SOME PRELIMINARY SUSCEPTIBILITY ANISOTROPY MEASUREMENTS ON GREYWACKES FROM THE TRINITY PENINSULA SERIES OF GRAHAM LAND

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IN recent years, considerable attention has been directed to examination of the magnetic susceptibility anisotropy exhibited by a wide variety of clastic sediments. The susceptibility anisotropy of such rocks has been shown (Rees, 1965*a*) to be due to the shape orientation of the small percentages of ferromagnetic grains contained within the rocks. The ferromagnetic mineral most commonly responsible for this effect is magnetite or a member of the magnetite-ulvöspinel solid-solution series, as shape anisotropy only predominates in those minerals with high true susceptibilities. Since the susceptibility anisotropy in these sediments is dependent on the grain shape, measurement of this property can be utilized as a means of determining the magnetic grain fabric. Information about the directional properties of the magnetic grain fabric can be used in estimating some of the directional properties of the grain fabric of the rock as a whole.

The advantage of this method of fabric determination, over conventional optical methods, is the ease and rapidity with which a determination can be made. Also, the method enables numerical values to be derived for various parameters which describe the magnitude of the anisotropy, and hence quantitative information is available which relates to the grain fabric itself. Further discussion of the principles and limitations of the method has been given by Rees (1965*a*).

Grain fabric provides information that can be utilized in studies of the depositional and subsequent history of clastic sediments, and already several such studies have been reported using this method of fabric determination (Hamilton, 1963; Rees, 1965*a*, *b*; Hamilton and Rees, 1965; Graham, in press). So far as is known, no measurements of the grain fabric of the greywackes from the Trinity Peninsula Series had been made prior to this study. The aims of the present study were:

i. To see if the greywackes of this succession exhibited a measurable susceptibility anisotropy that was an expression of grain fabric.
ii. If a measurable fabric was found, to identify it as either an original depositional fabric or as a secondary fabric.
iii. To see if the observed fabric was likely to provide information pertinent to the history of the Trinity Peninsula Series.

GEOLOGICAL SETTING

The Trinity Peninsula Series consists for the most part of a greywacke-shale sequence that accumulated in a geosynclinal environment. It is thought to be Carboniferous in age. In the area of outcrop of this succession in northern Graham Land, the known thickness of the sediments varies from 12,000 ft. (3,660 m.) (Elliot, 1965) to 45,000 ft. (13,715 m.) (Aitkenhead, 1965). It is thought that the whole of this sequence has undergone low-grade regional metamorphism, and there is evidence to suggest that the grade of metamorphism increases towards the south-west. Contemporaneously with the regional metamorphism the succession was folded into an anticlinorium, one limb of which is seen in Trinity Peninsula.

SELECTION OF SAMPLES FOR ANISOTROPY STUDIES

The greywacke samples that were available for study had been collected during earlier geological and geophysical surveys. Unfortunately, most of these samples were not orientated. For this reason the present study is only of a preliminary nature.

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From this assortment of samples, collected from localities scattered over an area of about 700 sq. miles (1,800 km.^{2}) and therefore likely to provide a fairly representative collection of the greywacke types, a selection was made of 20 samples on which to carry out anisotropy measurements. The criteria used in the selection of samples are as follows:

i. Grain-size, predominantly fine to medium sand size.
ii. Freedom from obvious macroscopic metamorphic textures.
iii. Freedom from excessive quartz veining.
iv. The samples to be in a fresh unweathered state.

The samples that were used are listed in Table I and the distribution of the sites from which they were originally collected is shown in Fig. 1. The samples have been divided into two

TABLE I. SELECTED GREYWACKE SAMPLES FROM TRINITY PENINSULA

Sample number	*Location of sampling site* Lat. (S.)	Long. (W.)	*Number of specimens*	*Orientation*
D.4407.2	63° 23·0′	57° 42·0′	3	Arbitrary
D.4405.1*	63° 22·5′	57° 39·0′	1	Arbitrary
D.4444.1*	63° 32·5′	58° 20·3′	1	Arbitrary
D.4452.1*	63° 30·2′	58° 14·5′	1	Arbitrary
D.4403.1	63° 23·0′	57° 35·5′	2	Arbitrary
D.3804.1†	63° 42·2′	58° 14·5′	3	Arbitrary
D.3872.1†	63° 30·5′	57° 55·0′	1	Arbitrary
D.3644.1†	63° 37·5′	57° 47·5′	1	Arbitrary
D.3645.1†	63° 37·0′	57° 46·0′	1	Arbitrary
D.3646.1†	63° 36·7′	57° 37·0′	4	Arbitrary
D.3657.1†	63° 34·0′	57° 54·0′	1	Arbitrary
D.3701.2†	63° 32·0′	57° 22·0′	1	Arbitrary
D.3702.1†	63° 29·5′	57° 42·5′	1	Arbitrary
D.3821.2†	63° 27·5′	57° 35·0′	1	Arbitrary
D.3824.1†	63° 28·8′	57° 17·0′	1	Arbitrary
D.5011.1	64° 18′	58° 58′	3	W.R.T. magnetic north and horizontal
D.5011.2	64° 18′	58° 58′	1	W.R.T. magnetic north and horizontal
D.5011.3	64° 18′	58° 58′	6	W.R.T. magnetic north and horizontal
D.5011.4	64° 18′	58° 58′	2	W.R.T. magnetic north and horizontal
D.5011.5	64° 18′	58° 58′	3	W.R.T. magnetic north and horizontal

* Grain-size and modal analyses given by Elliot (1965).
† Modal analyses given by Aitkenhead (1965).

