2758	0.34
AS 9–GS	154.1	−37.7	329.0	−52.3	1.1710	2.4097	2.0608	1.7661	0.22
AS 10–S	204.5	−32.1	344.7	−50.9	1.0165	1.3710	1.3488	1.3270	0.06
AS 11–GS	168.0	−54.4	152.2	34.6	1.0183	1.1025	1.0825	1.0631	0.08
AS 12–GS	62.1	15.7	350.9	−47.0	1.0088	1.0444	1.0354	1.0264	0.17
AS 13–GS	1.1	−9.1	238.3	−73.2	1.0252	1.1419	1.1138	1.0865	0.20
AS 14–GS	357.9	12.8	290.2	−59.2	1.0410	1.3884	1.3336	1.2811	0.14
AS 15–GS	175.5	−45.6	325.8	−41.7	1.0217	1.2264	1.2003	1.1748	0.11
AS 16–Q	7.5	56.2	330.9	−27.7	1.0513	1.2122	1.1530	1.0967	0.28
AS 17–Q	58.2	14.4	310.3	50.3	1.0388	1.1649	1.1214	1.0795	0.26
AS 18–V	120.0	−33.1	235.6	−33.5	1.0914	1.1505	1.0541	0.9659	0.63
AS 19–GS	242.5	−44.4	101.7	−38.4	1.0557	1.2636	1.1970	1.1339	0.26
AS 20–Q	64.7	12.3	148.2	−31.4	1.0396	1.1077	1.0659	1.0268	0.50
AS 21–Q	357.7	81.9	314.1	−3.9	1.0450	1.8875	1.8049	1.7280	0.10
AS 22–GS	213.9	−70.6	312.8	−0.9	1.0587	1.1564	1.0923	1.0320	0.42
AS 23–S	248.7	45.1	335.9	−2.8	1.0359	1.3317	1.2854	1.2408	0.14
AS 24–GS	99.2	−53.6	305.9	−33.2	1.2118	1.5752	1.2992	1.0721	0.48
AS 25–S	247.1	35.1	281.1	−48.6	1.0164	1.4960	1.4717	1.4479	0.06
AS 26–Q	95.9	−40.2	287.1	−47.7	1.3585	2.0306	1.4879	1.1298	0.48
AS 27–GS	84.4	−61.3	276.4	−28.9	1.1295	1.3958	1.2364	1.0955	0.41
AS 28–S	61.3	−51.3	121.9	21.5	1.0635	1.2624	1.1870	1.1162	0.29
AS 29–VB	12.3	−68.7	306.0	9.2	1.1493	1.4002	1.2187	1.0615	0.44
AS 30–VB	209.1	69.4	119.9	−0.5	1.0748	1.4082	1.3103	1.2193	0.24
AS 31–Q	25.0	53.1	312.5	−12.4	1.0560	1.2989	1.2297	1.1645	0.23

Lithology: Q = quartzite; GS = green schists; S = schists and phyllite; V = volcanic and VB = volcanic breccia.

principle. Such a comparison has not been carried out before and is of major importance when it comes to comparing fabric results from researchers from different laboratories.

In magnetic fabric analysis, it is not practical to use the absolute magnitudes of the susceptibility ellipsoidal axes, since they are dependent upon magnetic mineral concentrations within the sample. However, assuming a small concentration variation over a volume of, say, a half-metre cube, but uniform deformation, the ratios of the axes from sample to sample remain the same. Thus the magnitude and nature of the susceptibility ellipsoid is expressed in terms of the axial ratios P_1, P_2 and P_3 defined as:

$$P_1 = \frac{\chi_{max}}{\chi_{int}}, \quad \text{lineation factor}$$

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

$$P_3 = \frac{\chi_{int}}{\chi_{min}}, \quad \text{foliation factor.}$$

The ratio $P_3/P_1 = E$, the ellipticity of the susceptibility ellipsoid; thus if $E < 1$ the ellipsoid is prolate with a dominant lineation and if $E > 1$ it is oblate with a dominant foliation. A second ellipsoid form parameter, f, is defined as

$$f = \frac{\chi_{max} - \chi_{int}}{\chi_{max} - \chi_{min}},$$

such that if $0 < f < 0.5$ the ellipsoid is oblate, flattening and if $0.5 < f < 1.0$ the ellipsoid is prolate, constrictional. In general, the deviations from the site mean values are found to be less than 5% of the means and hence the site mean anisotropy parameters are given in Table 1. The site mean orientations of the maximum and minimum susceptibility axes (having $\alpha_{95} < 10°$ for one of the two axes in all cases and often for both) are also given in Table 1. These site mean fabrics are plotted in Fig. 1 to give a picture of the fabric variation over the study region. The anisotropy parameters are plotted in Flinn-type plots (Fig. 3) to study the variation in ellipsoid shape over the region, and in a profile across the region going NW–SE (Fig. 4) to give an indication of the degree of deformation within the subareas of the study region.

MAGNETIC FABRIC RESULTS

The study area has been split into seven zones (I–VII, Fig. 1) and for convenience the fabric results are presented in terms of these zones. The actual comparison of the magnetic and petrofabrics will follow in the next section.

