Applicability and Limitations of Petrofabric Analysis Without Use of a Universal Stage.

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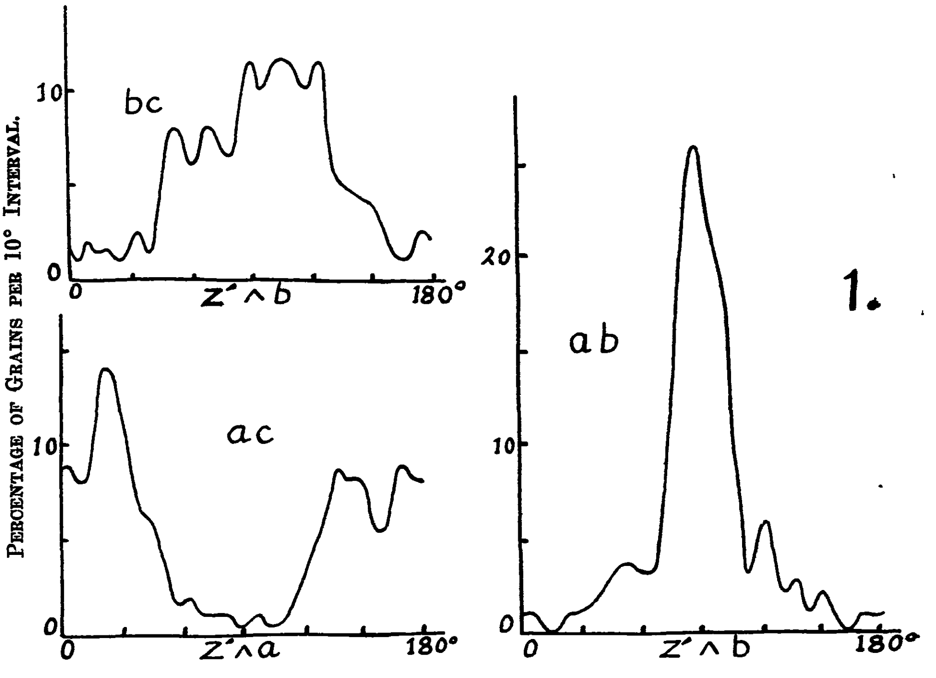
INTRODUCTION.

IN several recent papers on metamorphic rocks of southern New Zealand (Turner, 1936, 1938, 1938a, 1938b), the writer has given statistical analyses of orientation of grains of quartz and muscovite, based on simple microscopic measurements not involving use of a universal stage. The method employed (see Turner, 1938, p. 445) briefly may be summarised thus: Sections are cut at right angles to each of three mutually perpendicular reference axes which are selected provisionally as the *a, b* and *c* fabric axes. For two or three hundred grains in each section the angle is measured between a selected fabric axis lying in the plane of the section, and an easily determined crystallographic direction for the mineral in question—the slow vibration-direction *Z'* in quartz, the trace of the (001) cleavage in mica or chlorite. The percentage of grains in which the measured crystallographic direction makes any particular angle with the fabric axis, is now shown on curves constructed from these data, and the type and degree of preferred orientation is further brought out by correlating appropriate maxima and minima on the three curves.

It is here proposed to discuss the applicability and limitations of this type of work in the light of results more recently obtained from the same rock-sections using a universal stage and following the standard procedure of Sander (1930, p. 121).

ILLUSTRATIVE EXAMPLES OF QUARTZ DIAGRAMS.

