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FABRIC ANALYSIS OF A COARSELY CRYSTALLINE POLYMETAMORPHIC TECTONITE.[1]

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ABSTRACT.

Those laboratory methods of fabric analysis which are not elaborated in previous papers in English are discussed somewhat in detail, and illustrated concretely by applying each technique as it is described to the study of a muscovite-biotite schist, which has several s-planes. The different kinds of fabric diagrams are defined, and most of them are illustrated in the study of the quartz fabric of the rock. The quartz fabric is studied by determining what effect each s-plane has upon it, then correlating the partial fabrics with the quartz fabric of the whole rock. The quartz and mica diagrams, together with the microscopic and megascopic study of the rock, permit deciphering a fairly complete and accurate account of its history, and its description as a new type of tectonite.

INTRODUCTION.

In a recent paper Sander[2] has described a series of deformed clay and calc-clay slates. He divides them into convenient groups and illustrates the use of combined optical and X-ray methods in the study of such fine-grained metamorphic rocks. The present paper is in a measure a continuation of that work, and applies some of the principles developed in Sander's paper to the study, by optical methods alone, of a much more coarsely crystalline tectonite.

When the writer went to Innsbruck to do research in fabric analysis with Professor Sander during the winter of 1934-35, the latter had already selected as an important type the rock herein described (a muscovite-biotite schist from Niederthal, Tyrol, collected by Reithofer) and had had thin sections made, preparatory to describing the rock himself. He very gener-

[1] The work on which this paper is based was done at the Mineralogical and Petrographic Institute of Leopold-Franzens University, Innsbruck, Austria, while the writer held a Sterling Fellowship of the Graduate School of Yale University, during the academic year 1934-35.

[2] Sander, Bruno: Typisierung von deformierten Tonschiefern mit optischen und röntgenoptischen Mitteln, Zeit. für Krist., (A) Bd. 89, pp. 97-124, 1934.

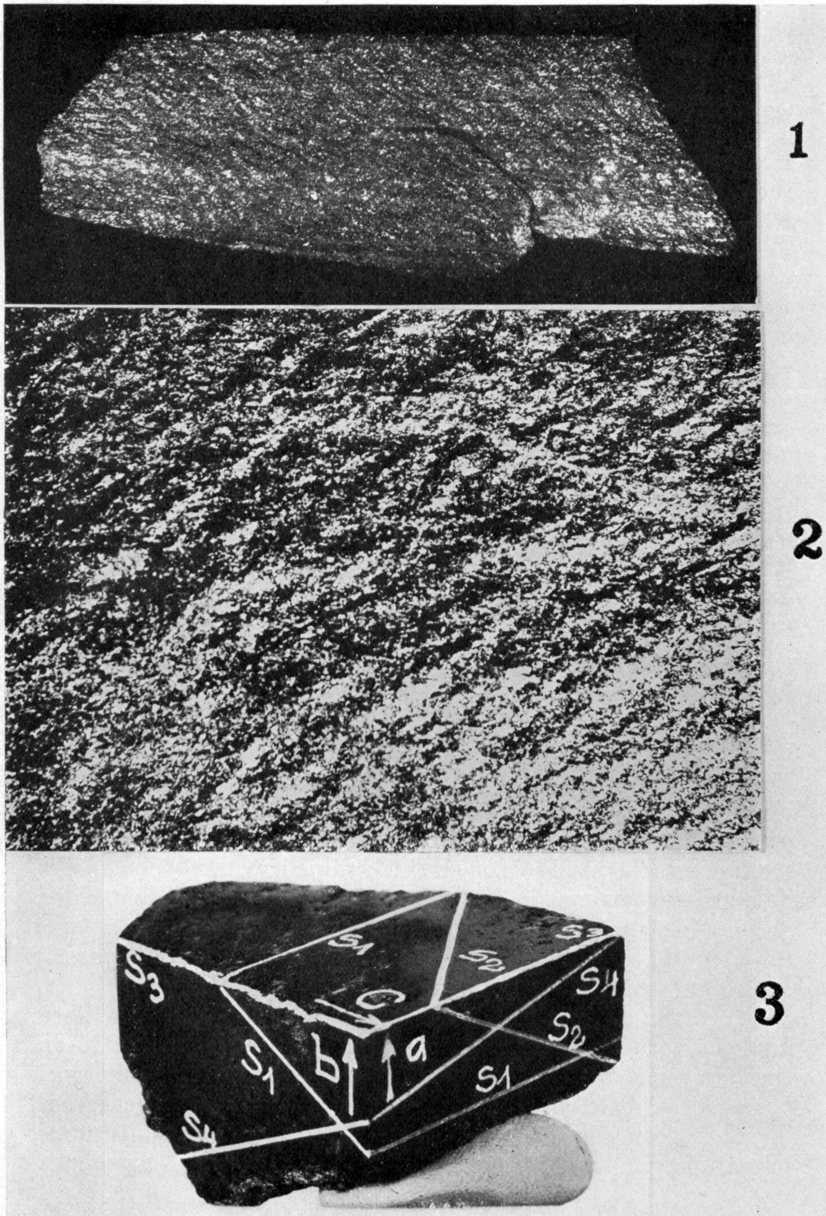

Fig. 1. Hand specimens of the Niederthal schist.

I—Complete hand specimen.
II—Enlarged portion of the cleavage surface showing the two lineations.
III—Thin section block. Compare the block diagram of Fig. 3.

ously gave the writer the privilege of carrying out the study and aided the work at every step by numerous suggestions, conferences on interpretation, and criticisms of the manuscript.

