Author's Note:

During the 18 months "in press" period for this paper two minor modifications have been applied to the "Small-Circle Net" technique.

(1) Intensities assigned (from x-ray data) to the small-circles are no longer summed and averaged at the net intersections (= arithmetic mean). The product and root is now taken of all intensities of small-circles passing through net intersections (= geometric mean). This procedure eliminates the element of non-rigor discussed on pp. 312-314 of the paper.

In spite of this more rigorous treatment the relative "highs" and "lows" of the diagrams are very nearly the same regardless of whether the arithmetic mean or geometric mean is used.

(2) Calculated intensities (from structure factor data, etc.) are now used entirely, or to modify standard intensity patterns for all minerals for which the intensities can be calculated. Even for a random fabric, however, calculated relative intensities will agree with the observed intensities only when the sample yielding the latter is larger than the x-ray beam. Therefore, at low angles (and with large slits) a simple correction must be applied to all intensities from peaks of such small 2θ value that the beam more than covers the sample. The observed intensity is simply multiplied by the ratio of beam area to irradiated area to obtain actual intensity.

Although the technique remains unchanged, except for the two items discussed above, it has also been found that only four rock surfaces (E, D, F, G, of Fig. 2-A) are quite sufficient to construct the net, as opposed to as many as six in previous studies.

B.L. Davis

[American Journal of Science, Vol. 262, March 1964, P. 307-324]

# THE SMALL-CIRCLE NET METHOD IN PETROFABRIC ANALYSIS*

BRIANT L. DAVIS

Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California

ABSTRACT. A new technique for use in petrofabric analysis has been developed using flat rock sections mounted on the goniometer of an x-ray diffractometer. Intensities of 10 to 15 reflecting planes of a mineral taken from four to six appropriately cut rock slices, as well as from the powder pattern, are sufficient to construct a complete petrofabric diagram.

The method is applicable to minerals of all symmetry with nearly equal ease, absorption corrections are eliminated, and the time required to process the data can be greatly reduced by means of a simple computer program.

X-ray petrofabric diagrams of quartzite tectonites from Sierra Pelona, California, and Fionne Allt, Scotland, show prominent a-c girdles, b-axis minima, and individual maxima in position II of Sander. A T-section of Yule marble shows the well-known point maximum normal to the foliation. A dunite from northwest Washington reveals an a-axis point maximum and a c-axis girdle lying in a plane normal thereto. X-ray and optical data are in close agreement.

## INTRODUCTION

Only recently have there been attempts to use the recording diffractometer in x-ray petrofabric analysis. Early studies were carried out using various film techniques most of which involved transmission or grazing incidence of the x-radiation. The use of such techniques for the study of the anisotropy of drawn wire or rolled sheet metal has become highly developed by the metals industry (see Taylor, 1961, chapter 13). Higgs, Friedman, and Gebhart (1960) give a brief summary of film and counter-recording techniques used in x-ray petrofabric analysis, and therefore further elaboration is not needed here.

Of considerable importance in recent developments using the diffractometer is that of Higgs, Friedman, and Gebhart (1960) which makes use of the spherical sample reflection technique described by Jetter and Borie (1953). This method requires an elaborate mounting apparatus which allows rotation of a hemispherical[1] sample about, (a) an axis parallel to but not coincident with that of the goniometer, and (b) another axis perpendicular to the goniometer axis. In obtaining the data axis (b) is first tilted 10° from the vertical, about axis (a), and a 360° traverse is made around the hemisphere. The axis is then tilted another 10°, and a second traverse made. At all times the reflecting surface remains tangent to the goniometer axis. In this way the lines of traverse on the hemispherical sample are seen as circles, concentric about the axis normal to that of the goniometer. The geiger arm is maintained fixed at the proper Bragg angle for the crystallographic plane under study. Intensity values are recorded on the conventional chart recorder. Here absorption can be ignored since the area of sample irradiated at any time is constant. This method has been applied to rock fabrics and the results verified by optical data. There is some disadvantage in (1) the special equipment needed to prepare

* Publication No. 249, Institute of Geophysics, University of California, Los Angeles 24, California.

[1] Higgs and co-workers modified the Jetter-Borie technique by using a hemisphere rather than the sphere.

the hemispherical sample and mount it for scanning, and (2) the dependence upon pinacoidal reflections in order to contour directly data for axial directions.

## SMALL-CIRCLE NET TECHNIQUE

The development of the small-circle net method came essentially as an answer to the question: Why should one not be able to make use of *all* of the crystallographic reflections obtained from flat rock slices for the determination of fabric anisotropy? It seems certain that all of the reflections of the mineral pattern are modified in some way by the anisotropy of the rock.

If one were to plot intensities of basal reflections from plane rock surfaces one would need to cut a prohibitive number of sections of different orientations to obtain sufficient data for a contourable diagram. By using fifteen or twenty of the more prominent reflections of the pattern, however, a complete petrofabric diagram can be constructed by the proposed method. Four to six flat rock sections and a powder specimen would all be scanned in the usual way in a high-angle goniometer.

For any crystalline material scanned in the goniometer it can be shown by simple diffractometery geometry and the Bragg law that only certain planes from the sample irradiated by the x-ray beam can contribute to an intensity measurement such as recorded by a peak on a diffractometer chart. First of all, the Bragg law must be satisfied in that for a particular angle of reflection, $\theta$, the d-spacing must be of a magnitude so that the paths of x-rays reflected from successive crystallographic planes will differ by an integral number of wavelengths of the radiation used. Secondly, these crystallographic planes must be coplanar with the sample surface which in turn is parallel to the goniometer reflecting surface.

If one were to take a slice of quartzite rock showing random orientation of grain and mount it like a normal "well" sample in the goniometer spindle (fig. 1), one should obtain a pattern similar to that of a firmly packed powder