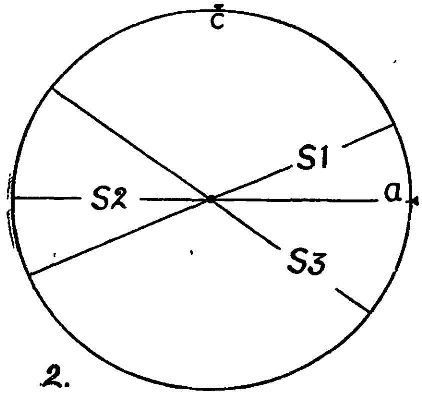
The three curves of Fig. 1 illustrate the preferred orientation of quartz in a fissile granite, No. 4525, from Lake Manapouri, as determined without use of a universal stage (see Turner, 1938b, pp. 134–139 for details). In these and subsequent orientation curves the percentage of grains for which *Z'* falls within successive angular intervals of 10° is plotted against mean angular distance from a selected reference axis *a* or *b*. From these it is deduced that the quartz axes Z tend to lie on a broken girdle about the axis *b*, with strong concentrations (maxima) for directions inclined at 25° on one

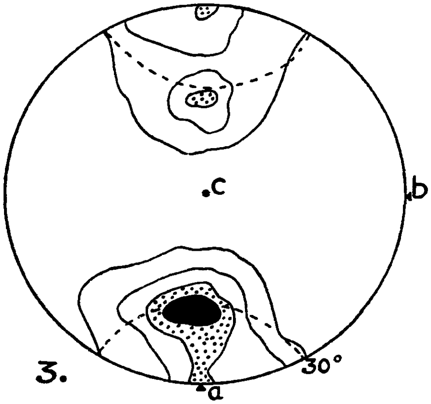


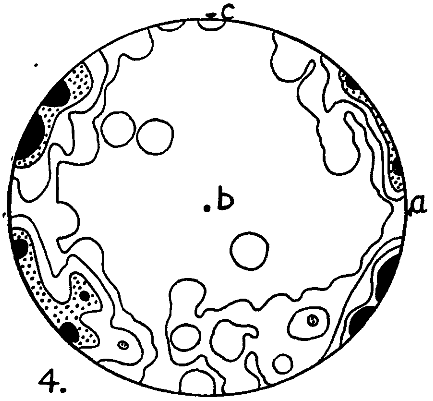
ANGULAR DISTANCE Z′ TO REFERENCE AXIS.

FIG. 1—Orientation curves for quartz in *bc*, *ac* and *ab* sections of fissile granite (No. 4525, Lake Manapouri; see Turner, 1938b, Figs. 4–6).

side and 35° on the other side of *a*, and a secondary concentration parallel to *a*. The pattern was thought sufficiently simple to warrant construction of a contoured concentration diagram showing qualitatively the distribution of the quartz axes Z on a stereogram (Fig. 3). The hidden *s*-surfaces S_1 and S_3 deduced from these data are shown in Fig. 2. The results obtained by measuring the orientation of 150 quartz grains in the *ac* section by means of a universal stage are shown in the standard fabric diagram Fig. 4. This was then rotated about the *a* and *c* axes to give Fig. 5, which represents a projection of the upper hemisphere upon the *ab* plane and is thus capable of comparison with Fig. 3. Agreement between the two is close, especially as regards the incomplete girdle, its slight obliquity with reference to *b* and the presence of maxima at 20°–30° from *a*. The simpler method was not, however, sufficiently sensitive to detect the minimal area between the two maxima nor to indicate which of the maxima was the stronger. The differences are nevertheless not sufficiently great to affect the tectonic interpretation of the diagrams, which appear to represent a typical case of " flattening " perpendicular