Zone I. Sites 1 and 2 were sampled between the

Highland Boundary Fault and the Aberfoyle anticline (Fig. 1). The magnetic foliation plane strikes approximately ENE–WSW, sub-parallel to the adjacent structures, and the lineations strike approximately SSE (Fig. 6b). The zone mean anisotropy parameter $P_2 = 0.21$, the ellipticity $E = 0.95$ and the form parameter $f = 0.70$. This is the only zone where the magnetic ellipsoid is prolate with a well-developed lineation. This prolateness is believed to have primary deformation origin, but may have been enhanced by the secondary effect of the Highland Boundary Fault whereby the superposition of two subnormal compressions has led to the production of a prolate ellipsoid—a concept discussed by Graham (1966).

Zone II. Sites 3, 4 and 5 were sampled between the Aberfoyle anticline and the Ben Ledi monoform. The zone mean fabric parameters are much higher than in Zone I: $P_2 = 1.44$, $E = 1.23$ and $f = 0.29$. The fabric is strongly oblate but the orientations of the axes are similar to those in Zone I (Fig. 6d).

Zone III. There is, in fact, only one sampled locality in Zone III, i.e. AS20. This locality is very near the Tarbert monoform and its primary deformation fabric has been overprinted by the secondary phase of folding. This is clearly seen in the fabric orientations of the two ellipsoids (Fig. 8). In the strain ellipsoid, the fabric shows the fold axis lineations in a *c.* NE–SW direction with the cleavage poles in the NW quadrant. The magnetic maximum axes group subhorizontally along N60°E and the minimum axes group around 330°/30°. The anisotropy degree is weak in this site with samples plotting on the plane strain line: $P_2 = 1.07$, $E = 1.03$ and $f = 0.5$.

Zone IV. Two groups of localities were collected in Zone IV: one along the shoreline around Knapdale from Ardpatrick Point to Ballyaurgan (Fig. 1, sites AS21–AS28), and the other group along the SW shore of Loch Fyne (sites AS6–AS9). The fabric parameters of the Loch Fyne group are much higher than those of Knapdale. The mean parameters are $P_2 = 3.08$, $E = 2.01$ and $f = 0.20$ along Loch Fyne compared with $P_2 = 1.56$, $E = 1.26$ and $f = 0.41$ from Knapdale. This suggests that although the fabric is compressional and oblate in the whole of Zone IV, there is a gradation in intensity upwards going from the coast to NE inland. The orientation directions for the two groups show a general

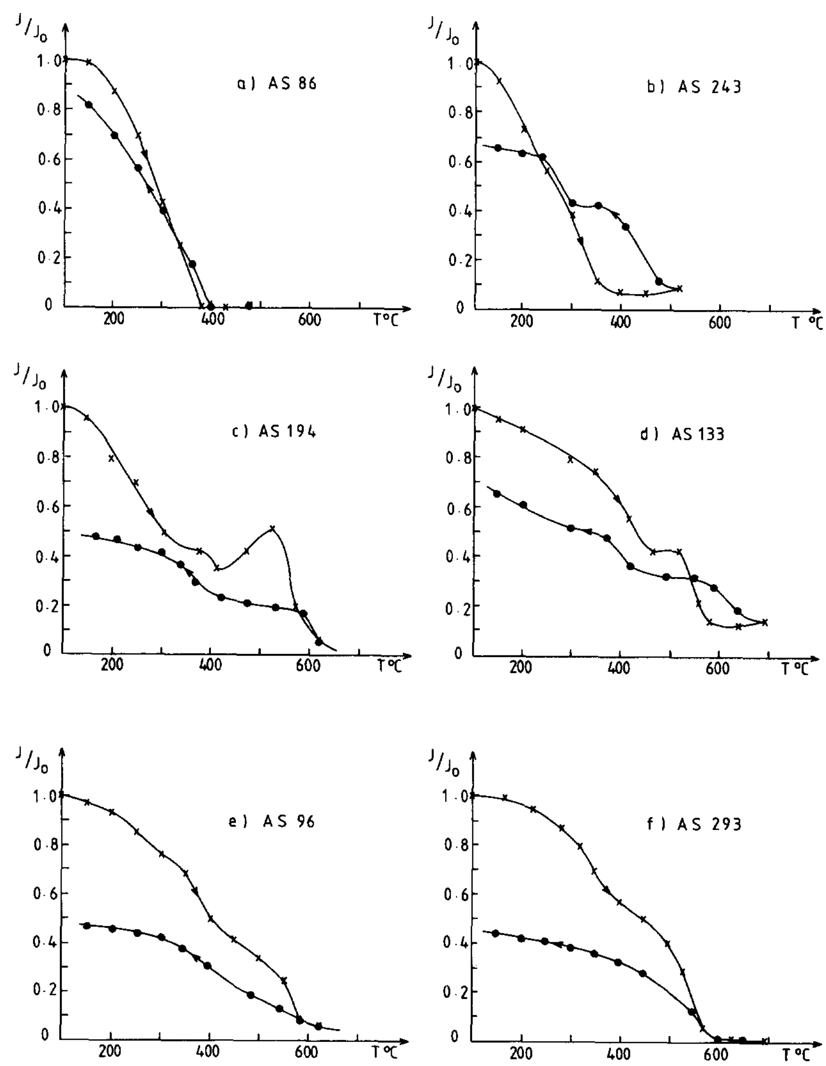

Fig. 2. Curie point determination curves for six randomly chosen samples. Normalised magnetic intensities (J/J_0) are plotted against temperature (T°C).

grouping of minimum declinations along a NW–SE direction. The lineations of this group are completely removed from those of site AS20 in Zone III (Figs. 6 and 7) and the tectonic implications for the differences between the fabrics of Zones III and IV are discussed later.