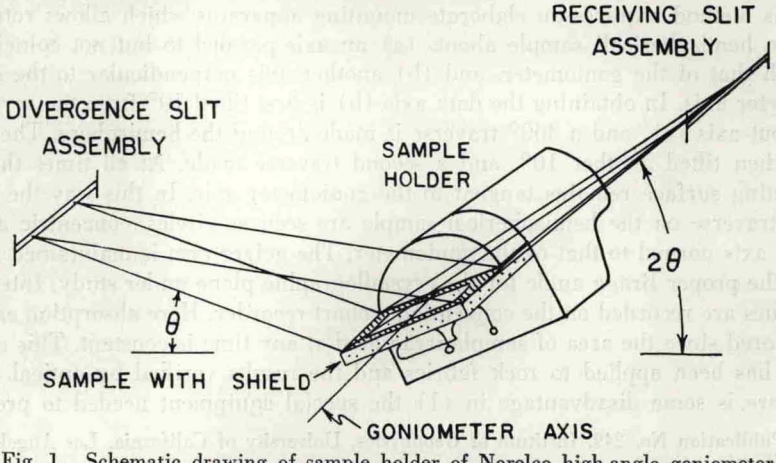
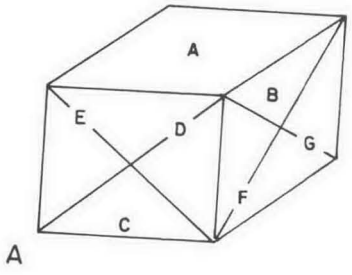
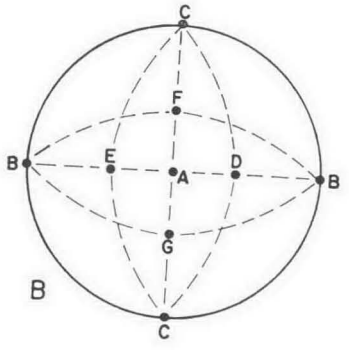



Fig. 1. Schematic drawing of sample holder of Norelco high-angle goniometer containing a sample (rock section) with thin metal shield. Fine lines represent beam path from divergence slit assembly to sample and then to receiving slit assembly.

"well" mount. Of course no x-ray method is reliable when applied to very coarse-grained rocks. To ensure a representative collection of grains, rocks should have an average grain size of no greater than 1 mm diameter. With 4° slits the area irradiated by the x-ray beam at 100° $2\theta$ (upper limit of scanning needed for most patterns) is 150 mm$^2$, and there will be approximately 190 grains irradiated by the beam. Material of coarser grain can be used if the section is mounted on an oscillator plate, such as found in the Norelco pole figure device. Another way to overcome the problem is to scan several different sections of the same orientation and average the resulting intensity measurements.

The theory of the technique is best illustrated by the determination of the position of a strong a-axis maximum by construction. The example is one ac-




STRONG REFLECTIONS

| | HKL | $\phi$ | SECTION |
|---|---|---|---|
| 1 | 210 | 13°06′ | A,G |
| 2 | 211 | 24°45′ | G, D |
| 3 | 322 | 31°33′ | G |
| 4 | 101 | 38°27′ | G |
| 5 | 130 | 54°24′ | E |
| 6 | 102 | 57°48′ | G, F, D |
| 7 | 122 | 61°29′ | — |
| 8 | 132 | 64°43′ | E |
| 9 | 113 | 67°35′ | E |
| 10 | 133 | 70°14′ | F |
| 11 | 134 | 73°55′ | — |
| 12 | 041 | 90°00′ | — |
| 13 | 061 | " | D |
| 14 | 020 | " | B |

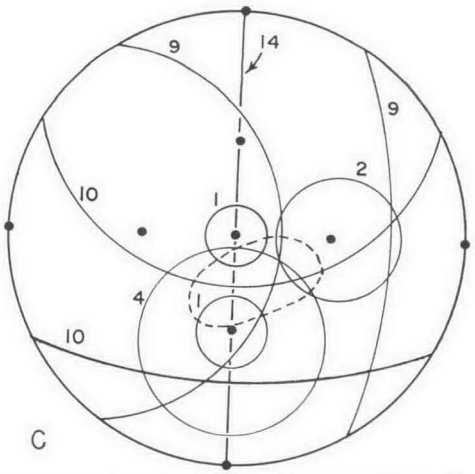



Fig. 2. Method for determination by construction of point maximum position: *A*, hypothetical sample showing the sections used; *B*, equal angle projection showing poles to sections of sample with section A as primitive circle section; *C*, seven small-circles representing crystallographic planes of anomalously strong intensity plotted on equal angle projection to show position of point maximum in sample.

tually carried out for a dunite from Cypress Island, Northwest Washington.[2] This rock has an average grain size of 1 mm (diameter) and therefore at 75° $2\theta$ (maximum $2\theta$ needed for olivine patterns) the number of grains irradiated is roughly 248. Figure 2A schematically illustrates the sample cut in the form of a cube having four cuts inclined 45° and two cuts 90° to surface A. In this example surface A corresponds to the plane of the stereographic net. The poles to sections A through G are shown on the stereographic net, figure 2B.

The rock slices cut parallel to planes A through G were inserted into the sample holder of the goniometer in the usual way, and the chart records taken. The slices were scanned from 16 to 75° $2\theta$ at 1°/min, using 4° divergence and scatter slits and 0.006-in. receiving slit. The chart speed was 1 in./min. Lead sheet with a rectangular opening 1X2 cm was placed on top of the sample to insure a constant low-angle area of irradiation (fig. 1). A special holder allowing adjustment of sample height was constructed for friable material or irregularly shaped fragments.

A direct indication of the amount of preferred orientation in the fabric cannot be gained from the absolute magnitude of the peak heights or peak areas alone. Therefore, the intensity for a particular reflection from the rock slice was divided by the intensity value for that reflection from the powder pattern, since the latter should represent complete random orientation of grain. Problems are encountered in obtaining completely unoriented powder material, however, especially from minerals with good cleavages. Of the four mineral types studied thus far—quartz, calcite, olivine, and mica—only the calcite and mica presented difficulties. The first determination of the Yule marble fabric showed that preferred orientation of grains in the powder pattern introduced anomalous effects in the center of the diagram (T-section) along with the expected point maximum. A second trial, using intensities based on a pattern by Swanson and Fuyat (1953) gave considerably better agreement with the optical data. A better way to solve this problem might be to modify the powder intensities obtained experimentally with those calculated with structure factor data. Future work with this technique will include the use of calculated intensities.

The material for the powder samples was derived in all cases from the rock under study so that impurities that would reduce the intensities of the desired peaks obtained from rock slices would also effect the powder intensities. In this respect care must be taken to see that reflections from impurities do not interfere with those of the mineral under study.

As stated previously the data for the dunite study were obtained by scanning rock slices A through G (fig. 2A). Upon examination of the diffraction pattern taken from rock slice D it was found that the olivine 211 peak was one of the strongest present in the pattern, it being 2.8 times as intense as the corresponding powder peak. In order to locate the possible positions for the a-axis maximum in the rock from the intensity of the 211 peak one must first know the angle between the a-axis and the normal to 211. This angle, along with

[2] This specimen was donated to the writer by C. B. Raleigh, Institute of Geophysics and Planetary Physics, University of California, Los Angeles.