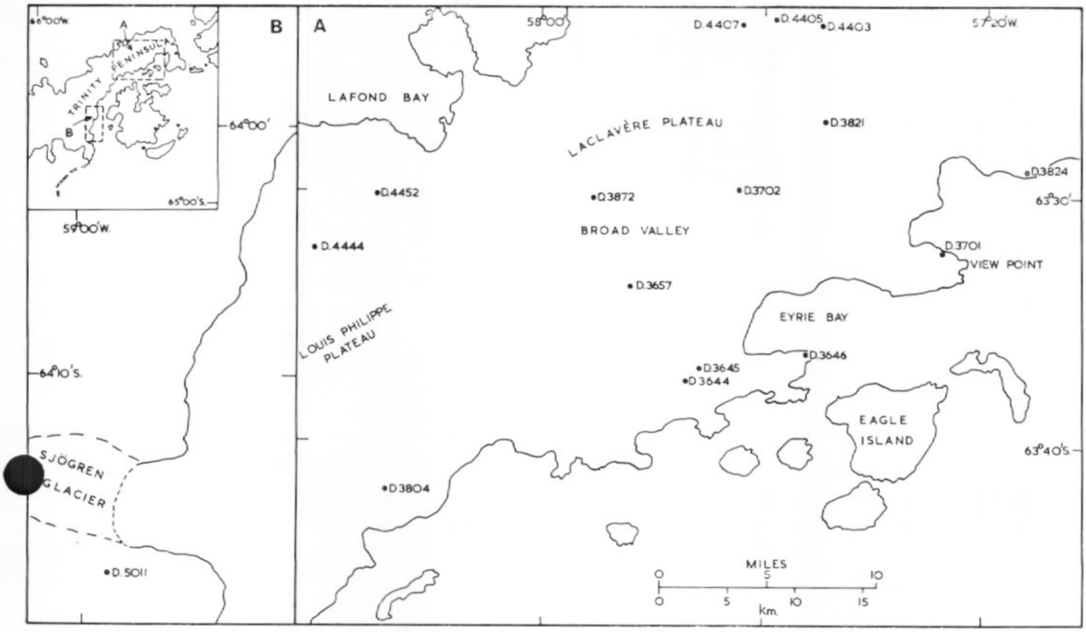

Fig. 1. Distribution of the sampling sites in Trinity Peninsula. The inset indicates the location of the larger maps in north-east Graham Land.

groups, A and B; group A includes all the unorientated samples, which comprise the majority of the selection, and group B the orientated samples. As well as division on the basis of orientation, group A samples are from sites at which the strata are thought to be relatively uncontorted on the small scale (Elliot, 1965), whereas Aitkenhead (1965) has referred to complex minor folding and contortion in the Sjögren Glacier area from which group B samples were collected.

LABORATORY SAMPLING

For anisotropy measurement on the instruments available at Birmingham, it is necessary to have cylindrical specimens of height equal to diameter. Either 1 in. (2·54 cm.) or 0·75 in. (1·90 cm.) diameter cores were taken depending on sample size. Group B samples were re-aligned in their field attitude prior to coring vertically, and the orientation, magnetic north, was transferred to the specimens so obtained. The unorientated samples of group A were cored, where possible, normal to the bedding (or other planar structure). Where no bedding was visible the coring direction was arbitrary (Table I). Each of these specimens was marked with an arbitrary reference orientation for the purpose of measurement.

MEASUREMENT, COMPUTATION AND PRESENTATION OF RESULTS

The anisotropy of susceptibility was determined with the torque magnetometer (King and Rees, 1962), using field strengths of 40–80 oersted r.m.s. The fields were chosen to give accurately measurable deflections of the suspended system. In order to completely specify the fitted susceptibility tensor, the bulk susceptibilities of the specimens were determined using an inductance bridge, previously calibrated against known standards.

Computer analysis of the resultant torque curves, determined in measurement, enables the directions and differences in magnitude of the principal axes of susceptibility to be found. Normally, these are referred to as the maximum, $k_{\text{max.}}$, intermediate, $k_{\text{int.}}$, and minimum, $k_{\text{min.}}$, principal axes of susceptibility, and they are necessarily orthogonal. The maximum axis has been shown to represent the direction of the preferred orientation of elongated particles, that is, the resultant orientation of particle long axes.

The anisotropy results for various samples are presented here stereographically. The procedure generally adopted has been to plot the directions of the maxima and minima, but in some cases the directions of the intermediate axes have been included to emphasize the spatial pattern of the axes.