The fundamental principles underlying fabric analysis have been described elsewhere, as have the methods of collecting oriented specimens, preparing diagrams, and performing other mechanical details.[3] The purpose of this paper is twofold: (1) To illustrate as accurately as possible the complete optical investigation of a rock by petrofabric methods and (2) to interpret the structures and fabric of the rock in terms of its tectonic history.

PROCEDURE.

Fabric analysis is by no means merely the preparation and interpretation of orientation (fabric) diagrams. In fact, some of the features of such diagrams would be without meaning if it were not for correlative data derived by other means. The following outline presents the methods in their normal order. This order, as well as the actual things observed, will obviously depend somewhat on the equipment available, the type of rock being studied, and the individual making the study.

Field work.—The first step in a complete fabric analysis is the careful observation and recording of all megascopic field data connected with the rock to be studied. At the same time accurately oriented hand specimens are collected so that it will be possible to correlate the results of the laboratory study with the field data.

Study of the hand specimen.—The first step of the laboratory procedure is a careful investigation of the hand specimens to see what visible structures or directions are present. A hand specimen of the rock under consideration (Fig. 1) shows a prominent cleavage which is tentatively taken to be the *ab* plane. In fabric analysis the data of the fabric are referred to conventional axes denoted by *a, b, c*: *a* is the direction of motion, *b* is the normal to the direction of motion in the plane of slip, and *c* is the normal to *ab*. In beginning an analysis the most prominent surface is taken tentatively as the *ab* plane.

It has been shown that in some rocks a linear structure

[3] Sander, Bruno: Gefügekunde der Gesteine, J. Springer, Vienna, 1930.
Knopf, E. B.: Petrotectonics, This Journal, (5) vol. 25, pp. 443-470, 1933.
Gilluly, James: Mineral orientation in some rocks of the Shuswap terrane as a clue to their metamorphism, This Journal, (5) vol. 28, pp. 182-201, 1934.

represents the line of intersection of two or more slip planes. If these slip planes were actually formed in one and the same act of deformation, their line of intersection may be a B-axis. Such is one type of B-axis, the other type being an axis of external rotation rather than the line of intersection of essentially contemporaneous slip planes. There are two lineations visible on the cleavage surface of the Niederthal schist and, therefore, there are possibly two B-axes in the fabric of this rock. The more prominent of these two lines is due to the intersection of the cleavage plane and a second plane that is easy to recognize on all sides of the hand specimen by the arrangement of the biotite flakes. It is arbitrarily called S_1. Its line of intersection with the cleavage is tentatively called a B-axis, and the line of intersection of the less prominent structure, S_2, with the cleavage is tentatively taken to be another B-axis, called the B′-axis to distinguish it from the other one. The directions of the two assumed B-axes make an angle of 38° with each other.

The problem now is to determine; first, whether one or both of these lineations is a true B-axis and, second, if these structures do represent such B-axes, to determine the relative ages of the two B-axes. If the assumption of two B-axes is correct, then there are six fabric axes in this rock, b, a, c, b', a', and c'. b and b', as tentatively chosen, lie in the cleavage. a and a' also lie in the cleavage and are normal to b and b' respectively. The structure which produces the cleavage is called S_3.[4] (Cleavage $= S_3 = ab$) By definition the c axis is normal to the ab plane, but as the tentative ab and $a'b'$ planes are identical in the Niederthal schist, c' coincides with c.

The choice of the above mentioned directions on the hand specimen determines the orientation of the thin sections to be used. Ordinarily, for a metamorphic rock with well-defined structures, the first choice of directions will give the essential thin sections, although it may be necessary to re-name some of

[4] This numbering of s-planes is entirely arbitrary and has nothing to do with the relative ages or importance of the structures, except that, according to the above method of procedure the more prominent structures are likely to bear low numbers. In the Niederthal schist S_1 and S_2 contain larger biotite flakes than does S_3 and are therefore more striking to the eye in spite of the fact that S_3 determines the best cleavage. If, after the study of the rock has been completed, it is possible to determine with certainty the relative ages of all its structures, then the oldest may be called S_1, the next youngest S_2, and so on. However, as it is commonly impossible to determine the relative ages of *all* of the structures, numbering according to age is usually not justified.

the assumed directions as the study proceeds. The thin sections are cut normal to the assumed fabric axes. From the Niederthal schist, therefore, five thin sections were prepared. For convenience in writing and reading, each section is designated by the letter representing the axis to which the section is normal. The sections are accordingly referred to as the *b*, *a*, *c*, *b'*, and *a'* sections and where a section is mentioned in the paper care has been taken to indicate that the section is meant, to avoid the possibility of confusing a section with an axis designated by the same letter. As a further precaution the B-axes are capitalized, except in some places in the general discussion of fabric axes. Thus, section *b*, or the *b* section, means the thin section normal to the B-axis. For a rock that is nearly, or quite structureless to the unaided eye, it may be necessary to determine the positions of the essential sections by first studying random sections and then cutting others, the positions of which are determined by the fabric diagrams prepared from the random sections.

Study with binocular.—After the oriented sections have been prepared the corresponding surfaces on the piece from which the slices were cut (Fig. 1, III) are polished and the thin and polished sections are studied carefully with a binocular and the thin sections with an ordinary petrographic microscope.

The binocular has the advantage of affording a three dimensional view of the sections. Ordinarily the greater part of the information is derived from the thin sections, but some things may be observed on the polished section that cannot be seen in the corresponding thin section. For example, in the ab surface, reflection from the mica plates may show that microfolding was symmetrical or asymmetrical with respect to the B-axis, whereas study of the corresponding thin section with a petrographic microscope will merely show a parallelism of the micas. Study of polished sections with the binocular may reveal much concerning the nature of the intergrain boundaries. If liquids of different viscosities, such as alcohol, water, glycol, and glycerine, are allowed to flow slowly over the surface of a polished section, the manner in which a liquid follows boundaries between grains may reveal structures that are otherwise hidden, or that show up only as minor features of the fabric diagrams.