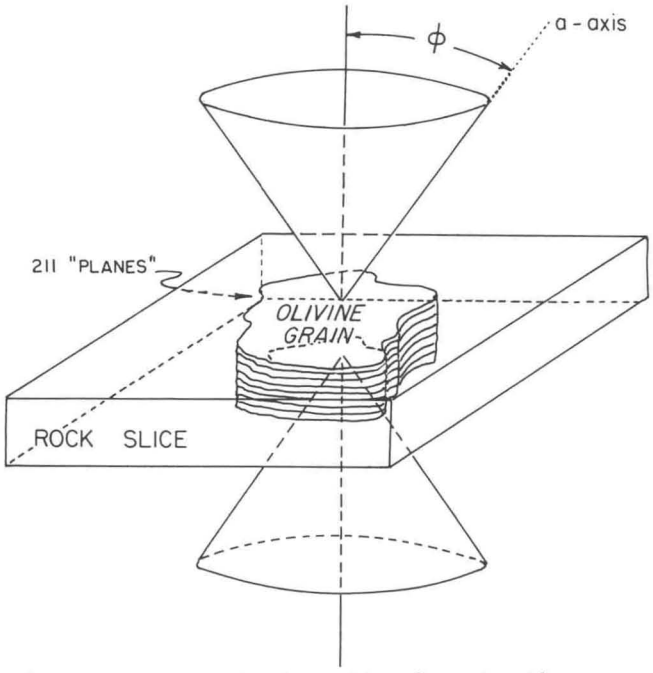



Fig. 3. Geometrical relations showing position of a grain with respect to rock slice necessary for reflection conditions to exist and the possible positions of the a-axis of the grain. See text for further explanation.

others, is designated as $\phi$[3] and is found in the table of strong reflections of figure 2. The relations between the poles to any two planes in a crystal structure are easily determined by simple trigonometry if the cell dimensions are known.[4]

Since the planes contributing to the strong intensity of the 211 peak must lie parallel to the sample surface (i.e. rock slice surface) we conclude that the a-axes whose orientations are related to the strong 211 reflection must lie at an angle of 24° 45′ to both the normal to 211 and the normal to the rock section. However, these 211 planes cannot be restricted to any one position about their own normals so that all we know so far is that this group of a-axes lies on a cone about the normal to 211. These relations are illustrated in figure 3 for one particular olivine grain of the appropriate orientation. When this cone (of half-angle $\phi$ = 24° 45′) intersects the lower hemisphere of the spherical projection in an orientation fixed by the attitude of the rock section with respect to the primitive circle (= section A) it creates a small-circle. This small-circle is projected from the lower hemisphere to the plane of the stereographic projection as a true circle. The small-circle of $\phi$-angle 24° 45′ is labeled 2 (fig. 2C).

The diffraction pattern for rock slice F was examined, and it was found that three peaks were very strong relative to the powder peaks and all had

[3] $\phi$ is here defined as the angle between normals to crystallographic planes and crystallographic axes.

[4] Except for the cubic system where only the indices are needed to determine $\phi$.

$\phi$-angles of similar magnitude. For example 133 is 3.2 times as strong as that of the powder pattern. The same geometrical relations apply here as for the case above except that the rock slice F has a different orientation. The resulting small-circle (10, fig. 2C) intersects the 211 small-circle in two places.

Similar construction of small-circles corresponding to strong reflections from planes lying parallel to rock slices A and G yield the remaining arcs of figure 2C. It is immediately apparent that there is a zone of intersections in the lower right-hand quadrant of the figure. When *all* of the strong reflections are used from the patterns obtained from the seven rock sections of figure 2A the restriction of intersections to this zone is even more remarkable. Of the fifteen recorded reflections that have an intensity of 2 times the powder value, or higher, only one lies outside of the region shown by the dashed line of figure 2C.

It is apparent from the x-ray (and optical) data that the dunite contains an a-axis point maximum. Yet a routine procedure such as that outlined above would be impractical from two standpoints: (1) the time-consuming nature of the constructions, and (2) the difficulty in describing the complete fabric anisotropy except for cases of point maxima.

Accordingly in order to generalize the technique it is necessary to standardize the number and orientation of the rock slices from the sample, and one such arrangement is that of figure 2A. Furthermore, for any one mineral the $\phi$-angles are constant, and there are usually a sufficient number of crystallographic planes in the structure to obtain $\phi$-angles from 15° to 90°. From this a net can be constructed composed of small-circles of varying $\phi$-angle concentric about each of the four sections inclined 45° to A (fig. 2A). The resulting "small-circle net" is seen in figure 4 (in this example one for *calcite*). Note the four zones of concentric circles centered about the poles to the four inclined rock sections. It should also be pointed out that, because of the symmetry of this net, the intersections at the periphery of the net cannot be used. The width of this peripheral zone for a 20 cm diameter net would be approximately 1 cm. Therefore, in diagram D, plate 1; diagram D, plate 2; and diagram D, plate 3, the contours of the diagram have been extrapolated outward to the periphery.

In order to establish the position of any point on the stereographic projection that might correspond to a maximum, one is required to use intersections of three or more small-circles. In this respect the method is similar to the "three drill core" problem of structural geology. Thus the practical aspects of deriving a petrofabric diagram based on x-ray data consist of (1) assigning intensity values[5] to the small-circles, (2) summing these values up at intersections of three or more small-circles, taking the averages, and plotting the values at the intersections, and (3) contouring over the entire net the values obtained.

The technique cannot be considered rigorous for the reason that false maxima can occur wherever small circles intersect at more than one place on the net. This situation is more readily visualized, and probably becomes more critical, when the orientation of grain becomes very perfect (i.e., when the grain aggregate approximates a single crystal).

[5] Ratios of rock-section intensity to powder intensity for every reflection used.