Various parameters for describing the magnitude of the anisotropy have been proposed by several authors. Those used here are the mean susceptibility, which approximates to $k_{\text{int.}}$, the percentage anisotropy, h, expressed as:

$$h = \frac{k_{\text{max.}} - k_{\text{min.}}}{k_{\text{int.}}} \times 100$$

and, q, a parameter for describing the strength of the magnetic lineation in terms of the resultant foliation, where q is given by:

$$q = \frac{k_{\text{max.}} - k_{\text{int.}}}{\frac{1}{2}(k_{\text{max.}} + k_{\text{int.}}) - k_{\text{min.}}}.$$

RESULTS

General remarks

The first aim of this study was to see if the greywackes exhibited a measurable anisotropy. The results show that all the specimens measured do have an appreciable anisotropy of susceptibility. Fig. 2 shows the distribution of this anisotropy, expressed as percentage anisotropy, for all specimens. Also included on this figure is a histogram of the bulk susceptibility. It can be seen that this varies only by a small amount about the mean value of $1 \cdot 75 \times 10^{-5}$ e.m.u./cm.^{3}, except for one specimen with an anomalously high value. Variation in percentage anisotropy is more marked, although 60 per cent of the values lie between 4 and 9 per cent. This variation can have several causes. Since the mean susceptibility is practically the same for all the samples, this variation must mean that for some samples the particles of magnetic material are contributing more to the anisotropy than for other samples. Hamilton and Rees (1965) have discussed a number of causes which could account for this.

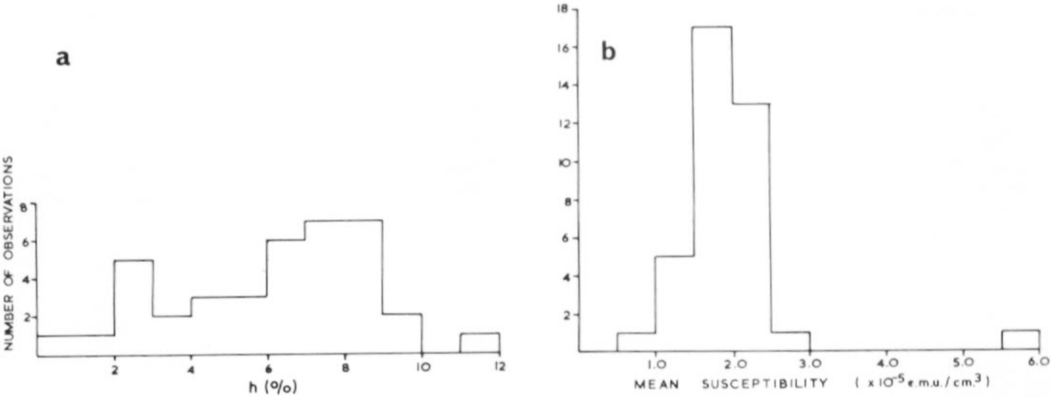

Fig. 2. Distribution of (a) percentage anisotropy, h, and (b) mean susceptibilities, for all specimens measured.

Before describing individual results it is necessary to show that the directions of the principal axes of susceptibility of these greywackes are in fact simply related to grain fabric. This has been done by optical examination of the preferred orientation of elongated non-magnetic grains seen in thin sections cut parallel to the measured plane of maximum susceptibility. The results of this are shown for two specimens, D.4444.1(1.1) and 4407.2(1.1), by the rose

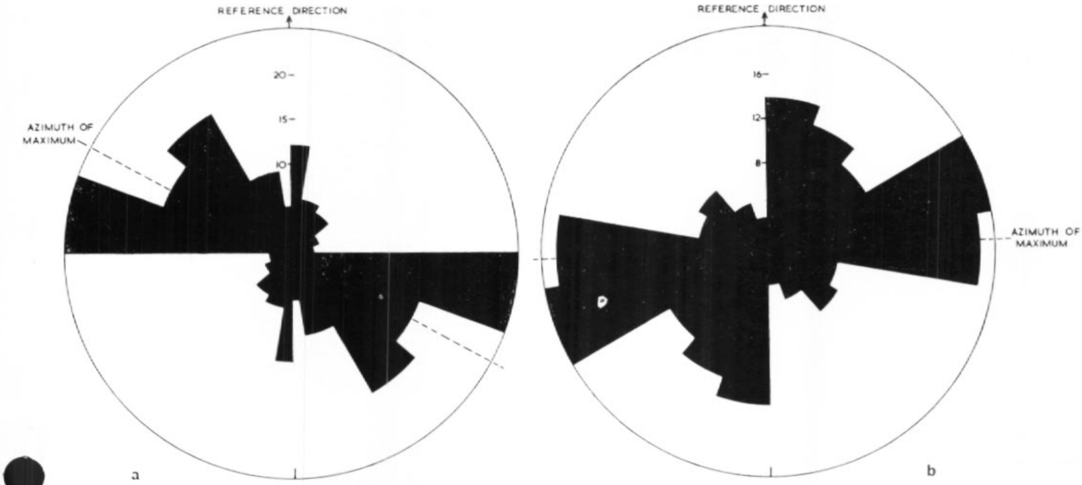

Fig. 3. The distribution of the long axes of non-magnetic grains in thin sections cut parallel to the magnetic foliation plane.
a. D.4407.2(1.1); b. D.4444.1(1.1).

diagrams (Fig. 3), on which the directions of the maximum susceptibility axes have been superimposed. The mean directions of long-axis orientation indicated from the optical measurements are not significantly different from the azimuths of the maximum susceptibility axes. This is in agreement with observations of earlier workers (Khan, 1962; Rees, 1965*a*).