Zone V. Three localities were sampled on the road going north from Inverary to Dalmally. These sites lie in Zone V between the Ardrishaig anticline and the Ballimeanoch (Kilmory Bay) syncline. The magnetic fabric is a well-developed flat shaped ellipsoid, having zone mean $P_2 = 1.15$, $E = 1.16$ and $f = 0.10$. The magnetic foliation strikes *c.* ENE–WSW and dips to the NNW at about 40° (Fig. 7a).

Zone VI. Zone VI covers the Loch Awe syncline, between the Kilmory Bay syncline and the Tayvallich syncline. Again, two groups of localities were sampled in this zone, sites AS29–AS31 from the Loch Sween region, and sites AS13–AS16 from the NW coast of Loch Awe. Within these two groups, the higher anisotropy parameters are found on Loch Sween and the Sound of Jura coast, and the lower ones inland. The parameters are $P_2 = 1.36$, $E = 1.56$, $f = 0.30$, and $P_2 = 1.23$, $E = 1.16$ and $f = 0.18$, respectively. The fabric ellipsoids have well-developed foliation planes and their orientations, with the exception of locality 13, show a strike direction of the foliation planes *c.* NE–SW and the minimum axes trend NW–SE.

Zone VII. Three localities were sampled to the NW of the Loch Awe syncline near Loch Melfort. Site AS18 was drilled in a pillow of a pillow-lava and hence its fabric was found to be different to that of the other two sites. Furthermore, site AS18 was found to be weakly prolate, $P_2 = 1.15$, $E = 0.97$ and $f = 0.63$, compared with the oblate fabric of sites AS17 and AS19, $P_2 = 1.23$, $E = 1.10$ and $f = 0.26$. The orientations of AS17 and AS19 show a strike direction of the foliation plane *c.* ENE–WSW, dipping to the SSE (Fig. 7f).

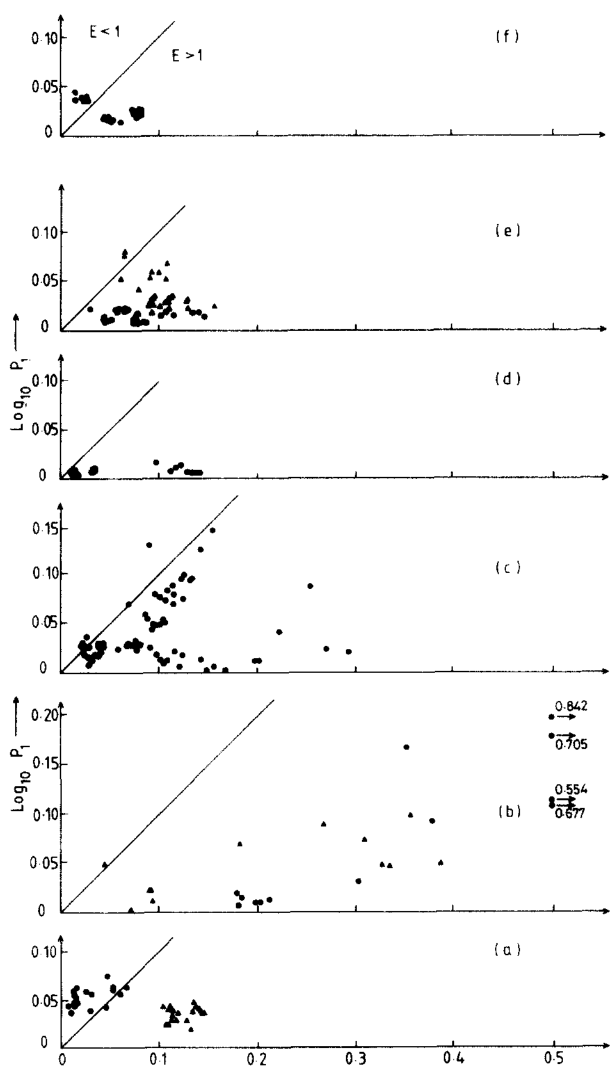

Fig. 3. Log P_3 vs log P_1 plots (Flinn-type diagrams) to study the variation of the ellipsoid shape over the region. $E < 1$ indicates prolateness and $E > 1$ oblateness. A Flinn diagram is one of log X/Y vs log Y/Z used in strain analysis to determine ellipticity of a strain ellipsoid. (a): zone I (●), zone II (▲) (b): zone IV—AS6–AS9, (c): zone IV—AS21–AS28, (d): zone V, (e): zone VI and (f): zone VII.

In Fig. 3, the ellipticity plots indicate a general increase of the degree of oblateness, going from Zones I (Fig. 3a, ●) and II (Fig. 3a, ▲) to Zone IV (Figs. 3b & c). In Zones V, VI and VII, the fabrics, although oblate, have lower ellipticities (Figs. 3d–f). In Zone VII, the pillow lava site, AS18, shows dominant lineation (Fig. 3f).