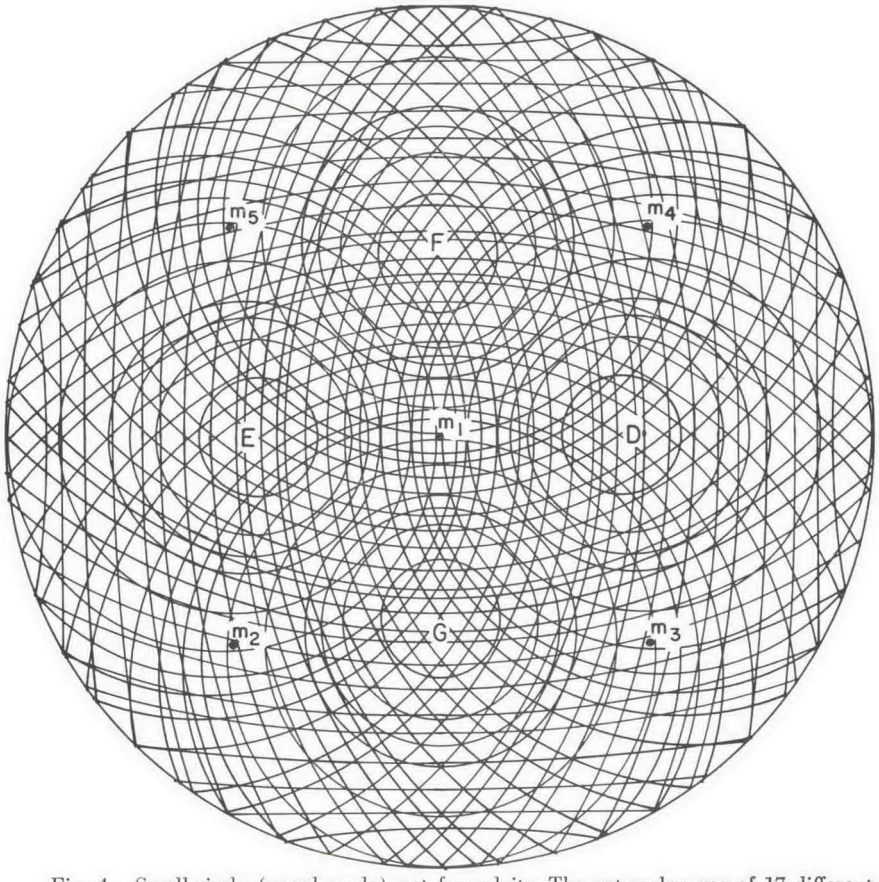



Fig. 4. Small-circle (equal angle) net for calcite. The net makes use of 17 different reflecting planes with $\phi$-angles ranging from 13 to 90 degrees. Each set of 17 is concentric about the normals to four inclined rock sections dipping 45° to the section containing the primitive circle (plane of the paper). Letters D, E, F, and G correspond to sections of figure 2A, B.

Consider, for example, point $m_1$, figure 4. Here four circles (those corresponding to the "r" planes of calcite) intersect at the center of the net, one from each of the sections D, E, F, and G (see fig. 2A, B). If there were a point maximum located here at the very center of the net, the intensities of all four of these planes would be very strong. But note also that two of the four circles intersect at points $m_2$, $m_3$, $m_4$, and $m_5$. However, other small circles pass through, or very close to, these four points but not through $m_1$. If the point maximum were very perfect, the calcite r planes would yield very strong intensities, whereas the others would probably not even be recorded on the diffraction chart. Consequently, the average intensity value for $m_2$, $m_3$, $m_4$, and $m_5$ would be very much reduced compared to the average for $m_1$, but not to zero intensity as would be expected for a perfect point maximum or single crystal. This phenomena is characteristic of most areas of the net.

That these potential weaker false maxima do not seriously affect the resulting diagrams is shown by the corresponding optical diagrams of plates 1, 2, and 3. In the event that a false maximum is suspected in the diagram, a simple inspection of the intensity data is usually sufficient to determine whether it is real or not. As an example we take the x-ray petrofabric diagram for the Yule Marble, diagram D, plate 2. The moderately strong maximum just to the left and below the center of the diagram does not appear in the optic diagram, C, plate 2, and therefore might not be real. The net used to construct the x-ray diagram is that of figure 4. Circles 9 to 15 of sets F and G in general have high intensity values because of the locality of the main point maximum. These circles also pass through the weaker maximum in question and thus contribute to high values of intensity averages in this area. If this maximum were real, then some or all of circles 2 to 6, set G, and circles 11 to 14, set D, should have stronger than normal intensities. None of these circles lie in the region of the net containing the main point maximum and therefore are appropriate for the test. Finally, examination of the intensities assigned to these circles shows that only one has an intensity greater than the random (powder) value, and hence it may be concluded that this weaker maximum is false or at least considerably exaggerated.

Although such tests as the above are simple and quick to perform, a search should be made for a correction or an improvement for the technique that would eliminate this uncertainty. It has been suggested that multiplication of intensities at intersections of small circles rather than summation would eliminate such false maxima. This possibility is presently under consideration.

There are several methods for speeding up the summation process, the most promising of which has been the use of high-speed computing systems. Mr. W. E. Sharp of this institution has designed a data handling program for the IBM 7090 which is now in use, and Mr. W. L. Reuter (South Dakota School of Mines and Technology) has modified this program to fit the IBM 1620.

## ABSORPTION

It is well known that the absorption of x-rays by powder spread thinly on a surface is a function of the Bragg angle and bulk density. For those of "infinite" thickness, however, absorption of x-rays is independent of Bragg-angle (Cullity, 1956, p. 189), providing that the sample is larger than the area irradiated by the beam at low angles. Provided that the sample areas and bulk densities are identical for all rock slices and that the irradiated area for rock slice and powder mount is the same, the absorption due to non-"infinite" thickness is quite irrelevant to the problem, inasmuch as the final data are expressed as rock-slice intensity to powder intensity ratios for each hkl.

Another source of error due to absorption is found in the difference in bulk densities between rock slice and powder mount. At the rock surface the grains are tightly packed or cemented, and pore space is nil; conversely, even in packed "well" samples, the pore space of the powder is considerable. The amount of error involved from this source is unknown, although it is expected that the increased penetration into the powder would at least in part offset the weaker reflection from the fewer grains in the immediate surface layer.

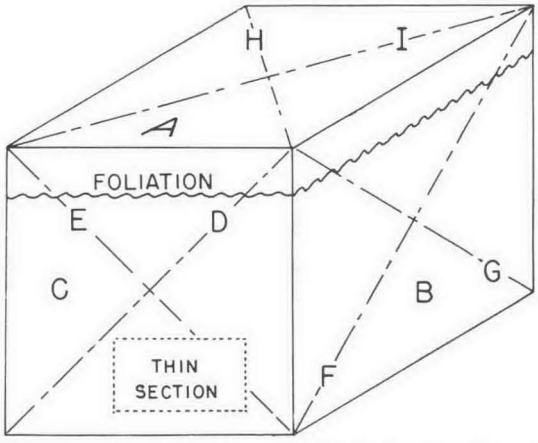



Fig. 5. Schematic sample in the form of a block showing thin section, sections for x-ray work, and foliation location. Block need not be larger than two inches on a side. See text for further explanation.

Errors related to this latter absorption factor will only increase or decrease the value of the final contour; it will not change the appearance of the diagram. This is to say that regardless of the absolute intensity values assigned to the peaks of the powder pattern (providing that the *relative* intensities agree with those of the correct powder pattern) the positions of the "highs" and "lows" of the diagram will remain unchanged. However, it would be better to obtain the correct absolute intensities of the powder pattern since the final contour values of the petrofabric diagram will then represent directly the amount of departure from randomness in the sample fabric. If this error did not exist then a contour assigned the value of three would enclose an area in which there would be at least three times as many crystallographic axes of that orientation than would exist if all of the axes were of random orientation.