Another general result obtained from the measurements is related to the scatter of axes of individual specimens from the same sample. In several instances more than one specimen was taken from a sample (D.3646.1, 3804.1, 4407.2); the distributions of the maxima and minima of specimens from these samples are illustrated by Fig. 4. Also shown for comparison is the distribution of the axes of specimens from one of the orientated samples of group B. All these stereograms show that the within-sample scatter is quite small; this again agrees with the results from other studies. The small scatter indicates that the anisotropy is constant within the samples and therefore over the sample size it can be taken to have a similar origin, and also that the preferred orientation is statistically significant.

Fabric types

In assessing the results using the directions and magnitudes of the anisotropy it should be possible, for those specimens from the orientated samples and for those specimens which come from unorientated samples, but which have been cored with respect to the apparent bedding, to say whether the observed fabric could be primary or secondary in origin.

Group A. The criteria that have been shown by earlier studies (Hamilton and Rees, 1965) to be of most use in recognizing primary sedimentary fabrics are:

i. The minima should be approximately perpendicular to the bedding plane.
ii. The magnitude of the lineation parameter q should be small ($<0\cdot5$).

Table II summarizes the anisotropy characteristics of the specimens of group A and includes a fabric type assessment, using these criteria, for those samples of known bedding/core relationship.

Group A includes two samples (D.4407.2, 3804.1) in which the fabric is probably primary. Other samples are seen in several instances to satisfy the first criterion but they fail to satisfy the second; D.4444.1 is such a sample. Examination of a thin section from this sample (personal communication from D. H. Elliot) shows that the rock exhibits strong shearing; this suggests tectonic modification of the original grain alignment which is qualitatively seen in the increased value of q (Table II). In contrast to this sample, D.3646.1 again satisfies (i) but it has an extremely high q value ($q = 1\cdot275$) (by definition the maximum possible value of