The data presented in Fig. 4 show the variations in the anisotropy parameters along a profile across the study region going from NW to SE. In all parameters, there appears a culmination around the central zone of maximum metamorphism near the Tarbert monoform. There is a slight but definite decrease of the parameters towards the end of the profile near the Highland Boundary Fault. These data support Roberts & Sanderson's (1974) contention that strain increases towards the SE from the NW end of the profile; however, there is a decrease in the anisotropy parameters near the Aberfoyle anticline. Nevertheless, a decrease in strain is suggested towards the Highland Boundary Fault. This decrease can be interpreted as either a decrease of strain intensity of the first major folding, or as a perturbation of the anisotropy during the secondary deformation phases.

ORIENTATION COMPARISONS OF THE MAGNETIC AND PETROFABRIC ELLIPSOIDS AND GENERAL IMPLICATIONS

Orientation correlations of the maximum and minimum susceptibility axes, with the stretching directions and the poles to slaty cleavages, are generally very good (Figs. 6 and 7). So the anisotropy compares very well with the visible elements of strain (Borradaile 1973, 1979b Fig. 1.) The strain ellipsoid data presented in Figs. 6 and 7 are taken from Roberts (1974) and Borradaile (1973). In all cases, the petrofabric data is reported to be due to the primary deformations. In most cases, the cleavage poles and the minimum axes occupy either the SE or the NW quadrant, in agreement with the primary Caledonian compression direction, approximately NW–SE (Fig. 5). The magnetic fabric orientations in Zones I and II are very

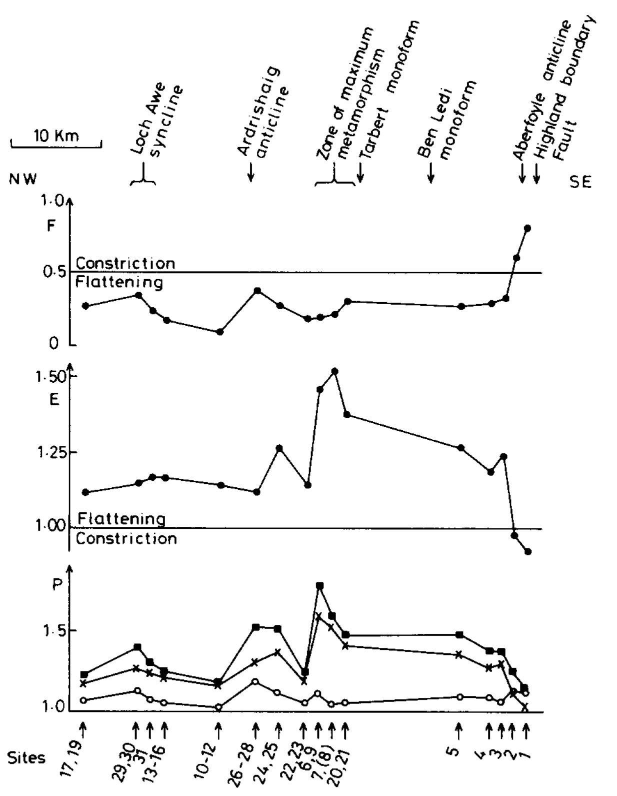

Fig. 4. The variation of the anisotropy parameters along a NW–SE profile. In (a), the open circles represent the P_1, the filled in squares represent the P_2 and the crosses represent the P_3 parameters. The structural elements along the profile are indicated above.

similar, and correspond well with the axial directions of the primary deformation ellipsoid. (Figs. 6a–d). Site AS20 from near the Tarbert monoform has magnetic principal axes aligned with the fabric of the secondary deformation. The magnetic lineation direction is aligned parallel to the secondary fold axes direction (Fig. 8). The orientation comparisons between the strain data reported by Roberts (1974) to be primary, and the magnetic fabric data for sites AS21 to AS27, show a very good correlation (Fig. 7a & b). These fabric lineations are orthogonal to the lineations

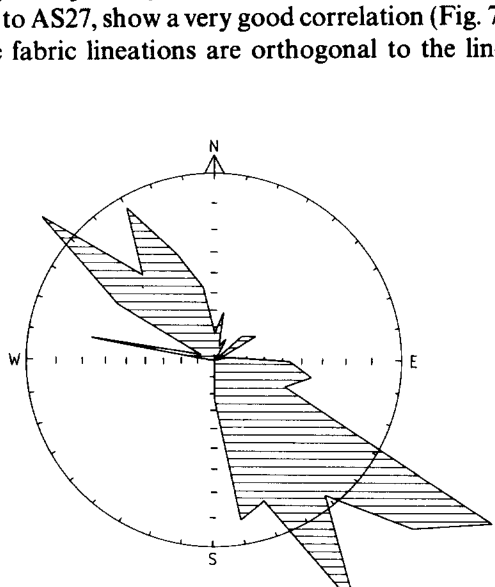

Fig. 5. A rose diagram of the magnetic minimum axes declinations. The maximum distributions are seen to be along the direction c. SE–NW, parallel to the main Caledonian compression direction.