The binocular is most useful in finding all visible structures in the thin sections. The section to be studied should be placed on a clean, smooth piece of glazed white porcelain and illuminated by means of oblique rays from a power lamp. Paper should not be used instead of the porcelain, because even the best glazed paper is apt to show structures that might be confused with the structures in the thin section. An enlarged sketch (2 or 3 diameters) of the thin section is prepared and all visible structures are represented accurately as to direction of the whole structure, directions of the elongate grains in each structure, relative motion along slip planes, relative ages of intersecting structures, and any other features that may be observable in special cases. Care must be exercised to see that each thin section is properly oriented during the study or confusion may result later when one begins the representation on a single block diagram of the information gleaned from all of the thin sections.

The direction of relative motion in a slip plane can usually be established where elongate or platy mineral grains have been affected by the motion. The sketches of the thin sections, Fig. 2, show how the relative motion is determined. For example, consider the motion in S_1 in the b section. S_3 is the older structure and the position of the biotites therein represents the position of all of the biotites before motion along S_1 took place. The motion changed the orientation of the biotites in the slip zone, but did not last long enough to bring the plates completely parallel to S_1. The angle that the biotites make with the average direction of S_1 indicates clearly that the direction of relative motion must have been that indicated by the arrows in the sketch.

The thin sections from the Niederthal schist reveal much of interest when they are studied with binoculars and microscope. The three structures visible in the hand specimen have a different expression in the different sections, and a fourth set of slip planes, S_4, appears in several of the thin sections. Fig. 2 shows the sketches of the various thin sections with the essential information regarding the structures recorded on each.

Study with the microscope.—After the sections have been studied as thoroughly as possible with the binocular, each is studied just as carefully with a petrographic microscope equipped with a calibrated micrometric ocular. All minerals are determined and then the following data are tabulated for each structure in each thin section: (1) kinds of minerals, (2) shape, size range, and mean diameter of each mineral species, (3) minimum, maximum, and mean widths of the structure zones themselves (w in Fig. 2, b), (4) minimum, maximum, and mean distances between the zones (w′ in Fig. 2, b), (5) character of the structure zones (regularity, continuity, genesis, etc.), (6) mean angle between the direction of the structure and the long axes of the inequidimensional grains in it, and (7) remarks. The remarks may contain a variety of important observations. For example, it is important to note the relation of the different minerals to deforma-

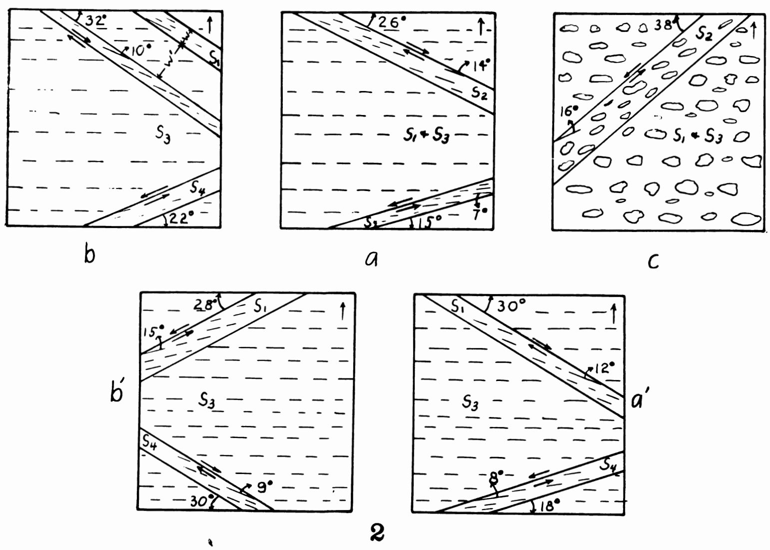

Fig. 2. Sketches showing the visible structures in each of the 5 thin sections of the Niederthal schist. Diagrammatic.

tion, any difference in the arrangement of different sized grains of a given mineral, and whether different inequidimensional minerals in the same structure are sub-parallel or not, and whether they are of sub-equal size.

In some studies, for example where grain form is of importance, as in studies of permeability or mechanical behavior of a rock, measurements with the integrating stage are most valuable. Bell,[5] working at the Innsbruck Institute, has made the most exact of such measurements thus far made in connection with the fabric investigation of a rock.

[5] Bell, James F.: "Festigkeit und Gefügeregel am Beispiele eines Granits," Ph.D. dissertation at the University of Munich, soon to be published in the Neues Jahrbuch für Mineralogie.