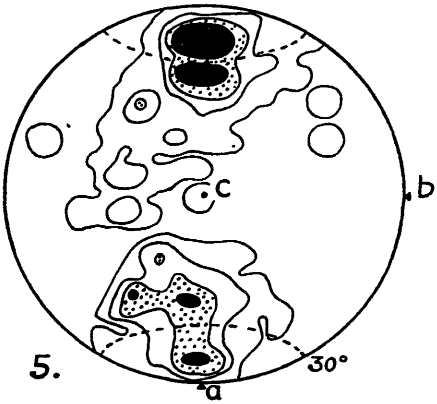


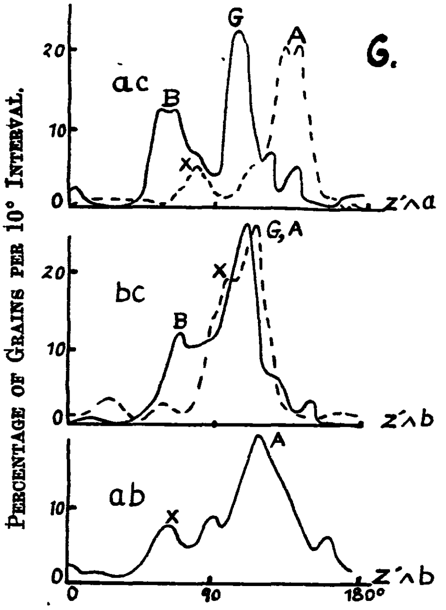
FIG. 2—Stereographic projection showing positions of deduced *s*-surfaces S_1 and S_3 and observed cleavage surface S_2 in granite No. 4525 (Turner, 1938b, Fig. 7b).

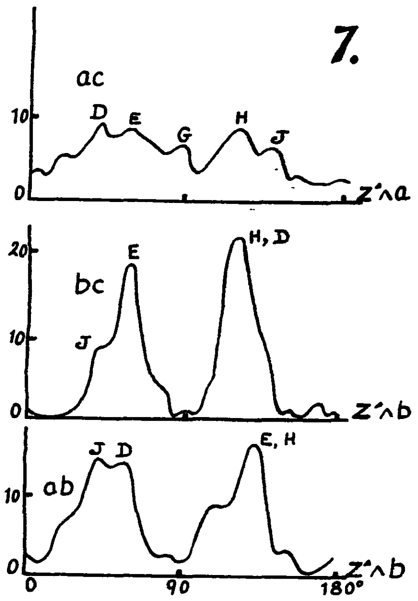
FIG. 3—Stereographic projection of *upper* hemisphere upon *ab*, with hypothetical density-contours for Z in quartz indicating the general type of preferred orientation deduced from the data of Fig. 1 (Turner, 1938b, Fig. 7c). The broken arcs are the projections of the small circles of 30° radius from *a*.

FIG. 4—Fabric diagram for 150 grains of quartz measured in *ac* section of granite No. 4525; projection of lower hemisphere upon Schmidt net. Contours 6, 4, 2, 0.7%; maximum concentration 9% of quartz axes per 1% area.

FIG. 5—Fabric diagram of Fig. 4 rotated to represent projection of *upper* hemisphere upon *ab* (cf. Fig. 3). The broken ellipses are the projections of the small circles of 30° radius from *a*.

to *c* by simultaneous slip upon two sets of *s*-surfaces intersecting at a comparatively low angle (cf. Knopf and Ingerson, 1938, p. 69, p. 145, Fig. 38). The compression causing the flattening would have operated parallel to *c* and hence at right angles to the plane of schistosity *ab*—in this case a horizontal force since the schistosity is vertical.





ANGULAR DISTANCE Z' TO REFERENCE AXIS.

FIG. 6—Orientation curves for quartz in corrugated veinlets in *ab*, *bc* and *ac* sections of schist No. 4457 from Patearoa, Otago (Turner, 1938, Fig. 7). Broken and full curves for *ac* represent two different sets of limbs in the same folded vein. The *bc* curves are based upon measurements of two different veinlets or two sectors of the same veinlet.

FIG. 7—Orientation curves for quartz in *ab*, *bc* and *ac* sections of quartz veins lying parallel to schistosity (*ab*) in schist No. 4487 from Waipori, Otago (Turner, 1938a, Figs. 4, 5, 6).