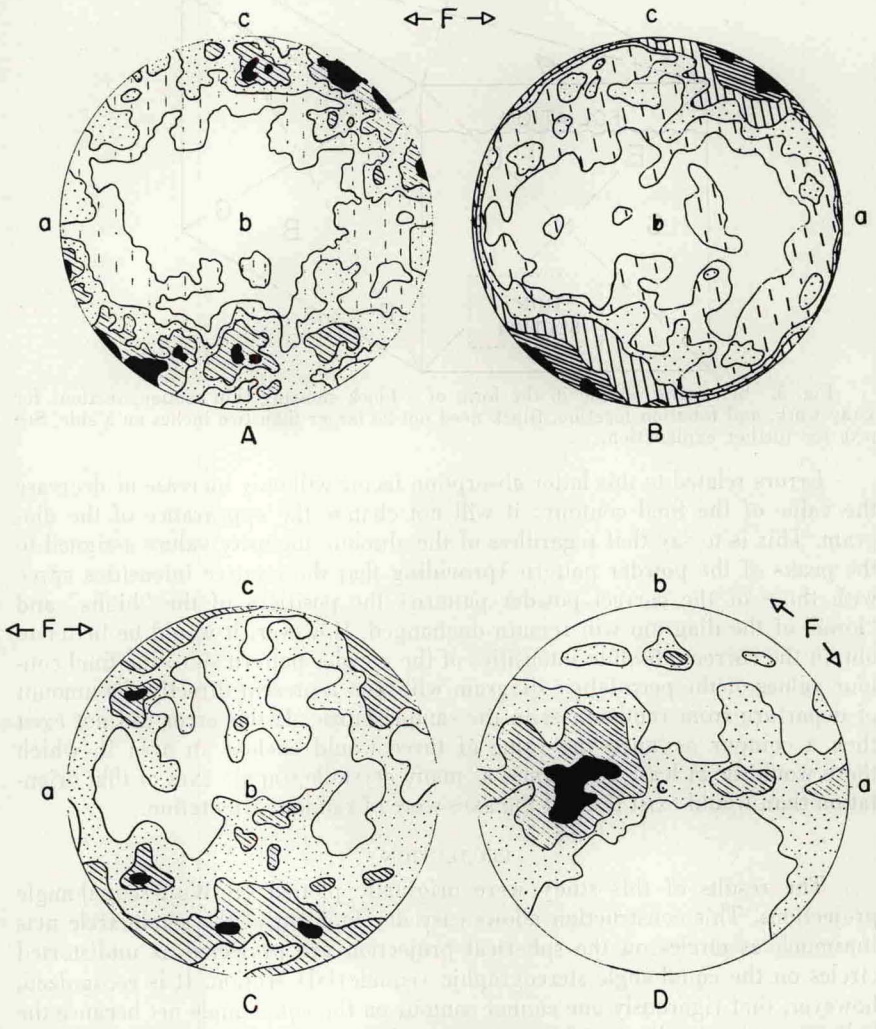
## PROJECTION

The results of this study were originally plotted on Wulff equal-angle projections. This construction allows easy development of the small-circle nets inasmuch as circles on the spherical projection are projected as undistorted circles on the equal-angle stereographic (equatorial) section. It is recognized, however, that rigorously one cannot contour on the equal-angle net because the half-way point in distance between two values on the spherical projection is not the half-way point when projected onto the stereographic section. Therefore, all petrofabric data have been transferred to the Schmidt equal-area net.

## APPLICATION TO SELECTED TECTONITES

*Sierra Pelona Quartzite.*—This sample, collected by the writer from Sierra Pelona, California, was studied as part of a more general program to determine possible directions of tectonic movement in the vicinity of the San Andreas Fault. The rock is a loosely coherent, nearly pure quartzite containing only 1 percent muscovite and a trace of calcite. Traverses normal to the foliation

PLATE 1




A. Quartzite, Sierra Pelona, California. 250 c-axes with contours 0, 0.8, 2, 3, 5% per 1% area. F and b are foliation and lineation, respectively. Schmidt Equal Area Net.

B. X-ray petrofabric diagram of Sierra Pelona quartzite. Contours 1.0, 1.3, 1.5, 2.0, 2.5 times powder intensity. Schmidt Equal Area Net.

C. X-ray petrofabric diagram of Sierra Pelona quartzite, using data from two sections of B (above) and from two other closely adjacent sections. Contours 1.0, 1.2, 1.3 times powder intensity. Schmidt Equal Area Net.

D. X-ray petrofabric diagram of Sierra Pelona quartzite using data employed in both diagrams B and C (above). Note difference in orientation compared to B and C. Contours 1.0, 1.3, 2.0 times powder intensity. Schmidt Equal Area Net.

showed a grain diameter of 0.13 mm, and traverses parallel to the foliation, 0.29 mm.

Figure 5 schematically illustrates the sample and the sections used to obtain *B*, *C*, and *D*, plate 1. Diagram *B* makes use of data from sections A, D, E, H, and I; diagram *C* makes use of data from sections A, B, F, G, H, and I; and diagram *D* makes use of data from sections B, C, D, E, F, and G. Diagrams *C* and *D*, therefore, make use of four sections inclined 45° to the plane representing the primitive circle and two sections normal thereto, whereas diagram *B* makes use of two inclined and three normal sections. In diagrams *B* and *C* the primitive circle corresponds to section C and in diagram *D* the primitive circle corresponds to section A. Although the type of orientation of diagram *B* yields a net giving results that agree in major detail with optical data, there appears to be some duplication of minor detail in the diagram. This feature seems to be the result of the symmetry of the net itself.

Diagram *A*, plate 1, represents optical data for the Sierra Pelona quartzite and is based on 250 c-axes of the quartz. Note the small-circle girdle (in addition to the main a-c girdle) whose axis diverges slightly from the c fabric axis. The x-ray petrofabric diagram *B* might show a trace of this girdle, but diagram *C* confirms this feature in a more definite way.

Although rotation of data points or contours will give diagram *D* from diagram *B* directly, the data from the four inclined sections D, E, F, G and two normal sections B and C (with A = primitive circle) were combined and recontoured.