Some of this information will commonly be superfluous and only a small part of it will be included in a finished paper, but it is well to have all information possible at hand before attempting the interpretation of a rock that has had a long and complicated history. These data in tabular form are very useful in constructing a block diagram and in making various interpretations. Most of the essential information from the thin sections of the Niederthal schist is shown graphically in

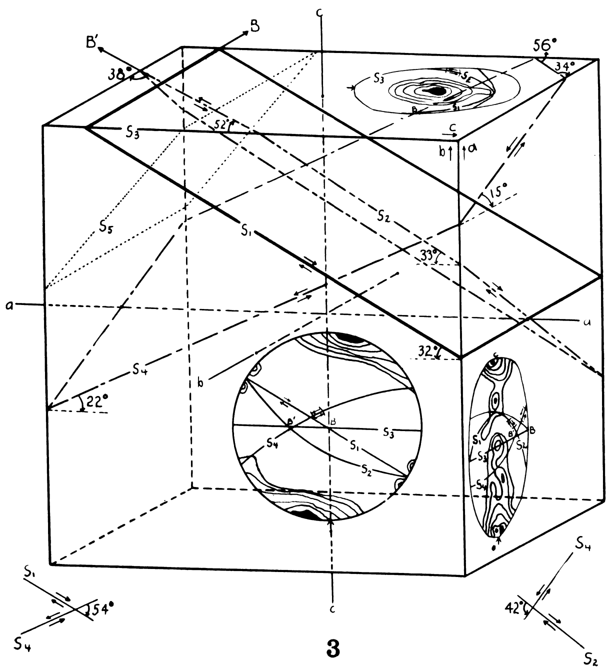

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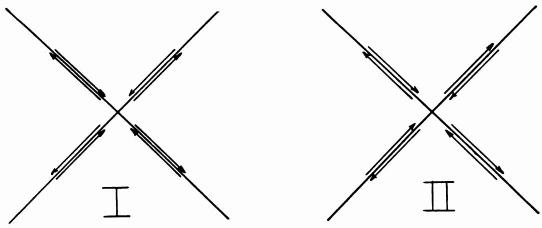
Fig. 3. Representation of the slip planes of the Niederthal schist on a clinographic projection. Only the three principal axial planes of the fabric are used, for simplicity in representation.

Fig. 2. In addition, it is interestng to note that the muscovite appears to be younger than the biotite.

Construction of a block diagram.—A block diagram summarizing the structural information obtained from the thin sections indicates clearly whether all of the thin sections were properly oriented during the study, whether the structures were properly correlated in the different sections, and whether the measured angles were approximately correct. Any type of block diagram may be used; of the common one- and two-point perspective diagrams, the one-point is better, because the front face can be drawn directly from the corresponding thin section and used as a starting point. For the Niederthal schist a preliminary one-point block diagram was prepared and from it a clinographic projection was drawn, using the isometric axes (Fig. 3). Such a diagram gives a much better representation of the relation of the s-planes to one another and to the principal axial planes than does an ordinary block diagram, and it is easier to prepare a stereographic projection from the clinographic projection.

Stereographic projection.—It is evident from Fig. 3 that the direction taken as the B-axis corresponds to the intersection of S_1 and S_3 and is, therefore, probably a real B-axis. The orientation diagrams will afford a positive check. It is also evident that the intersections $S_2 \wedge S_3$, $S_2 \wedge S_4$, and $S_3 \wedge S_4$ approximate the direction originally taken as the B′-axis (i.e., $S_2 \wedge$ the cleavage), but just how close this approximation is must be determined by (1) spherical trigonometry, (2) construction of a model, or (3) stereographic projection. The last named method is the simplest one and, as it is accurate within the limits of error in measuring the angles on the thin sections, it is the one here employed.

The method is again like the one used in crystallography. Fig. 4 shows the essential construction for determining one of these directions, $S_2 \wedge S_4$. The lower hemisphere is the one projected and thin section b is the one used in this example. The intersection of S_4 with the *b* section is represented by a straight line that passes through the center of the projection ($S_4 \wedge b$ sec., Fig. 4). A line that is normal to this one represents a plane that is normal to the intersection of S_4 and the *b* section. The point $S_4 \wedge a$ sec., Fig. 4, is the projection of the line formed by the intersection of S_4 and the *a* section. A great circle 90° from this point ($\perp S_4 \wedge a$ sec., Fig. 4) represents the plane normal to this line. As these two planes are normal to S_4, their line of intersection gives the pole to S_4 (represented by a point, $\perp S_4$, on the projection of Fig. 4). A great circle 90° from this point represents the actual plane S_4. S_2 is located in the same manner, except that $S_2 \wedge b$ section cannot be used, because S_2 cannot be seen in the *b* section; its trace on the *b* surface of the clinographic projection is found by construction. Therefore, $S_2 \wedge c$ section and $S_2 \wedge a$ section are used. The point where S_4 and S_2 intersect



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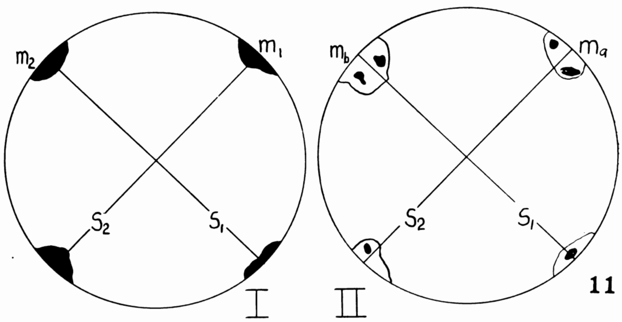

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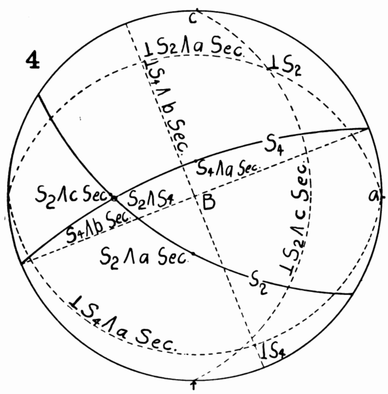

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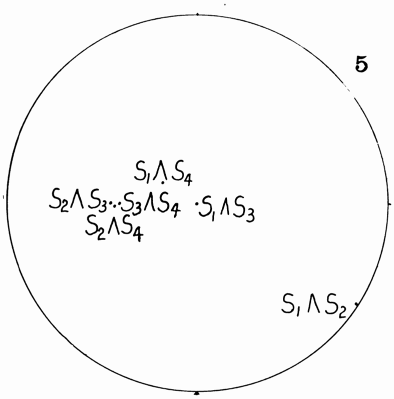


Fig. 6. I—Slip planes related to the same act of deformation. Internal rotation about a B-axis possible.