A second illustration is furnished by the fabric of corrugated veinlets of quartz crossing the main cleavage of a schist (No. 4457) from Patearoa, Otago (Turner, 1938, pp. 452–458). The orientation curves for Z' as measured in *ab*, *bc* and *ac* sections are reproduced in Fig. 6, while Fig. 8 shows the positions of maxima deduced from these as plotted on a Schmidt equal-area projection of the lower hemisphere* to allow comparison with Fig. 9. The latter is a fabric diagram representing the distribution of the optic axes of 100 quartz grains measured in the *ac* section by Dr. E. Ingerson, using a universal stage. The positions of the maximum A–G and the most important of the submaxima, B, correspond closely in the two diagrams. The lesser submaximum X, however, is only imperfectly indicated in Fig. 9. It should be noted that discrepancies in the comparison are possibly due as much to the fewness of grains measured for Fig. 9 as to lack of accuracy in Fig. 8.

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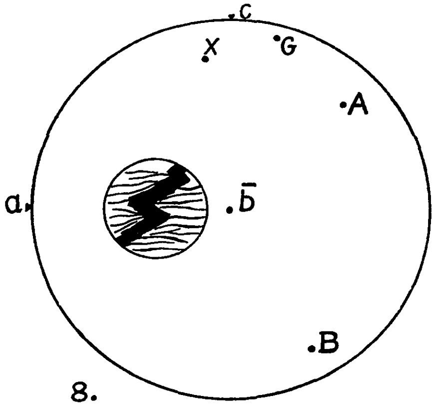
* The original figure (Turner, 1938, Fig. 9) represents a stereographic projection of the upper hemisphere.



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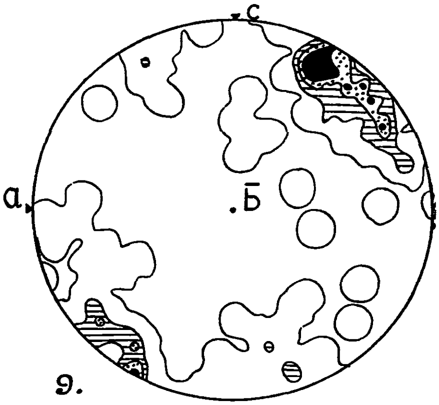

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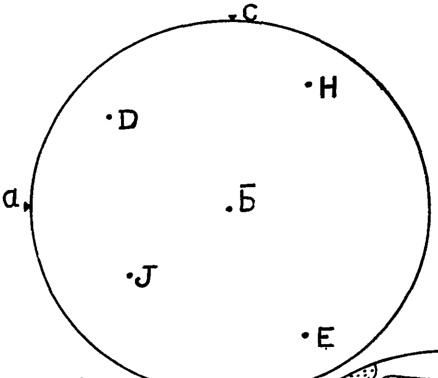

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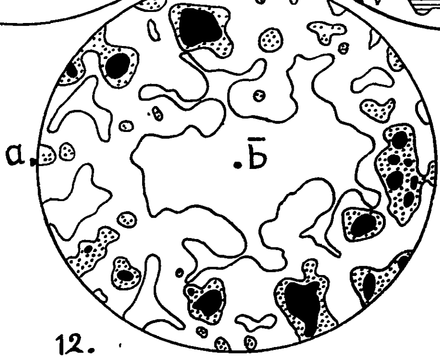

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All Figures Represent Projections of the Lower Hemisphere Upon a Schmidt Net.

Fig. 8.—Positions of maxima A, B, G, X for quartz in No. 4457, as deduced from curves of Fig. 6 (cf. Turner, 1938, Fig. 9). Inset circle shows outline of vein with reference to schistosity.

Fig. 9.—Fabric diagram for quartz (100 grains) in veinlets cutting schist No. 4457. Contours 8, 6, 4, 1%; maximum concentration 11% of quartz axes per 1% area. Measurements by Dr. E. Ingerson.

Fig. 10.—Positions of maxima D, E, H, J for quartz in veins in schist No. 4487 as deduced from curves of Fig. 7 (cf. Turner, 1938a, Fig. 7).

Fig. 11.—Fabric diagram for quartz (400 grains) in three parallel veins in *ac* section of schist No. 4487. Contours 3.5, 2.5, 1.5, 0.25%; maximum concentration 4% of quartz axes per 1% area.