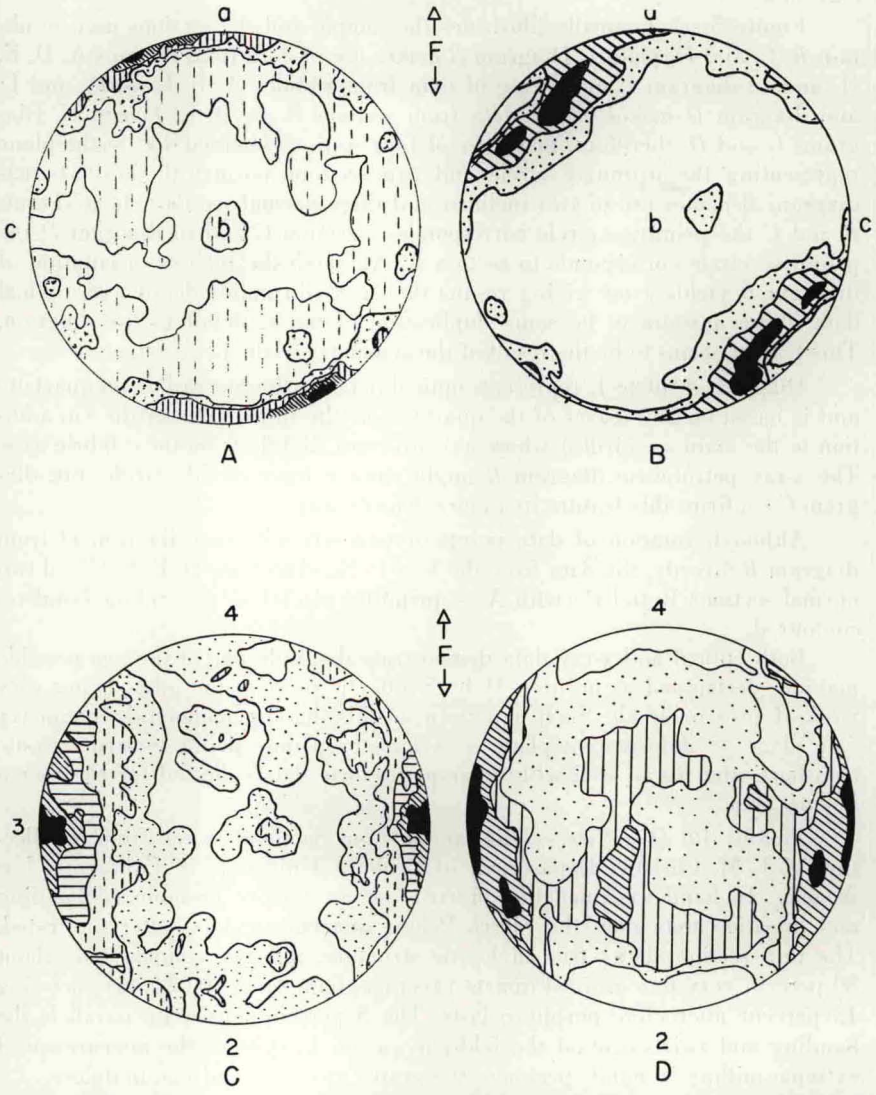
Both optical and x-ray data demonstrate that only one of the two possible maxima designated as position II by Sander is present, the other being very weak if present at all. Such a pattern as this, having monoclinic symmetry (a-c plane = deformation plane = symmetry plane) points toward tectonic transport, and fits in well with other petrofabric data collected for the Sierra Pelona area.

*Fionne Allt Quartzite.*—This sample from Scotland is one from a collection of J. M. Christie, Department of Geology, University of California, Los Angeles. In hand specimen the quartzite shows a more pronounced banding and lineation than does the Sierra Pelona quartzite and is better indurated. The thin section shows true mylonitic structure, it being composed of about 80 percent very fine grained quartz (average diameter = 0.03 mm) inclosing 15 percent microcline porphyroclasts. The 5 percent muscovite parallels the banding and swirls around the feldspar augen. In spite of the appearance of extreme milling in hand specimen, the grains are clear and non-undulose.

Diagrams *A* and *B*, plate 2, show the fabric based on 300 c-axes of quartz and the x-ray data respectively. The data for the x-ray diagram was compiled from two sections inclined 45° and two sections normal to the primitive circle section.

Again, as in the Sierra Pelona example, the major features of the x-ray and optical diagrams agree, but the reality of the small-circle girdle of the x-ray diagram is questionable. The symmetry of fabric is monoclinic with unequal development of Sander's maximum II.

PLATE 2




A. Fine-grained quartzite from Fionne Allt, Scotland. 300 c-axes with contours 1, 3, 5, 8, 10% per 1% area. F and b are megascopic foliation and lineation, respectively. Schmidt Equal Area Net.

B. X-ray petrofabric diagram for Fionne Allt quartzite. Contours not precisely identifiable but approximately 1.5, 1.8, 2.1 times powder intensity. Megascopic coordinates as in A. Schmidt Equal Area Net.

C. Optical data for Yule marble, T-section. 300 c-axes with contours 0.3, 1, 3, 5, 7% per 1% area. From Turner and others (1956). F = foliation. Schmidt Equal Area Net.

D. X-ray petrofabric diagram for Yule marble, T-section. Contours 1.0, 1.3, 1.5, 2.0 times powder intensity. Schmidt Equal Area Net.

*Yule Marble.*—The Yule marble is a very pure rock composed of moderately coarse, occasionally twinned, interlocking grains. In an average of data from traverses both normal and parallel to the foliation, the grain size is near 0.5 mm. The foliation is strong, and there is not marked lineation. According to Turner and others (1956), the initial fabric (before their deformation experiments) is quite homogeneous with respect to the c-axis distribution.

The optical data, diagram *C*, plate 2, is taken from Turner and others (1956) and represents 300 c-axes of the calcite grains. The plane of the projection here and in the x-ray petrofabric diagram is the T-section (see Turner and others, 1956, p. 1264). The rock sections used in the x-ray petrofabric analysis consist of four inclined 45° to the T-section and two normal to the T-section. The well-known point maximum which lies normal or at a high angle to the foliation is obvious in both diagrams, but there are some differences in detail. It appears that a weak girdle might exist lying in the plane of the T-section as determined optically but a similar girdle lies normal to the T-section in the x-ray diagram. In better agreement with the x-ray data is the c-axis diagram of Yule marble compiled by Higgs, Friedman, and Gebhart (1960, p. 286) showing a weak girdle also normal to the T-section. The small maximum to the left and below the center of the diagram is probably not real (see p. 9).

Possible explanations for these deviations will be discussed below.

*Cypress Lake Dunite.*—The optic analysis on this specimen from northwest Washington was carried out by C. B. Raleigh. Results were compiled on a- and c-axis distributions.

The dunite is relatively coarse grained, having an average grain size near 1 mm. For this reason one study was made using the usual one scan per rock slice, and another study was made using four scans from different parts of the rock slices, taking an average of the data.