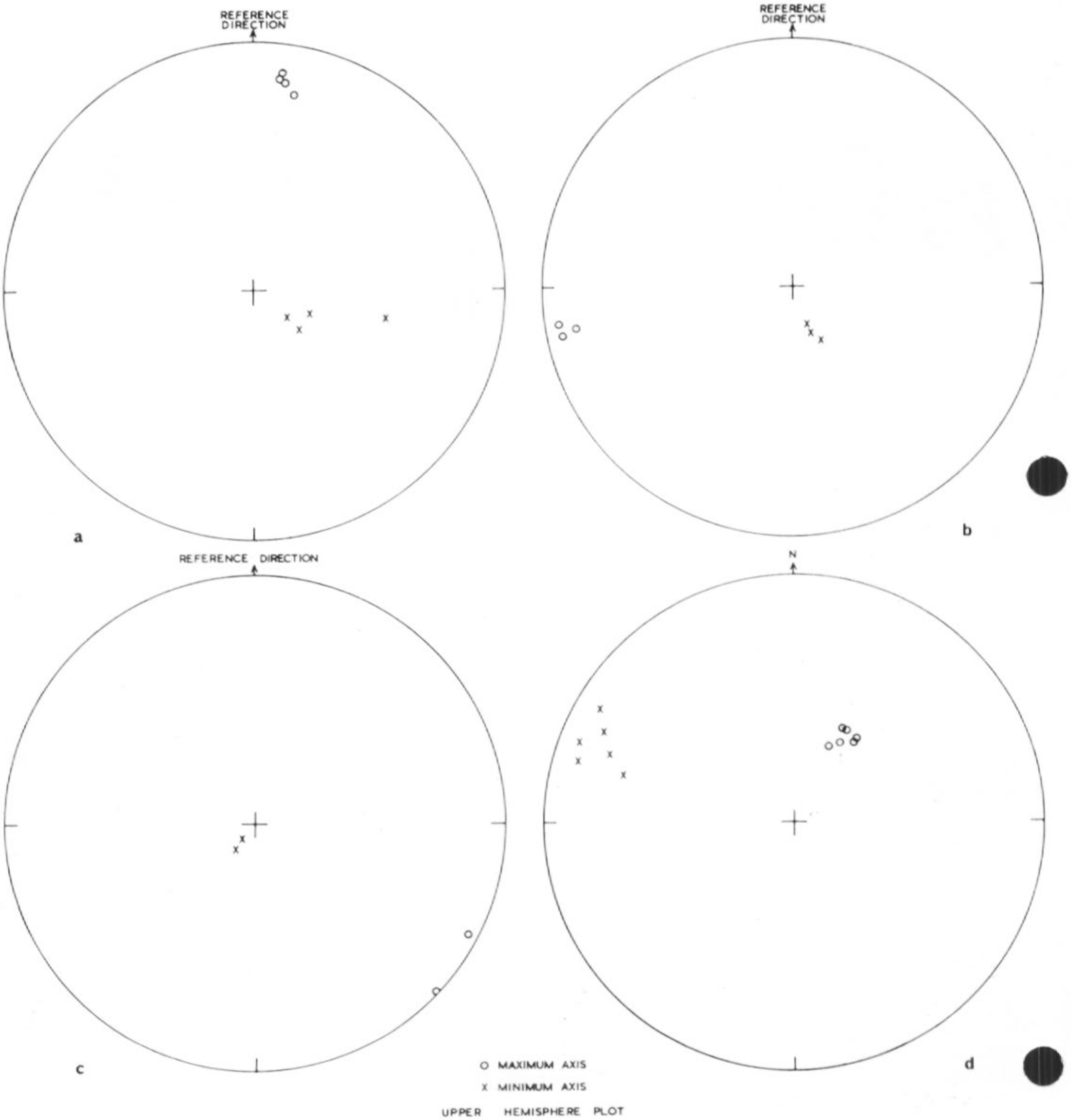

Fig. 4. Within-sample scatter of the axes of maximum and minimum susceptibility. a. D.3646.1; b. D.3804.1; c. D.4407.2; d. D.5011.3.

q is 2·0). However, in this case the rock shows no sign of shearing or recrystallization, and therefore the origin of the increased value of *q* must be sought elsewhere.

Similar anomalously high *q* values ($q > 1{\cdot}0$) are found for several other samples from group A. The majority of these samples are lithic greywackes. Abundance of the rock fragments, particularly shale clasts, in these samples suggests deposition in a high-energy environment, such as would be the case for deposition on to a steep slope. Under these conditions mass movement down-slope could act to modify an original fabric. Destruction of the magnetic foliation could occur and this may bring about a relative increase in the intensity of the lineation which would be reflected in an extremely high *q* value. Under these conditions

TABLE II. GROUP A SAMPLES (UNORIENTATED)

Sample number	*Number of specimens*	*Bedding/core orientation relationship*	*Attitude of maximum axis of susceptibility*	*Attitude of minimum axis of susceptibility*	*q (mean value if more than one specimen)*	*Lithological comments*	*Possible magnetic fabric type*
D.3644.1	1	No bedding visible			0·737	Quartz-rich lithic greywacke (recrystallized)	
D.3645.1	1	No bedding visible			0·872	Quartz-rich lithic greywacke (recrystallized)	
D.3646.1	4	Perpendicular	Horizontal	Vertical	1·275	Quartz-rich lithic greywacke (no sign of alteration)	Secondary
D.3657.1	1	Perpendicular (to shale clasts)	Horizontal	Horizontal	1·325	Lithic greywacke (no sign of alteration)	Secondary
D.3701.2	1	No bedding visible			0·704	Lithic greywacke (no sign of alteration)	
D.3702.1	1	No bedding visible			0·513	Feldspathic greywacke	
D.3804.1	3	Perpendicular	Horizontal	Vertical	0·383	Lithic greywacke	Primary
D.3821.2	1	No bedding visible			1·316	Feldspathic/lithic greywacke	
D.3824.1	1	Shale clasts dip across core			0·640	Feldspathic/lithic greywacke	
D.3872.1	1	No bedding visible			0·558	Feldspathic greywacke	
D.4403.1	2	Perpendicular (to shale clasts)	Near vertical	Near horizontal	1·243	Feldspathic greywacke Little shearing in thin section	Secondary
D.4405.1	1	No bedding visible			0·580	Little shearing in thin section	
D.4407.2	3	Perpendicular	Horizontal	Vertical	0·399	Little shearing in thin section	Primary
D.4444.1	1	Possibly perpendicular	Horizontal	Vertical	0·686	Strong shearing in thin section	Secondary
D.4452.1	1	No bedding visible			0·337	Little shearing in thin section	

it might be expected that the included rock fragments would develop a preferred orientation. Many of the samples exhibiting these high *q* values were observed to have a tendency for the shale clasts in them to show a preferred orientation. Examination of the samples allows this preferred orientation to be estimated visually. For samples D.3657.1 and 3821.2, this alignment of the shale clasts is approximately parallel to the azimuth of the maximum susceptibility axes. However, apart from the heterogeneous nature of these greywackes, there is little field evidence to suggest the presence of original depositional slopes, although slumping has been observed at a few other localities by both Aitkenhead (1965) and Elliot (1965).

Group B. The five orientated samples that comprise this group were taken from a series of outcrops in the area immediately south of Sjögren Glacier, and thus are from the most southerly site in this study. According to J. Mansfield (personal communication), the outcrops in this area show a wide variety of strikes combined with high angles of dip, and Aitkenhead (1965) has pointed out that there is minor complex folding here.

The distribution of the maxima and minima for the individual samples is shown in Fig. 5, plotted with respect to north and horizontal. There is no obvious correlation between these individual results. However, the magnitude of the anisotropy, expressed as percentage anisotropy and by the parameter *q*, is quite distinctive (Fig. 6). Both histograms show well-developed modes, which are in marked contrast to those shown by the group A samples drawn on this figure. Group B is characterized by a higher percentage anisotropy.