II—Slip planes either (1) derived from the superposition of two unrelated deformations, or (2) produced by a single deformation with external rotation, not necessarily about a B-axis.

Fig. 11. I—Idealized mica diagram from a rock with two sets of slip planes at right angles to one another.

II—Quartz diagram from the same rock. Both diagrams from the b section.

Fig. 4. Stereographic projection showing the method of determining the direction of the line of intersection of the two sets of slip planes S_2 and S_4, from the thin section normal to the B-axis.

Fig. 5. Stereographic projection of the section normal to the B-axis from which the construction lines have been omitted, showing the directions of the lines of intersection of the various sets of slip planes of the Niederthal schist.

is the projection of their line of intersection and gives that direction accurately. A check on this determination may be made by drawing the great circle through the normals to S_2 and S_4. If this great circle is just 90° from the point previously determined as $S_2 \wedge S_4$, the determination is correct.

The other intersections are determined in like manner, and Fig. 5 shows their orientations on a stereographic projection from which the construction lines have been omitted. It is evident that the directions $S_2 \wedge S_3$, $S_2 \wedge S_4$, and $S_3 \wedge S_4$ are parallel to the B′-axis within the limits of error in measuring.

Sander[6] mentions two different relations that intersecting slip planes may bear to each other in regard to directions of motion. These relations are shown and explained in Fig. 6.

Relations of this kind in a coarsely crystalline tectonite have not been heretofore described. Sander[7] suggested that they would be visible in such rocks as well as in the fine-grained ones that he was studying at the time. The sketches of the thin sections, Fig. 2, show what can be told of the relative movements in the Niederthal schist. The relations between S_1 and S_4 as seen in thin sections *b*, *b′*, and *a′* are like Fig. 6, I, but other considerations indicate that their line of intersection is not a principal fabric axis of the rock. S_2 and S_4 also show the relations of Fig. 6, I, in section *a*; they probably show the same relations on section *b′* (determined from a clinographic projection representing all five of the thin sections). No relative movement was distinguished in S_3. These considerations, especially the determination of the directions of the inter-sections of S_2, S_3, and S_4, indicate that *b′* is really another B-axis. Its relation to the s-planes is clear, but the effect that it has on the rock fabric, if any, must be determined from the orientation diagrams.

Preparation of the diagrams; definitions.—Orientation diagrams are prepared for each important mineral from each thin section. The following types of orientation (fabric) diagrams should be carefully distinguished:

I. *Elemental* diagrams are units that are combined to form other diagrams known as *collective* diagrams. The total number of points in a collective diagram represents the sum of all the measurements in the individual elemental diagrams. The

[6] Sander, Bruno: Typisierung von deformierten Tonschiefern mit optischen und röntgenoptischen Mitteln, Zeit. für Krist., (A) Bd. 89, p. 100, 1934.

[7] Sander, Bruno: Fortschritte der Gefügekunde der Gesteine, Anwendung, Ergebnisse, Kritik; Fort. der. Min., Krist., und Pet., 18, pp. 111-170, 1934.

elemental diagrams of a collective diagram are commonly from a single rock (usually from one thin section), but in the special case of a *composite* diagram (See II, 4, below) the elemental diagrams are from different rocks. Elemental diagrams may be either non-selective or selective. When they are selective they are called

1. *Partial* diagrams (Teildiagramme) which are elemental diagrams that have been prepared by a definite selection of grains. This selection may be; directional (a partial diagram prepared from a single traverse across a thin section, or from grains along a line parallel to some structure): areal (from grains lying *in* a given structure); or it may be according to grain size; or according to any other "fabric element of a higher order than the grain." (Gefügekunde, p. 133)

II. A *collective* diagram is prepared by collecting the points from a number of similar elemental diagrams, commonly from the same thin section, into a single diagram.

1. *Non-selective* (Gewöhnliche) diagrams are made from measurements of grains (of a given mineral) of all sizes in all the structures of a thin section. A collective non-selective diagram may be prepared from directional partial diagrams, which are in themselves selective, provided that the direction of moving the thin section during the preparation of the partial diagrams is such that grains from all of the structures will be measured.

2. Collective *selective* diagrams are prepared from similar partial diagrams so chosen that the collective diagram will be entirely from some fabric element of a higher order than the grain.

3. A *complete* diagram is one that is prepared from *all* of the appropriate grains in a given thin section. For example, a complete non-selective quartz diagram would be prepared from every quartz grain in a given thin section. A complete selective quartz diagram prepared from the area of S_1 in the *b* section would represent every quartz grain lying in the area of S_1 in that section.

4. A *composite* diagram is made by putting together (using maxima as points) a number of analogous diagrams from similar rocks in order to see which maxima occur most commonly. The collective diagrams from the individual rocks thus become elemental diagrams of the composite one, whether they were selective or non-selective with respect to the fabrics of the different rocks. For example, if it is desired to see

which quartz maxima are most common in a group of S-tectonites the quartz maximum (from, say, the c section) of each of 50 different S-tectonites may be plotted on an orientation diagram exactly as 50 quartz axes would be plotted on an ordinary diagram. The composite diagram is completed just as an ordinary fabric diagram is drawn and the maxima of the composite diagram give the positions of the most common maxima in the group of rocks being studied.