observed in site AS20 (Fig. 8; also included in Fig. 7b for comparison) and show that this fabric has not been overprinted by the formation of the later Tarbert monoform. Hence, it can be inferred that, the two deformation phases were of different strengths, the primary being stronger than the secondary. The same can be said of the region containing sites AS6–AS9: the fabric orientations are in agreement with the above sites, only site AS6 may have suffered minor secondary effects since the maximum axes directions in this site are similar to the secondary deformation fold axes direction. Site AS12 from Zone V shows similar tendencies, yet the fabric minimum axes like those of sites AS11 and AS13 are in excellent agreement with the primary fabric directions from Borradaile (1973) (Figs. 7c & d). In the Loch Awe syncline, the petrofabric data from Borradaile was compared with magnetic localities AS14, AS15 and AS16. Locality AS13 has an altered fabric which is perhaps related to the secondary deformation fabric. The fabric directions of the other three sites compare well with Borradaile's observations of the primary deformation fabric directions. The magnetic orientation data for localities AS17 and AS19 fit well into the corresponding fields mapped by Roberts for the primary strain directions of this region (Fig. 6e & f). The site AS18 sampled in a pillow lava had a very weak deformation fabric corresponding to an $X/Y = 1$ (Roberts & Sanderson 1973), but note their assumption of plane strain, and the directions of the maximum and minimum axes appear to have interchanged in relation with the other two sites (Table 1). This pillow lava site was expected to give a particular result since the samples were drilled in a pillow which was embedded in a muddy, loose matrix. Hence, although the fabric in this region is a primary deformation fabric as seen in sites AS17 and AS19, site AS18 has to be disregarded.

In general, there is a high degree of correlation between the two fabric directions. The magnetic fabric direction variation can be clearly associated with the regional deformation variation. Moreover, in sites AS21 and AS22 which lie in neighbouring areas to the Tarbert monoform, and in site AS10, the dispersion of the maximum axes can also be explained by an effect of the secondary deformation (Henry 1974, 1980).

In brief, in the majority of sites, minimum and maximum axes are related with the cleavage poles and the stretching directions of the primary deformation strain fabrics. Maximum axes remain connected to the stretching directions, even in fold axial zones where fold hinges are well developed. Moreover, form parameters show that magnetic lineation is stronger in these zones. This clearly underlines the tectonic style of the primary deformation, with strong stretching indicating a 'flowing' of the rocks under very high pressure in a fanning pattern as proposed by Borradaile (1979b).

In site AS20, magnetic fabric is related to the cleavage and fold axes of the secondary deformation strain fabric. There is some local disturbance of the primary deformation magnetic fabric. Folding during the secondary deformation took place under moderate pressure.

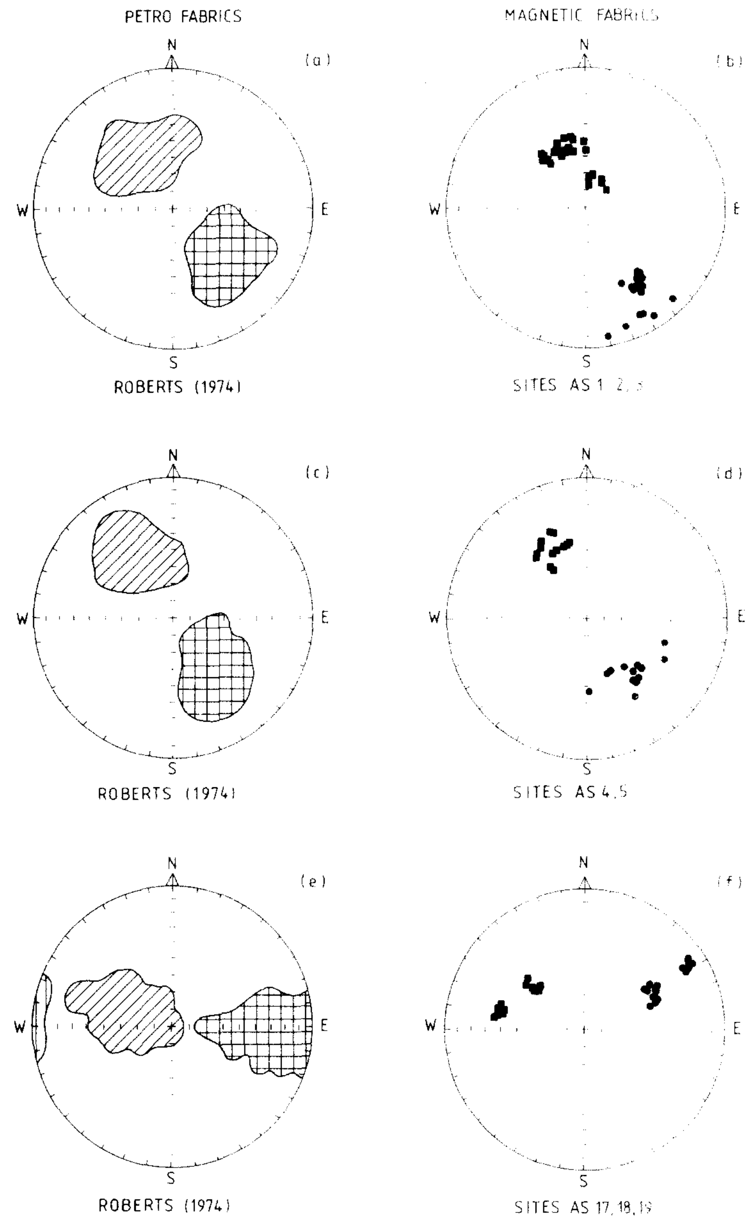

Fig. 6. Lower hemisphere equal area stereographic projections of the strain of the primary deformation and magnetic anisotropy axes. The groupings of cleavage poles (diagonal hatching) and stretching lineations (checked) are given and the maximum and minimum axes of the sites from the corresponding regions are plotted in the magnetic fabric stereograms. The strain data are obtained from Roberts (1974, fig. 3) and from Borradaile (1973, fig. 3). The areas of diagonal hatching depict the concentrations of strain cleavage poles, and those checked in the strain lineations. In the magnetic fabrics, the filled-in circles represent the maximum axes and the filled-in squares the minimum axes.