Fig. 12.—Fabric diagram for quartz (200 grains) in one vein in *ac* section of schist No. 4487. Contours 3, 2, 0.5%; maximum concentration 4% of quartz axes per 1% area. The measurements upon which Fig. 12 is based are included with 200 additional measurements in the data for Fig 11.

The third example selected involves a more complex fabric. In a schist from Waipori (No. 4487, Turner, 1938a, pp. 113–117) quartz veins 2 mm. to 20 mm. thick are regularly developed parallel to the main schistosity *ab* and cutting more or less perpendicularly across an older contorted set of *s*-surfaces. Orientation curves drawn for *ab, bc* and *ac* sections of typical veins are shown in Fig. 7, while in Fig. 10 the maxima deduced from these have been replotted on a Schmidt net. The positions of the optic axes for 400 grains of quartz in *ac* sections of three typical veins were measured with a universal stage and form the basis of the fabric diagram Fig. 11; Fig. 12 is a partial diagram showing the orientation of 200 grains from one of these veins. In comparing Figs. 10 and 11 it will be seen that maxima at D and E in Fig. 10 have exactly equivalent maxima in Fig. 11, while there is a submaximum roughly equivalent to H. However, there appears to be no concentration in Fig. 11 corresponding to J of Fig. 10, while a strong maximum in the lower left quadrant of Fig. 11 has been confused with H in preparing Fig. 10. The latter therefore gives only an imperfect picture of the preferred orientation of quartz in the rock. Two important conclusions not brought out in the earlier paper might logically have been deduced: the strong maxima in the *bc* curve of Fig. 7 as compared with the less prominent widely distributed maxima of the *ac* curve indicate the existence of a girdle of quartz axes more or less perpendicular to the axis *b*; further, the development in both *ab* and *bc* curves of sharp maxima at about 30° from *c* suggests that the maxima lie upon a small circle of the *ac* projection, not on the periphery (cf. Sander, 1930, D. 52, p. 311; Fairbairn, 1939, Figs. 5–9). In this instance the applicability of the method based on orientation curves is limited by two factors both of which were recognised at the time of writing the earlier paper (see Turner, 1938a, p. 116). In the first place, the quartz fabric is not perfectly homogeneous so that measurements from different veins will give somewhat different maxima, while, secondly, the fabric itself is so complex that the curves are in some respects ambiguous and capable of more than one interpretation. Comparison of Figs. 11 and 12 shows the extent of inhomogeneity in the quartz fabric. In Fig. 12 there is a distinct maximum near the end of the *a* fabric axis, which is lacking in the partial diagrams for the other veins and hence in Fig. 11. Again the strong maximum adjacent to *c* in the top left quadrant of Fig. 12 is reduced to a submaximum in Fig. 11. It may be noted that the *ac* orientation curve for *Z′* in quartz of the same vein as that upon which Fig. 12 is based shows somewhat similar departures from the collective curve of Fig. 7 (compare with Fig. 10 in Turner, 1938a).

INTERPRETATION OF ORIENTATION CURVES FOR QUARTZ.

The following generalisations are now put forward with regard to interpretation of orientation curves based on measurements of extinction angles in quartz:—

(1) Substantial homogeneity of the fabric throughout the field of a hand-specimen is essential to a satisfactory correlation of maxima in *ab, bc* and *ac* curves. This condition is fulfilled only if curves constructed from measurements on parallel sections cut from different parts of the specimen are essentially similar.

(2) For certain simple types of fabric dominated by point maxima as contrasted with a girdle pattern, the principal features can be deduced exactly from orientation curves. The single maximum characteristic of certain tectonites that have been affected by strong slip in a single set of planes (Sander's maximum I) should readily be detected in this way (e.g., the fabric represented by D27, 28, Sander, 1930, p. 307). Again the pair of maxima (Sander's maxima II) developed symmetrically in the *ac* plane of many tectonites that have undergone simultaneous slip in two sets of planes with resultant " flattening " in the plane of schistosity, should also be able to be deduced as in the first example described in this paper (Figs. 1–5).