Strictly speaking, only the collective selective and composite diagrams correspond to the German *Sammeldiagramme.* However, it seems to be less confusing to define the special types in the above manner than to follow the three-fold classification in use in Europe (Teil-, Gewöhnliche-, and Sammeldiagramme) and then attempt to explain clearly the different kinds of collective diagrams without using special names.

For the Niederthal schist, diagrams for quartz, biotite, and muscovite were made from the *b*, *a*, *c*, and *b'* sections. These non-selective diagrams were made by moving the sections parallel to their widths, hence, by measuring parallel to S_3 and across all other structures (except in the a and c sections, where S_3 and S_1 are parallel) and including grains from all of the structures in preparing the diagrams.

For the complete fabric investigation of a rock these non-selective diagrams are not sufficient. They picture the net effect of all of the structures on the fabric and may or may not permit evaluation of the influence of the individual structures. Partial diagrams are prepared from each traverse across a thin section, and a marked difference of one of these partial diagrams from the corresponding collective diagram indicates the presence of a "super-individual" (Ueberindividuum) lying parallel, or sub-parallel, to the direction of moving the thin section during measuring. Such super-individuals are groups of grains that approximate some preferred orientation different from the statistical orientation of the grains of that mineral in the whole thin section. Detection of such super-individuals may reveal hidden slip planes, fillings of veinlets, or other structures, especially in equant minerals like quartz.

Detection of hidden structures in this manner is largely incidental to the preparation of the principal diagrams. In many cases it is desirable to make a special attempt to detect such structures and at the same time to see whether structures which are visible in inequidimensional grains, like mica, affect the orientation of equant grains, like quartz. Selective diagrams are prepared from the quartz grains that lie along lines parallel to a given structure and from grains *in* the given structure. These selective diagrams are prepared separately. Comparison of these diagrams with the non-selective one from the same section will show whether the quartz fabric is different in the structure considered, and if it is different the diagrams will likely suggest a reason for the difference. The diagrams also show whether the quartz fabric is like the mica fabric, a comparison often important in deciphering the history of a rock.

For example, suppose that a collective selective diagram has been prepared from quartz grains lying along lines parallel to S_1 in the *b* section (See Fig. 2, b, and Fig. 9) and that the diagram shows a maximum that does not correlate with S_1. If the maximum lies near the periphery of the diagram, it is possible to make another diagram by moving the thin section parallel to the direction of the maximum (Fig. 10). This new diagram may either definitely reveal a hidden structure suggested by the other diagram, or correlate the maximum with a known structure in the rock. (This is an actual example taken from the study of the diagrams of the Niederthal schist. See the explanations of Figs. 9 and 10 for details.)

Interpretation of the diagrams.—The method and order of procedure in studying and interpreting diagrams varies with different types of rocks. Collective and partial diagrams from a rock whose fabric is homogeneous down to the field of the individual grains (Kornbereich) are so nearly alike that only the collective diagrams need be considered. Also, diagrams made by measuring in different directions are alike; therefore, only the non-selective diagrams are needed.

The case of a rock with inhomogeneous fabric, especially one with several visible structures, is much more complicated. The complete fabric analysis of such a rock would involve the preparation of collective and partial diagrams for each mineral, parallel to each structure, and in the area of each structure, from each section, besides the non-selective diagrams and their component partial diagrams. Such a work is too detailed and painstaking for ordinary research. It would never be required except in the working out of an ideal example, because all of the essential information can be obtained from a comparatively few well selected and carefully prepared diagrams.

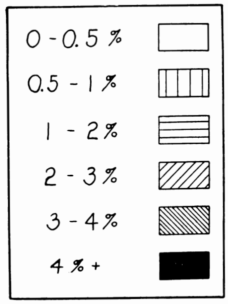
In practice, non-selective diagrams are prepared from each thin section. For minerals like quartz, whose preferential orientation is not readily observable unless it is very strong, it is desirable to prepare diagrams for more than one direction (i.e., to prepare selective diagrams) from at least one thin section, usually the one normal to the B-axis. These diagrams, by comparison with their elemental diagrams and with the non-selective diagram from the same section, will show whether the fabric is homogeneous. If the fabric is not homogeneous, a study of the diagrams will suggest others to be prepared. The new diagrams may suggest still others until all hidden structures have been revealed and all of the features of the first prepared diagrams are explained.

Quartz diagrams from the Niederthal schist; section b.—In addition to the non-selective diagram a selective quartz diagram was prepared from the *b* section, measuring parallel to S_1. The one measured parallel to S_1, Fig. 9, shows a stronger maximum than does the non-selective one, Fig. 8.[8] It is evident that the strong maximum is practically normal to S_3 and it is probable that most of the grains from which it was derived lie in S_3, because the areas of S_3 are wider than those of S_1 (Fig. 2). The appearance of such a strong maximum suggested the possibility of invisible slip planes in the quartz fabric parallel to the direction of the maximum. In order to check that possibility another selective diagram was prepared by measuring quartz grains lying along lines parallel to the maximum. This third diagram, Fig. 10, shows a strong maximum in essentially the same place as does the diagram made by measuring parallel to S_1, and another maximum practically normal to S_1.