STRAIN IN THE DALRADIAN ROCKS AND ITS CORRELATION WITH MAGNETIC ANISOTROPY

The Dalradian rocks have varying mineralogy and texture according to the origin of the detrital and volcanic particles which formed the sediments. Furthermore, the metamorphic effects are not the same over the whole of the study area. Consequently the nature and magnitudes of the measured strains are expected to vary from locality to locality. The strains due to the primary deformations may further be modified by the stresses of the secondary deformations such that inhomogeneities in the strain over the study region are only to be expected. Uniform strain would only be found on the small or local scale. For the strain-to-anisotropy correlation in this study, the strain data was used, in part, from measurements made on deformed vesicles (in lavas) and pebbles (Borradaile 1973) and breccia fragments (Roberts & Sanderson 1974). The first problem that faces such strain determination is the estimate of the pre-deformation fabric. Using a method proposed by Ramsay (1967), the different authors assumed that the vesicles and breccia fragments and pebbles were randomly oriented. However, strain ratios obtained over a small region present variations of the order of 20%. This scatter seems to be related more to inhomogeneous deformation than to the initial fabric of the strain marker. In some cases, the strain measurements were made in

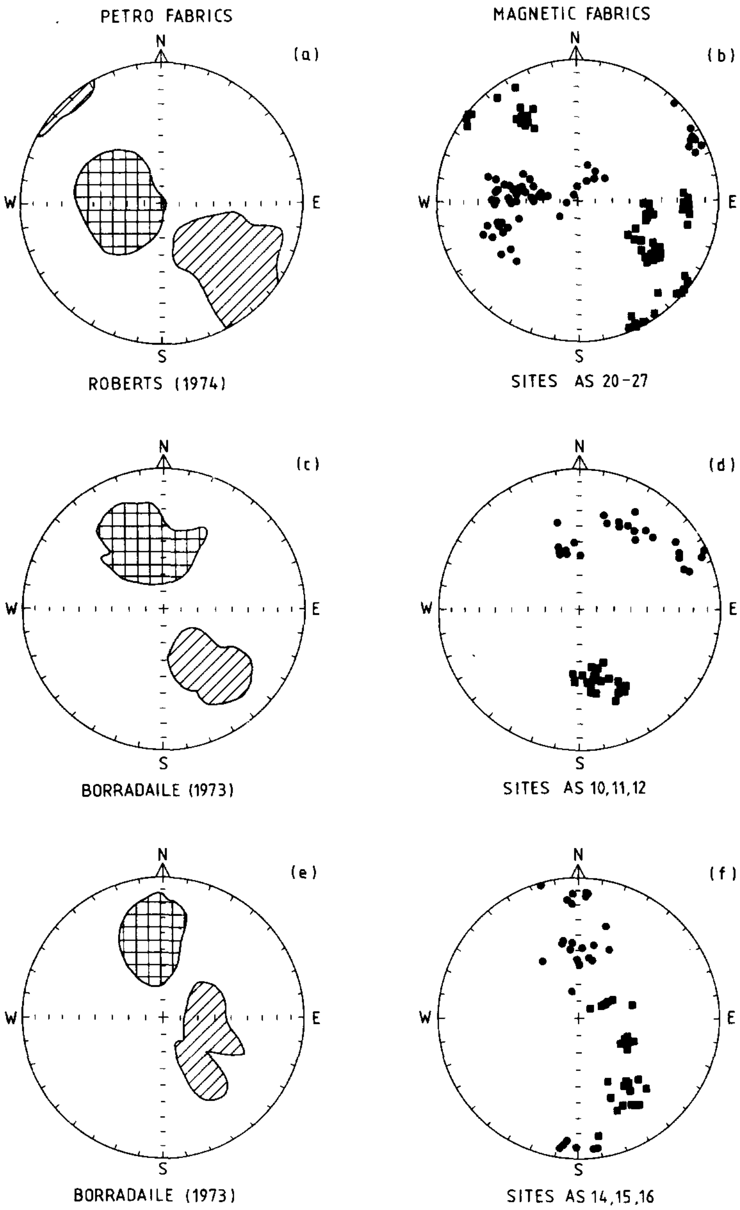

Fig. 7. Legend as for Fig. 6.