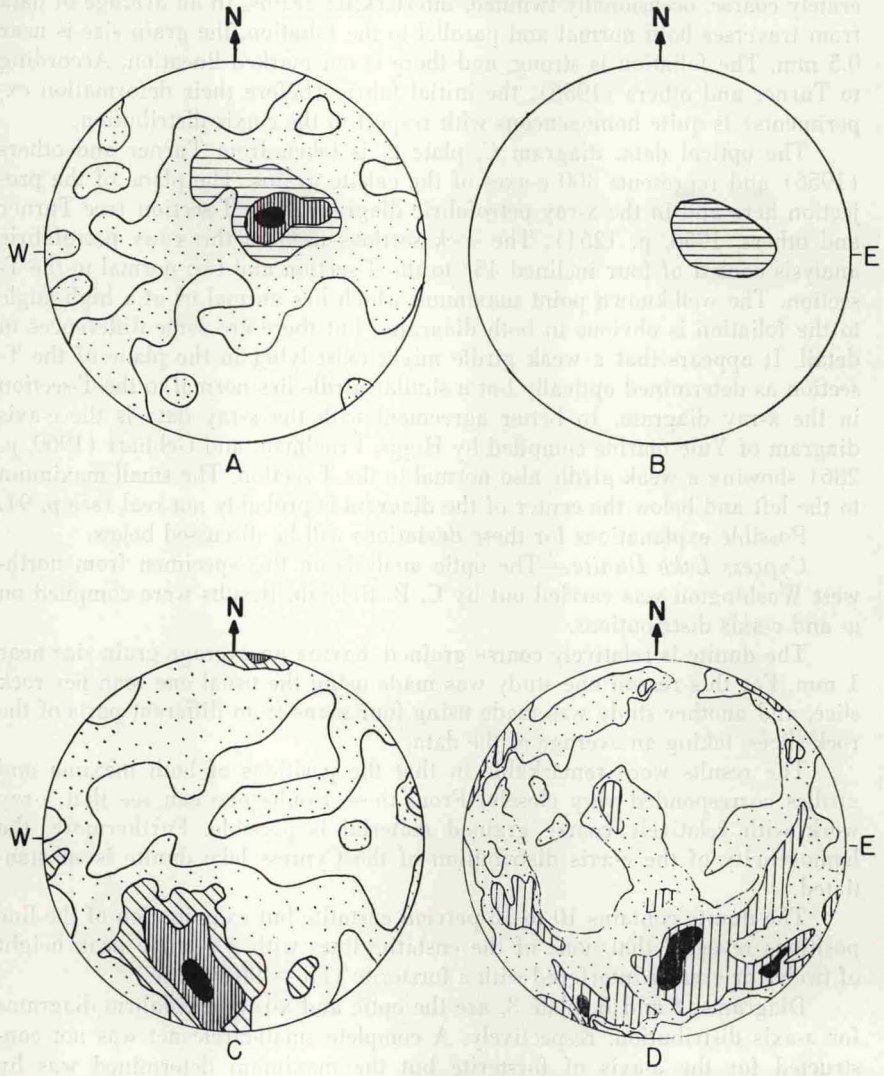
The results were remarkable in that the positions of both maxima and girdles corresponded very closely. From these results one can see that x-ray work with relatively coarse grained material is possible. Furthermore, the homogeneity of the c-axis distribution of the Cypress lake dunite is substantiated.

The dunite contains 10 to 15 percent enstatite but examination of the line positions revealed that none of the enstatite lines with a relative peak height of twelve or greater interfered with a forsterite (Fo = 90+) line.

Diagrams *A* and *B*, plate 3, are the optic and x-ray petrofabric diagrams for a-axis distribution, respectively. A complete small-circle net was not constructed for the a-axis of forsterite but the maximum determined was by construction as discussed in a foregoing section. Of course, the weak girdle determined by optical means could not be delineated by construction.

Diagrams *C* and *D*, plate 3, represent the optic and x-ray petrofabric diagrams, respectively, for c-axis distributions. The x-ray data differ from that of the optic diagram in that the strong point maximum of the latter is spread out into a broad zone lying in a girdle that dips moderately south to southeastward. Other petrofabric data determined by Raleigh (personal communication) show that the general pattern in these dunites is a girdle dipping moderately southwestward.

PLATE 3




A. Dunite, specimen 0A10 from Cypress Island, Northwest Washington. 150 a-axes, contours 0.7, 4, 7, 10% per 1% area. Schmidt Equal Area Net. After C. B. Raleigh.

B. Location, by construction from 17 small circles of abnormally strong reflection value, of point maximum from dunite specimen 0A10, Cypress Island, Northwest Washington. Ruled area represents reflection intensity $\geqslant 3\frac{1}{2}$ times powder pattern. Schmidt Equal Area Net.

C. Dunite, specimen 0A10 from Cypress Island, Northwest Washington. 150 c-axes, contours 0.7, 2.7, 4, 7% per 1% area. Schmidt Equal Area Net. After C. B. Raleigh.

D. X-ray petrofabric diagram of dunite from Cypress Island, Northwest Washington, representing c-axis concentration. Contours 1.1, 2.2, 3.6 times powder intensity. Schmidt Equal Area Net.

The orientation of sections used for the x-ray analysis is identical to that of the Yule marble experiment, except that the plane of the stereo-net for the dunite represents the horizontal.

### EVALUATION OF DIFFERENCES BETWEEN OPTIC AND X-RAY DATA

Although there is good correspondence in major detail between the optic and x-ray results there are certain noticeable differences in some of the dia grams. Examples are (1) the small-circle girdle of *B*, plate 2, that is not present in the optic data of *A* (Fionne Allt quartzite), (2) the weak point maximum of *D*, plate 2, that is not apparent in the optic diagram, *C* (Yule marble), and (3) the existence of a more broad girdle of strong maxima in *D*, plate 3, instead of a point maximum as seen in the optic data, diagram *C*. (Cypress Lake dunite).

The small-circle girdle of *B*, plate 2, might be related to the symmetry of this type of net. Sufficient results have been obtained with this net to show that it should be discarded in favor of the one having four sections inclined to the primitive circle section rather than just two. Results obtained so far with the former net have shown no reproduction of minor detail.

The differences in the x-ray and optic data for the Yule marble and Cypress Lake dunite might result from one or more of the following causes:

(1) The difficulty in obtaining the correct powder intensity data for calcite because of the excellent cleavage.

(2) The inability for one working with the universal stage to record orientations for the fine-grained fraction. The x-ray technique is completely non-selective in this respect.

(3) Inhomogeneity of fabric.

(4) The occurrence of "false" triple points (see p. 312-313).