With reference to the distributions of the anisotropy axes of these samples, that of sample D.5011.1 is the most interesting. Close examination of this sample revealed that it contained a similar fold (Fig. 7). The specimens that had been taken from it were not in the same position relative to the fold axis.

Fig. 8 shows the three principal axes of susceptibility plotted for these specimens together with the trace of the axial plane of the fold, determined from angular measurements on the sample. The fold axis, which is marked on the stereogram, is itself plunging. It can be seen that the distribution of the susceptibility axes is closely related to the trace of the axial plane. The maximum and intermediate axes lie in this plane whilst the minima are normal to it. The grouping of the axes is good and, since the specimens are simply related to the fold crest, it is possible to draw some conclusions from the scatter of the axes in a manner analogous to the fold test used by Graham (1949). If the rock possessed a primary fabric at the time of folding and this was unaffected by the folding process, then the scatter of the principal axes between individual specimens would be appreciable. This is not so here. Therefore, the fabric must have been derived during or after the folding. The close association of the axes with the axial-plane trace suggests that the fabric is related to the folding.

Graham (in press) has shown how the fabric pattern changes during a compressive phase associated with folding, assuming that the material being deformed behaves plastically. With increasing deformation the principal susceptibility axes become orientated in a particular manner with respect to the axis of compression. The maxima are preferentially directed away from the axis of compression into the direction of the axis of extension. Accompanying this Graham has postulated that the minima are re-orientated in the direction of the compression axis. It is apparent that the distribution of the anisotropy axes observed for the similar-fold sample (Fig. 8) is similar to the theoretical pattern predicted by Graham and observed by him in some of the sediments of the Appalachian formations.

An attempt to analyse this observed anisotropy further has been made by examining a thin section cut from this sample parallel to the horizontal plane. In this section, the opaque ferromagnetic grains (assumed to be magnetite or titanomagnetite) tend to occur in distinct string-like arrangements within the matrix. The rock itself has a semi-schistose texture (Fig. 9). A count of the preferred orientation of about 100 of these ferromagnetic strings was made. The results of this are shown by the rose diagram in Fig. 10. Also marked on the figure is the mean azimuth of the susceptibility maxima. A histogram of the dimension ratios (length : width) of the ferromagnetic strings is also given. Agreement between the direction of the maxima and the resultant preferred orientation of the strings is extremely close. The occurrence of the strings, particularly in association with the chlorite flakes that are present, is suggestive of secondary rather than original detrital magnetite, providing further evidence