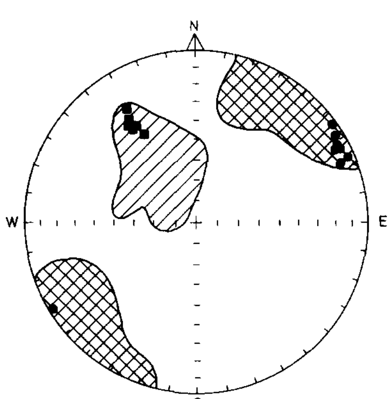

Fig. 8. A comparison of the strain magnetic and anisotropy axial orientation data for locality AS20 from within the secondary deformation area (Tarbert monoform). The strain data is from Roberts (1974, fig. 3), and the diagonal checked regions represent the secondary fold axes direction concentrations. All other symbolism is as in Fig. 4.

inhomogeneous rocks which included fragments within a matrix. The strain values in the matrix and the inclusion are found to be different. Borradaile (1973) estimated that the vesicles were less competent than lavas, so strain determinations determined from the vesicles are too high for the whole rock. On the other hand, pebbles are more competent than their slaty argillaceous matrix, and strain estimates using pebbles are too low. The presence of marked strain shadows about the pebbles emphasises this point. These are some of the systematic errors which must be considered when determining strain in rocks.

Finally, since the presence of a strong cleavage makes it difficult to determine the shortest axis of the strain ellipsoid and Roberts & Sanderson (1974) measured strain only in the XY plane, only X/Y ratios have been used in this strain-to-anisotropy correlation. Other strain values used were obtained by an analysis of minor fold axes arranged obliquely to the stretching lineations (Roberts & Sanderson 1974). The authors give an areal mean value of

Table 2. Magnetic anisotropy and strain axial parameters for the compared localities

Magnetic sites	National Grid references	Petrofabric sites	Mean P_1	$\text{Log}_{10} P_1$	Mean X/Y	Log_{10} X/Y
AS1, 2, 3	NS222818–NS227806	Barons Point	1.1089	0.0449	4.0	0.6020
AS4	NS217831–NS219831	Knockderry	1.0942	0.0391	4.5	0.6532
AS5	NS207878–NS216850	Coulport	1.0966	0.0401	3.5	0.5440
AS6, 9	NN090033–NN087021	Strachur	1.1097	0.0452	4.0	0.6020
AS7, 8	NR945871	Largiemhor	1.1809	0.0722	3.9	0.5910
AS13	NN034221	*B.4, 5	1.0252	0.0108	1.98	0.2955
AS14	NN020208	*B.5, 6, 7	1.0410	0.0175	1.77	0.2479
AS15	NN012195	*B.8	1.0217	0.0093	1.5	1.1761
AS16	NN003185	*B.9	1.0513	0.0217	2.04	0.3096
AS20	NR733580–NR748586	Ardpatrick Point	1.0396	0.0169	1.5	0.1761
AS21	NR718608–NR730614	Loch Stornoway	1.0450	0.0191	2.0	0.3010
AS22, 23	NR703626–NR718608	Tiretigan	1.0471	0.0200	2.5	0.3979
AS24, 25	NR707664–NR702644	Kilberry Head	1.1097	0.0452	3.5	0.5440
AS27, 28	NR945871	Ballyaurgan	1.0956	0.0397	2.7	0.4314
AS29, 30	NR689804	Keills	1.1112	0.0458	2.45	0.3892

the X/Y ratio and state that this value is within $\pm 20\%$ of the true strain value for the region. In two localities where there are true three-dimensional strain determinations using breccia fragments, the axial ratios are from 1/4 to 1/3 lower than those obtained by the fold axes analysis. Hence, Roberts & Sandersons' (1974) strain data have margins of error which are at least 20% of the given values. The determinations by Borradaile (1973) were three-dimensional and have specified error limits.

Since it was not possible to make strain measurements on the actual samples used for the anisotropy measurements, the correlation was carried out by matching the grid references of the strain localities with those of the mean magnetic anisotropy sites (Table 2). Following the strain-to-anisotropy correlation carried out successfully for slates from the Cambrian slate belt of North Wales (Wood *et al.* 1976, Rathore 1979) and slates from the Borrowdale volcanic group (Rathore 1980), where it was shown that $\log P_1 = \log (X/Y)^a$, the parameters $M = \log_{10} P_1$ and $N = \log_{10} (X/Y)$ were calculated for a possibly similar correlation (Table 2). The error bars shown on the strain values are equal to the 20% of the strain values as suggested by their authors. Error bars on the magnetic values are shown where more than one magnetic fabric site lies within a strain fabric locality. A linear regression plot of M vs N gave the result

$$Mi = (-0.004 \pm 0.008) + (0.088 \pm 0.017)\, Ni \quad (2)$$

with a regression coefficient, $r = 0.821$ (Fig. 7). The great uncertainty of strain values perhaps explains this r value being smaller than those from Wales and the Lake District. Moreover, since there is a dominant over-estimation of strain (particularly from vesicles, indicated by squares in Fig. 9), correcting for it would mean moving all the points along the abscissa to the left a little. This would mean the regression line would pass through the origin. On the other hand, within the error limits on the intercept, it can be assumed that the line passes through the origin (a basic necessity if the magnetic anisotropy is a function of strain) and thus equation (2) reduces to