(3) The more frequent case where the pattern of the quartz fabric is dominated by a girdle of optic axes perpendicular to the *b* fabric axis can be only imperfectly worked out from the orientation curves. The most important feature of the fabric from the tectonic viewpoint is the direction of *b,* and this can usually be deduced approximately from the curves. Thus in Fig. 1 the strong maximum in the *ab* curve indicates the presence of either a single maximum approximately perpendicular to the lineation (megascopic *b*), or more than one such maximum lying in a girdle perpendicular to the lineation; the *ac* curve shows that the latter is the actual condition and that the *b* axis of the quartz fabric coincides with *b* of the megascopic fabric. Again in Fig. 7 the sharp strong maxima in the *bc* curve as contrasted with the weaker, more numerous, widely distributed maxima of the *ac* curve suggest that *b* of the quartz fabric does not depart widely from the megascopic *b*. It should be noted that the maximum in the *ab* curve does not necessarily lie exactly at 90° to the *b* axis of the girdle, for its position is determined partly by that of the dominating maxima within the girdle. In an earlier account of the Patearoa schists (Turner, 1938) it was assumed that the eccentric position of maximum A (Fig. 6) indicated lack of coincidence between *b* of the megascopic fabric and *b* of the quartz girdle. The fuller analysis depicted in Fig. 9 shows that the main quartz maximum is indeed somewhat eccentric with regard to the megascopic *b*, but the quartz girdle as a whole is approximately centred at *b*. When the quartz maxima lie on a double girdle with a single *b* axis (i.e., on a small circle of the fabric diagram projected on the plane perpendicular to *b*), there will be two strong maxima in both *ab* and *bc* curves symmetrically located with reference to *b*. This is well shown in the curves constructed for quartz veins in the Waipori schists (Fig. 7), and originally was wrongly interpreted as

indicating the existence of two independent quartz girdles with independent *b* axes neither coinciding with *b* of the megascopic fabric. [The corresponding deduction of late tectonic movements affecting only the quartz fabric (Turner, 1938a, pp. 120, 121, Table III (3)) was therefore not justified.]

(4) Investigation of the quartz fabric by the extinction-angle method is advisable only in cases when a universal stage is not available or difficult to use (as in measuring large sections of coarse-grained rocks). The writer finds that little time is saved, even in measuring simple fabrics, by employing the extinction-angle method.

MEASUREMENT OF MICA FABRIC.

Analysis of the fabric of mica or chlorite is based on determination of the orientation of the (001) cleavage. Since this tends to lie parallel to the *b* fabric axis and especially to visible or concealed *s*-surfaces intersecting in or curved about *b*, the fabric diagrams are used mainly in determination of *b* and verification of the positions of the main *s*-surfaces.

In the simple analyses previously made by the writer (e.g., Turner, 1938, pp. 446–449), the trace of the (001) cleavage was measured in oriented thin sections and plotted with reference to one of the three fabric axes. Subsequent work with the universal stage shows that this method is satisfactorily accurate, especially for determining the *b* axis of the mica (or chlorite) fabric. The following examples illustrate the applicability of the simple analysis.

(1) In a section of the schist No. 4457 cut parallel to the schistosity (*ab* of the megascopic fabric), the trace of (001) in muscovite was measured with reference to the direction of lineation in *ab* (*b* axis of the megascopic fabric) for all flakes in which the cleavage was visible. The result is shown in the upper curve of Fig. 13, in which the maximum does not quite coincide with *b*. This was interpreted as indicating that while there is a strong tendency for the flakes to lie with (001) nearly parallel to the lineation *b*, the axis of the mica girdle (*b* of the mica fabric) is actually inclined at about 10° to the *b* axis of the megascopic fabric (trend of lineation $b = 165°$; trend of axis of mica girdle $= 175°$). This is borne out exactly by the eccentricity* of the girdle with reference to *b* (megascopic) in the fabric diagram Fig. 14, which depicts the orientation of 100 flakes in the *ac* section of No. 4457 as measured with a universal stage by Dr. E. Ingerson. It might on first thoughts be objected that measurement of the cleavage-trace in mica crystals seen in a thin section cut parallel to the schistosity would not give a true picture of the fabric, since only those flakes in which (001) is inclined at a high angle to the plane of the section are included in such a series of observations. However, it is the orientation of precisely such crystals that allows determination of the exact position of the girdle axis from the standard fabric diagram Fig. 14 based on measurements with a universal stage.