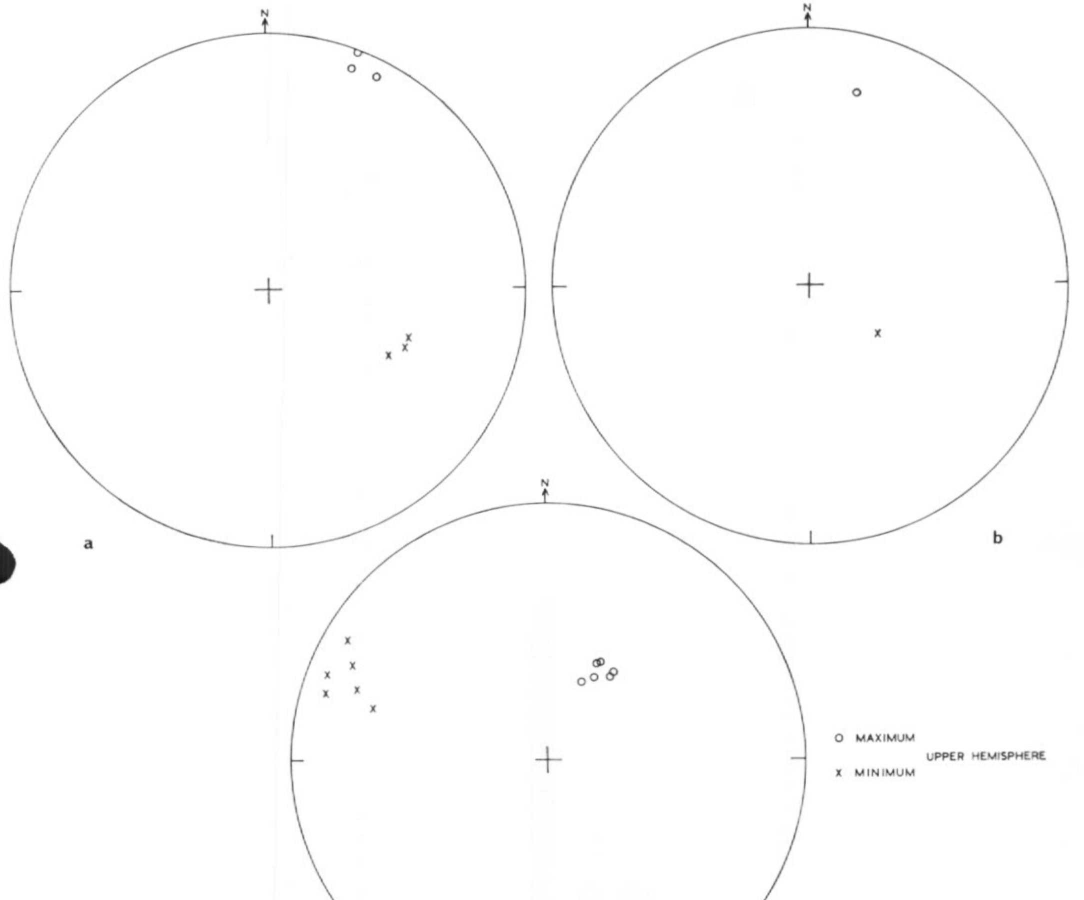

Fig. 5. Upper hemisphere stereographic projections of axes of maximum and minimum susceptibilities of group B samples.
a. D.5011.1; b. D.5011.2; c. D.5011.3; d. D.5011.4; e. D.5011.5.

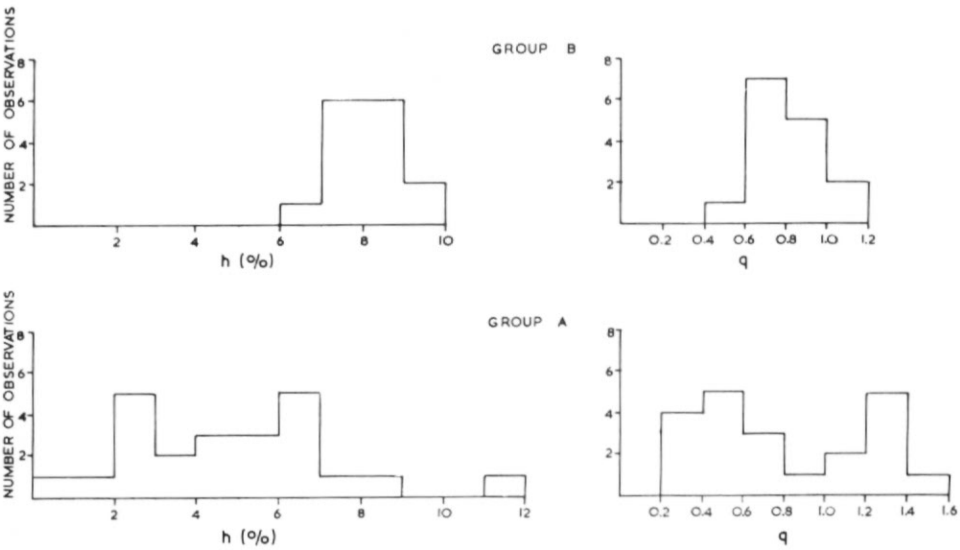

Fig. 6. Comparison of the intensities of *h* and *q* for group A and B specimens.

Fig. 7. Photograph of sample D.5011.1 showing a similar fold.

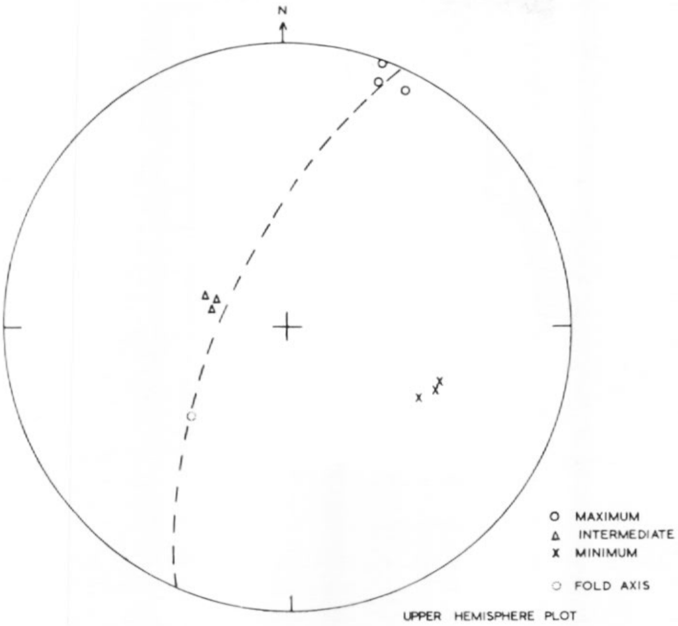

Fig. 8. Upper hemisphere stereographic projection of the principal axes of susceptibility of sample D.5011.1.