The meaning of these maxima depends upon the manner in which quartz responds to stresses placed upon it. Sander[9] mentions two ways in which quartz may respond to stress: (1) By gliding parallel to a flat rhombohedron, or (2) parallel to the prism. In either case the whole grain turns until the gliding plane is essentially in the slip plane of the rock. The

[8] In all of the fabric diagrams relative motion along the slip planes is indicated by arrows. Where the slip plane is normal to the thin section the general direction of relative motion is definite (e.g., $S_1 \wedge b$ section). However, where the planes are inclined the true direction of relative motion may be quite different from the apparent direction as seen in thin section. This uncertainty is indicated by enclosing the arrows in parentheses (e.g., $S_1 \wedge b$ section). Where the direction of relative motion was not apparent in the thin section and was determined from the block diagram dashed arrows have been used (e.g., $S_2 \wedge b'$ section).

[9] Sander, Bruno: Gefügekunde der Gesteine, J. Springer, Vienna, 352 pp. (p. 181), 1930.



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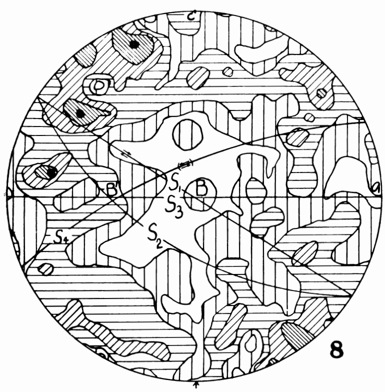

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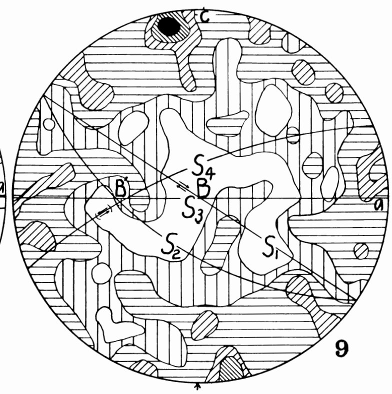

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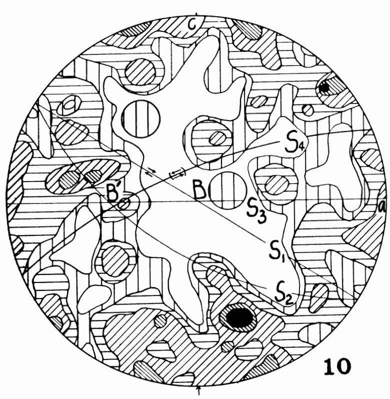

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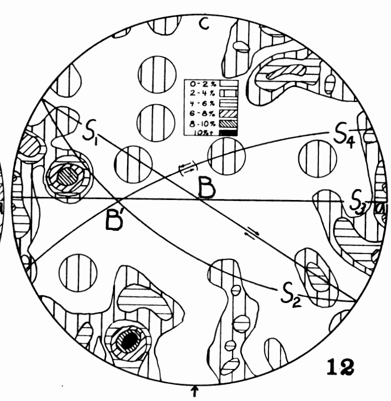

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Fig. 7. Legend for all of the quartz diagrams except Figs. 12 and 13 and the maxima of Figs. 19 and 20.

Fig. 8. 300 quartz axes from section b, measured parallel to S_3.

Fig. 9. 408 quartz axes from section b, measured parallel to S_1.

Fig. 10. 200 quartz axes from the b section, measured parallel to the maximum of Fig. 9.

Fig. 12. 54 quartz axes from the area of S_1, section b.

first of these methods produces "ring maxima" with the centers of the rings approximately normal to the slip planes, and the second produces single maxima lying approximately in the slip planes.

In the case of a rock with slip planes inclined at high angles to one another it may be impossible to tell which of these processes has been effective. Fig. 11 shows why this is true. I, Fig. 11, shows a mica diagram from such a rock. It is evident that the maximum, m_1, corresponds to the slip plane s_1, and m_2 to s_2. With quartz, II, Fig. 11, however, the maximum m_a may have been produced either by rhombohedral gliding in s_1 or by aligning the c-axes parallel to s_2. Likewise, m_b may be related to either s_2 or s_1.

Where the slip planes are inclined at low angles, as in the Niederthal schist, it is easier to correlate the quartz maxima with the proper slip planes. The collective diagrams of Figs. 8-10 seem to indicate that the quartz of the Niederthal schist has been oriented by rhombohedral gliding, because the principal maxima are essentially normal to visible slip planes and are mostly ring maxima. The rings from all the quartz diagrams average 28° in radius.

A good check of this hypothesis is afforded by preparing diagrams from the areas of S_1 and S_3. (To be distinguished carefully from the directions S_1 and S_3.) Two of these diagrams, Figs. 12 and 13, are partial diagrams of the collective diagram of Fig. 10. The third, Fig. 14, was prepared from the second by measuring more grains in S_3, section *b*, and adding to Fig. 13. Hence, Fig. 13 is also a partial diagram of Fig. 14. In the diagram from the area of S_1, Fig. 12, the principal maximum is practically normal to S_1, and in those from the area of S_3, Figs. 13 and 14, the maxima are essentially normal to S_3, in good correspondence with the hypothesis of rhombohedral gliding.

In the diagram prepared from the area of S_1, Fig. 12, there is a strong sub-maximum near S_1. This maximum appears also in other diagrams, especially Figs. 8, 9, 14, and 18. It could mean aligning of the quartz axes in the visible slip plane S_1, or it could mean rhombohedral gliding along invisible slip planes approximately normal to S_1. The facts that it is a ring maximum and that aligning of the c-axes of the quartz is not indicated in any of the other slip planes suggest that rhombohedral gliding along invisible slip planes is the more probable explanation. The biotite diagram from section *b*, Fig. 22, shows a sub-maximum that coincides with this quartz sub-maximum, indicating clearly that the postulated hidden slip planes (S_5) actually exist in the rock. The maxima are hereinafter referred to by the names of the slip planes to which they are normal, for brevity.