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* Slight divergence between *b* of the mica fabric and the megascopic lineation is common in Otago schists (Turner, 1940, p. 79).

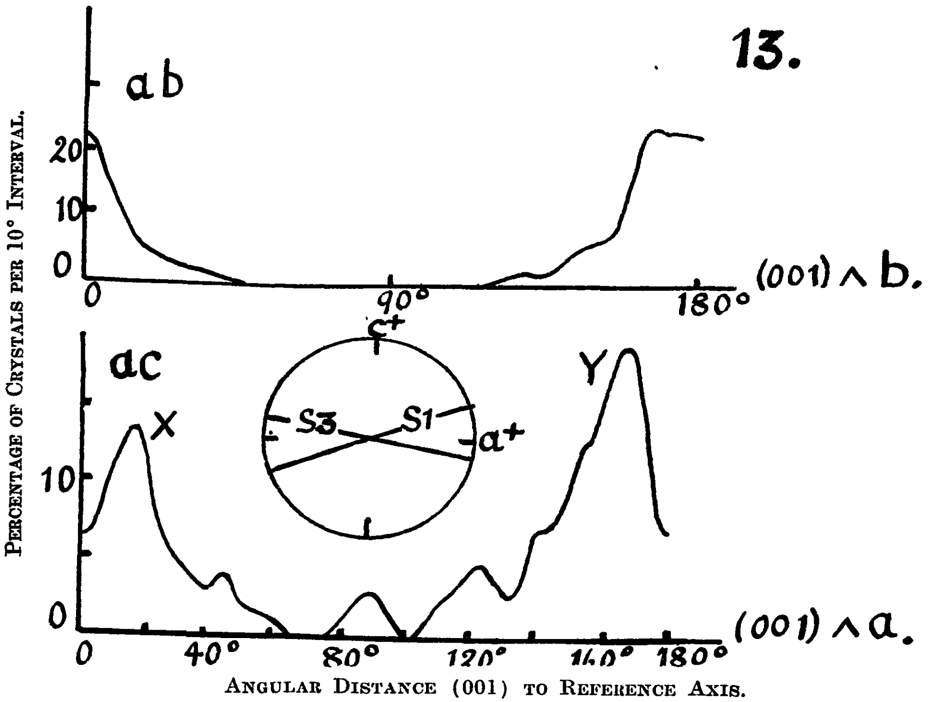

Fig. 13—Orientation curves for muscovite in "groundmass" of schist No. 4457 from Patearoa, Otago, measured in sections parallel to *ab* and *ac* respectively (Turner, 1938, Figs. 2, 3). Angular distance is measured anticlockwise from the positive end of the fabric axis in question. Positions of possible concealed *s*-surfaces S_1 and S_3 corresponding respectively to maxima X and Y are shown in inset circle.