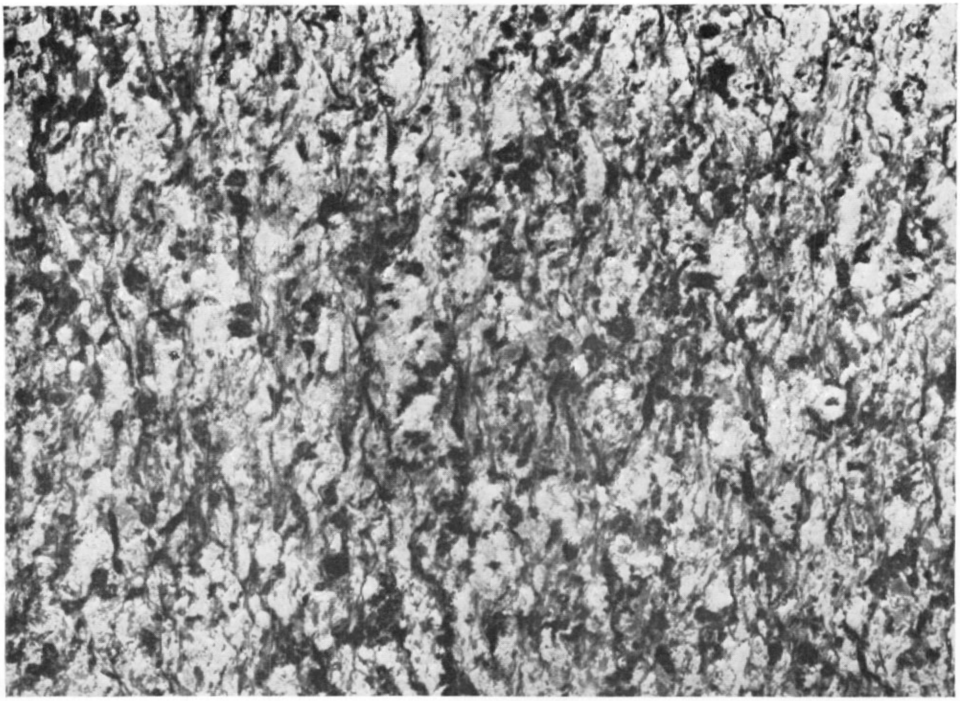

Fig. 9. Photomicrograph of a thin section from sample D.5011.1, showing the schistose texture of ferromagnetic strings. (Ordinary light; ×30)

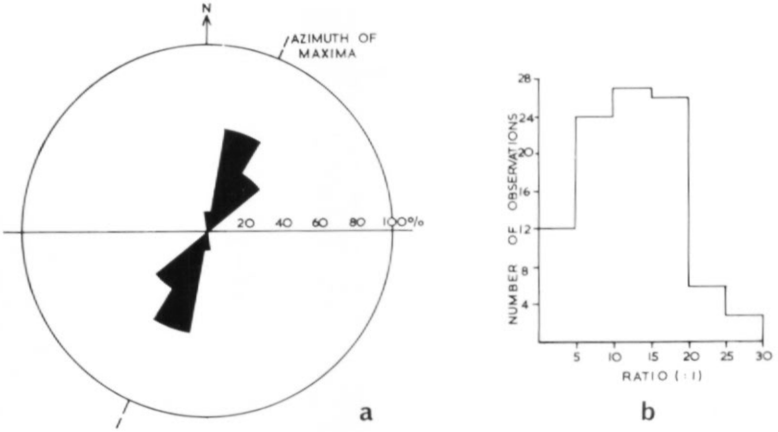

Fig. 10. a. Distribution of long axes of ferromagnetic strings.
b. Dimension ratios of ferromagnetic strings.

that the observed fabric is secondary in origin. It is probable that both the strings and the chlorite were derived during the low-grade regional metamorphism that these greywackes were subjected to, and that this accompanied the folding.

In view of the results from this sample, and the close similarity of the magnitude parameters of the group as a whole, it can be inferred that the fabrics of these samples are probably of the same type and are likely to have been produced in the same manner. Certainly, in most of these other four samples the bedding traces are steeply dipping and the strike of this often coincides with the direction of the maxima of specimens from them. The high mean value of percentage anisotropy of the group is probably the result of better alignment of magnetic particles, as would be expected for secondary magnetite growing during a compressive phase. The higher shape ratio must also contribute to this.

CONCLUSIONS

At the outset of this investigation it was apparent that, since the majority of the measurements would be carried out on unorientated specimens, a full appraisal of the fabric of the greywackes would not be possible. However, despite this limitation the results that have emerged are not without significance.

It has been clearly demonstrated that the greywackes of the Trinity Peninsula Series have a measurable anisotropy of susceptibility which is related to grain shape and is therefore an expression of grain fabric. Interpretation of this fabric has been possible for some samples from group A in terms of a primary depositional fabric, whilst for others a secondary origin for the fabric must be postulated. The group B samples have been shown to possess a probable secondary fabric that is closely related to folding and low-grade regional metamorphism.

In view of these encouraging results a full-scale study of the susceptibility anisotropy of the Trinity Peninsula Series greywackes would seem to be a worthwhile undertaking. Careful separation of the greywackes into those showing primary fabric and those showing secondary fabric would be necessary. If this could be achieved satisfactorily, then the primary fabrics could be used as a basis for palaeocurrent estimation, information on which is extremely limited at the present time. This would enable a more precise appraisal to be made of the palaeogeography of this geosynclinal formation. The role of the secondary fabrics is nonetheless important, as it could be used as a means of determining the importance of post-depositional deformation, and hence provide a quantitative means of assessing the extent of the tectonism that affected this geosynclinal assemblage.

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