$$M = (0.088 \pm 0.017)\, N. \quad (3)$$

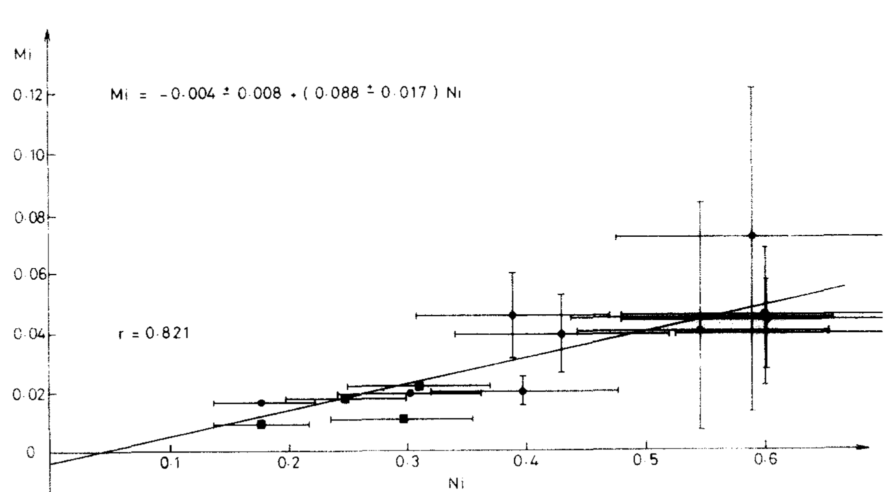

Fig. 9. Linear regression plot of Mi vs Ni: yielding $Mi = (-0.004 \pm 0.008) + (0.008 \pm 0.017)\, Ni$. Petrofabric data: filled-in circles from Roberts & Sanderson (1974), and filled-in squares from Borradaile (1973).

Hence, the empirical relationship between the magnetic susceptibility anisotropy axes and strain axes in the samples of various lithologies from the Dalradian sequence of the southwest Highlands can be expressed generally as

$$\left(\frac{\chi_i}{\chi_j}\right) = \left(\frac{l_i}{l_j}\right)^a, \tag{4}$$

(for $i = 1, 2, 3$; $j = 1, 2, 3$, and $i \neq j$) where i and j are two of the three principal axial directions and the exponent $a = 0.088 \pm 0.017$. This relationship is of the same type found in the slates from Wales and from the Lake District, but on this occasion rocks of different lithologies were used. However, the correlation exponent is not similar to the one found before (Wales: $a = 0.145 \pm 0.005$; Lake District: $a = 0.142 \pm 0.001$).

It is interesting to note that the magnetic fabric determinations on the slates from Wales and the Lake District were made on the prototype CRAD and the measurements of the present suite of rocks were made on the new modified version, yet working on the same physical principles (Rathore 1975). Hence, the whole suite of rocks were re-measured on the old machine to determine if there existed any discrepancy between the two hardware units. The whole magnetic data proved to be highly repeatable with a per cent or two variation in all sites. The final comparison between the magnetic and strain parameters gave the relationship

$$Mi = (-0.003 \pm 0.013) + (0.097 \pm 0.028)\,Ni$$

with regression coefficient, $r = 0.693$. This result once again reduces to a $y = mx$ graph, and hence, from the nature of M and N, to a power law type relationship. There is a small difference in the slope, but the error limits are larger and the regression coefficient is lower. The modified instrument is expected to give better results, since the modification is designed to reduce the effect of the sample shape on the anisotropy. Hence, within the error limits of the two instruments, there is no discrepancy in the fabrics measured, and thus the magnetic-to-strain correlation for this set of samples is taken to be that in equation (3).

DISCUSSIONS AND CONCLUSIONS

The detailed magnetic fabric to strain axial correlations show a strong parallelism between the two ellipsoidal minimum and maximum axes. The observance of the primary deformation fabric in the majority of the localities, and the secondary fabrics in a few of the localities, indicate that the magnetic fabric, like the strain fabric, is only locally overprinted by a weaker secondary deformational phase. In the localities with a primary fabric, the lineations are parallel to the stretching directions and not to the fold axes. In the secondary fabric sites, the lineations are parallel to the fold axes. The two fabrics clearly show a difference in deformation style, in particular the importance of stretching in the primary deformation. The regional deformation pattern of the magnetic fabric clearly shows the Caledonian direction of compression, NW–SE, with a culmination of the deformation parameters over the central zone, which is also the zone of main metamorphism. There is a decrease of the deformation and also a change in the nature of the ellipsoids near the Highland Boundary Fault, indicating perhaps the effects of secondary deformation on a pre-existing fabric. The same is true of the effect of the Tarbert monoform on the fabric of sites AS20 and AS6 and to a lesser extent on AS12. The study clearly indicates the possibility of using magnetic structural methods for conducting large regional studies. The speed of the method also means that large quantities of statistically reliable data can be collected in a very short time.

The test for the power-law between the anisotropy and the strain axial ratios gave positive results for the law-type; however, the correlation exponent was in this case (0.088 ± 0.017) not the same as that found in the two previous studies (0.142 ± 0.005, Rathore 1979, 1980). The regression coefficient is also lower and the error limits higher. This is possibly due to the fact that strain values are often the mean values for the area instead of a given locality. The anisotropy ellipsoids clearly indicate that the magnetic fabric has distinct parameters which are consistent within sites but which vary markedly from site to site. The difference in the correlation exponent from the previous value was not due to the instrument since the magnetic fabric was measured on the old machine for a comparison and showed no significant deviation from the new machine. Hence, although a power-law was found to hold for these samples, as had been previously, the possibility of finding a universal correlation exponent without further analysis involving the different mineralogies, textures, bulk moduli, etc. of the rocks seems remote. However, it is still early days in this type of strain/anisotropy analysis and the accumulation of a lot more experimental data is called for.

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