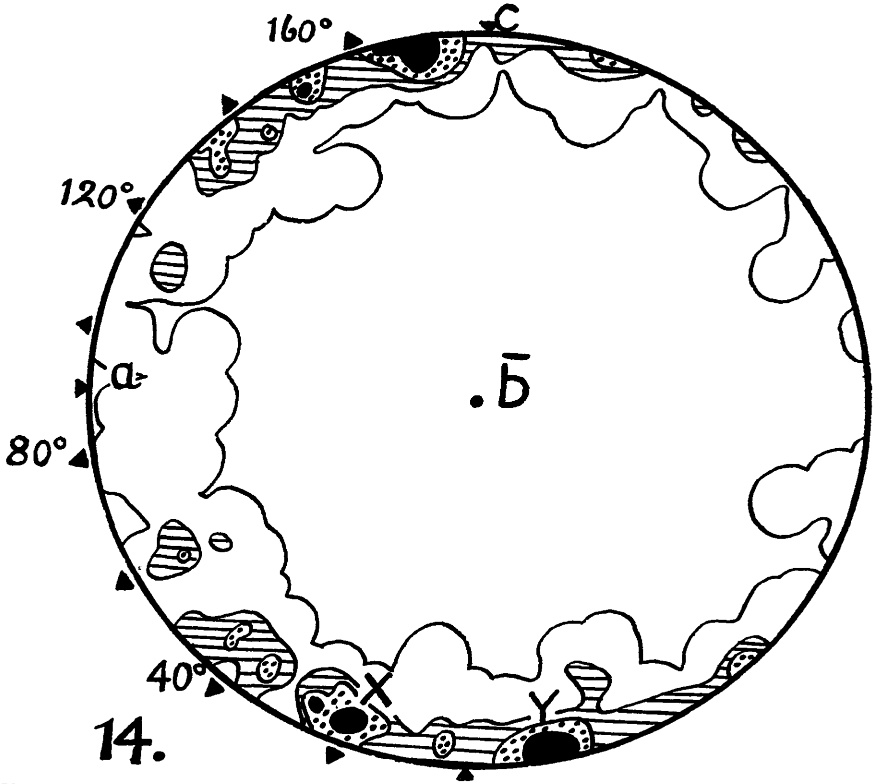

Fig. 14—Fabric diagram for muscovite (100 flakes) in "groundmass" of No. 4457 measured by Dr. E. Ingerson. Contours 8, 6, 4, 1%; maximum concentration 10% of cleavage poles per 1% area.

(2) In the schist No. 4487 from Waipori two lineations are apparent in the hand-specimen; the most conspicuous, *b*, has a trend of 170°–175°, while the fainter one, *b′*, trends at 160°. From the *ab* orientation curve for muscovite (Turner, 1938a, Fig. 2, pp. 11, 112) it was established that the axis of the mica girdle approximates to *b* and is not related to *b′*. A fabric diagram based on measurement of mica in the *ac* section, using a universal stage, shows a girdle centred at *b* and thus confirms the original conclusion.

(3) In the *ac* section of schist No. 4457 measurement of the trace of (001) in muscovite gave the lower curve of Fig. 13. The maxima at X and Y were interpreted to indicate that while the majority of the flakes lay subparallel to *ab* (the schistosity surface), they tended to be concentrated in planes S_1 and S_3 inclined respectively at 20° and 10° to *ab*, rather than in *ab* itself. This, too, is borne out exactly by the occurrence of appropriately located maxima X and Y in the fabric diagram Fig. 14. Since the latter shows the distribution of *poles* of (001) as seen looking from the *positive* end of the *b* axis, points measured clockwise from the negative end of *c* in Fig. 14 will correspond to points on the *ac* curve of Fig. 13 measured anticlockwise from the positive end of *a*. It will be seen that there is good agreement in detail as well as for the maxima, when Figs. 13 and 14 are compared on this basis. Whether the maxima X and Y are due to the presence of two distinct *s*-surfaces S_1 and S_3, or represent curvature of a single set of *s*-surfaces about *b* has not been established.

ACKNOWLEDGMENTS.

The writer is greatly indebted to Dr. Earl Ingerson, of the Geophysical Laboratory, Washington, who was kind enough to make independent measurements of quartz and mica in two of the rocks discussed in this paper. Figs. 6 and 9 have been prepared from Dr. Ingerson's results. While accepting full responsibility for the conclusions here put forward, the writer is also glad to acknowledge the benefit of critical discussion of the problem with Mrs. E. B. Knopf and with Dr. Ingerson.

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