Future work with calculated intensities, or other methods of handling the data that would eliminate the need for a powder pattern, will tend to remove (1) as an error factor. It is not likely that problems resulting from (2) can ever be eliminated. In consideration of (3) it should be obvious that any comparisons made must rely on homogeneity of the fabric, at least within the realm of the hand specimen, otherwise fabric differences would result in unavoidable differences in both the optical and x-ray results. Point (4) has already been discussed in detail (p. 312-313) and is probably a greater source of uncertainty than the other three items listed above.

### COMPARISON WITH PRESENT TECHNIQUES

Once the small-circle net and points of small-circle intersections are established for each mineral they are permanent and need not be considered in the time consumed in producing an x-ray diagram. With this consideration it would be desirable to compare the time necessary to turn out a petrofabric diagram by the x-ray method and by the Universal stage method. The following is a comparison of times consumed by an experienced person in each technique. The sample is assumed to be a coherent quartzite of moderately coarse grain (¼ to ½ mm).

The contouring time for the x-ray method comes solely from the drawing of iso-lines around approximately four hundred numbers. The contouring time for the universal stage method, however, includes for each point of the grid the summation of c-axes within a circular area representing 1 percent of the entire net area, using the usual point counter, and then actually contouring the approximately three hundred points of the net.

SMALL-CIRCLE NET

| | hours |
|---|---|
| Sample Preparation | 1.50 |
| Scanning[6] | 2.50 |
| Table compilation | 0.75 |
| Summations and results to net | 6.00 |
| Contouring | 0.25 |
| Total | 11.00 |

UNIVERSAL STAGE

| | |
|---|---|
| Sample Preparation (two thin sections) | 1.50 |
| Axes measurements (300 grains) | 5.00 |
| Transfer results to Schmidt net | 2.00 |
| Contouring | 2.00 |
| Total | 10.50 |

The estimated time for the x-ray technique is for the case of hand summation of the intensities at the intersections of small-circles, rather than summation[7] by high-speed computer. Nevertheless, the data can be typed out on program cards (45 min) and added to a program stack (already punched out and considered permanent) for computer summation.[8] This reduces the summation time to one hour and therefore makes the x-ray technique far superior to the Universal stage technique when considering actual operator time. A further reduction in operator time comes from continuous scanning of the rock pieces in which the operator merely mounts and removes the sample. A person experienced in the use of the diffractometer and in the small-circle net technique can turn out a diagram in five hours.

Furthermore, the above comparison assumes a sample material of quartzite, optical measurements from which are relatively simple. Minerals of lower symmetry (orthorhombic, monoclinic, triclinic) are much more complex in optical properties, and measuring time on the Universal stage increases to perhaps 10- or 20-fold. Crystallographic properties also become more complex which means considerable more time in construction of the small-circle net. But once this net is complete it is permanent; the time needed to complete an x-ray diagram from this net is no greater than for one based on a quartz net.

[6] Operator scans only desired lines.

[7] Summation of intensities assigned to small circles at every intersection of three or more small-circles over the net.

[8] This has been done and successfully tested for calcite using IBM 7090.

A further advantage in the x-ray technique is the applicability to opaque minerals and metals, as well as non-opaque minerals, and the use of one net only for all isometric minerals and metals.

The x-ray technique allows study of any crystallographic direction in a mineral, at no extra cost in time, once the net has been constructed. With the U-stage, however, such a direction could be determined in a mineral grain only by laborious construction from considerable optical and crystallographic data (cleavage, twinning, crystal faces, etc.), and this must be repeated for every grain counted. The time needed to obtain a petrofabric diagram this way would be prohibitive.

For rocks too fine grained for optical analysis the x-ray technique (whether the small-circle net method or some other) is the only alternative. But the above discussion applies to relatively coarse-grained rocks as well, and in the writer's opinion the old belief that x-ray analysis must be reserved for very fine grained rocks need not apply to the small-circle net method.

Concerning the relative accuracy of the x-ray diagrams compared to those of optical derivation one can only say that extensive testing and use of the x-ray method will give the answer. From the data collected so far it seems most likely that major features of the diagrams are faithfully portrayed. It is true that minor features are in doubt, but in optical analysis it is common to see the minor features change about in the diagram as each 100 grains is added to the count. Just how many grains are necessary in the U-stage method to reveal correctly the minor features is anyone's guess, but if the minor features of the x-ray diagram are real they represent the best picture available since x-rays do not omit fine grains and are non-selective.

## CONCLUSIONS

The small-circle net method appears to represent a general technique for the quantitative evaluation of fabric anisotropy that requires only the use of the x-ray diffractometer and goniometer and does not require special sample preparation or rotation equipment. Moreover, the small-circle net method is applicable with equal ease to all minerals, regardless of symmetry, once the proper net has been constructed. Absorption corrections are eliminated by the geometry of the technique.

Processing of the x-ray data by hand allows reduction of the data to the usual petrofabric diagram in a reasonable length of time, and application of computing techniques to the problem offers a possible means to speed up the process.

Results obtained both petrographically and by use of the x-ray method on quartzite, marble, and dunite tectonites agree in major detail. The technique demonstrates that point maxima, scattered irregular maxima, and girdles can be located precisely by contouring the x-ray data and that strong maxima can be located precisely merely by graphical construction.

Limitations of the technique may permit spurious maxima to appear, but the reality of these may be ascertained by quick inspection of the experimental intensity data.

ACKNOWLEDGMENTS

The author wishes to thank Dr. Leason H. Adams, Dr. Earl Ingerson, and W. E. Sharp for review of the manuscript and for helpful discussion and comments.

REFERENCES

Cullity, B. D., 1956, Elements of X-ray Diffraction: Reading, Mass., Addison-Wesley Pub. Co., Inc., 514 p.

Higgs, D. V., Friedman, M., and Gebhart, J. E., 1960, Petrofabric analysis by means of the x-ray diffractometer: *in* Rock Deformation, Griggs, D. T., and Handin, J., eds., Geol. Soc. America Mem. 79, p. 275-293.

Jetter, L. K., and Borie, B. S., Jr., 1953, Method for the quantitative determination of preferred orientation: Jour. Appl. Physics, v. 24, p. 532-535.

Swanson, H. E., and Fuyat, R. K., 1953, Standard x-ray diffraction patterns: [U.S.] Natl. Bur. Standards Circ. 539, v. 2, p. 51-54.

Taylor, A., 1961, X-ray Metallography: New York, John Wiley & Sons, Inc., 993 p.

Turner, F. J., Griggs, D. T., Clark, R. H., and Dixon, R. H., 1956, Deformation of Yule marble, Pt. VII; Development of oriented fabrics at 300°C-500°C: Geol. Soc. America Bull., v. 67, p. 1259-1293.