These quartz diagrams show, in general, a girdle about the B-axis. Therefore, this direction is a true B-axis with respect to the quartz fabric, although the girdle arrangement is far from perfect. They also show that the fabric is decidedly inhomogeneous with respect to quartz.

Quartz diagram from section b'.—The non-selective quartz diagram from section *b'*, Fig. 15, shows a much more complete girdle than does the one from section *b*. Therefore, there are two B-axes with respect to the quartz fabric of this rock and the one that is less readily discernible in the visible structures is more readily discernible in the quartz fabric diagrams. This definite determination of two B-axes raises the question of their relative ages. In order to describe the determination of their relative ages it is necessary to refer briefly to some of the mica diagrams that are described more in detail below. The biotite diagram from section *b*, Fig. 22, shows a girdle about the B-axis, but there is no trace of a biotite girdle about the B'-axis, Fig. 24. This orientation of the mica with respect to the B-axis alone and the better orientation of the quartz with respect to the B'-axis suggest that B is the older of the two, because experience up to the present time indicates that to change the orientation of mica requires much more differential movement than to re-orient quartz.

A check on this hypothesis is afforded by the relative ages of the slip planes characteristic of the two axes. The quartz diagrams from section *b*, Figs. 8-10 and 12-14, show a predominance of the S_1, S_3, and S_5 maxima. This is logical in view of the fact that the B-axis is the line of intersection of the slip planes S_1 and S_3. S_5, although invisible, has been determined from its maxima to lie in the same zone. The quartz diagram from section *b'*, Fig. 15, shows maxima for the slip planes S_1, S_2, and S_4. Therefore, the characteristic slip planes of the B-axis are S_3 and S_5 and those of the B'-axis are S_2 and S_4. S_5 is invisible, so the determination must rest on the ages of S_2 and S_4 with respect to S_3. Fig. 2 shows that S_2 and S_4 are definitely younger than S_3; therefore, the B'-axis is younger than the B-axis.

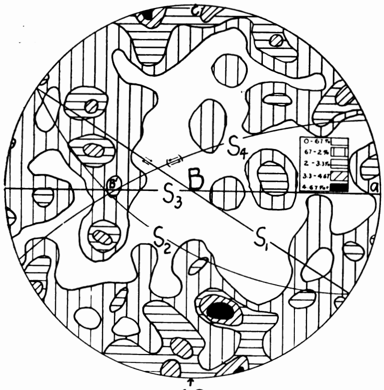
Other quartz diagrams; control by rotation; inhomogene-

ity.—If the fabric of a rock is homogeneous with respect to a given mineral (for a rock volume the size of a thin section block), a non-selective diagram of that mineral measured from one section and rotated to the position of a second will be very similar to a diagram measured from the second section. If the fabric is inhomogeneous, however, the measured and rotated diagrams will be unlike and the degree of dissimilarity will depend upon the degree of inhomogeneity and upon the relations of the thin sections concerned to the slip planes in the rock and to each other. For example, imagine a B-tectonite with two sets of slip planes approximately at right angles to one another. Section *b* will show equal areas of the two sets and a non-selective diagram from that section will show sub-equal maxima for the two sets of slip planes, if they are equally well developed. A thin section cut parallel to one set of the slip planes and nearly at right angles to the other, however, may give a diagram showing one maximum very strongly developed and the other almost eliminated.

The non-selective diagrams from the other sections of the Niederthal schist were all rotated to the position of the *b* section for the purpose of comparison. All of them, except the one from section *a*, show some similarity to the diagram measured from section *b*, but they are all dissimilar enough to confirm the inhomogeneity of the quartz fabric.

The diagram measured from section *b′*, Fig. 15, and rotated to the position of the *b* section, Fig. 16, shows the S_1 maximum very strongly. This is logical in view of the fact that S_1 is quite prominent in section *b′*. There is a ring maximum essentially normal to S_2 and a weaker one for S_4. S_2 cannot be distinguished from S_1 in the thin section, because the traces of the two structures are practically parallel on the *b′* section, but it has a considerable effect on the fabric. The B girdle is but poorly shown on the rotated diagram and the characteristic hole around the B-axis is not as evident as it is in the diagram measured from section *b*.

The quartz diagram measured from the *c* section, Fig. 17, and its rotation to the position of the *b* section, Fig. 18, show the S_5 maximum very clearly. The other maximum is probably the one corresponding to S_2, but it has been somewhat displaced by other factors. The B girdle and hole are shown about as well by these diagrams as they are in those from the *b* section. The total absence of the S_3 maximum is very interesting. The *c* section is parallel to S_3 and the absence of



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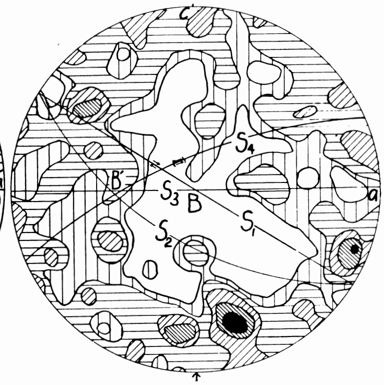

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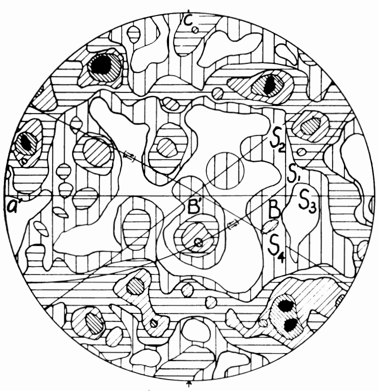

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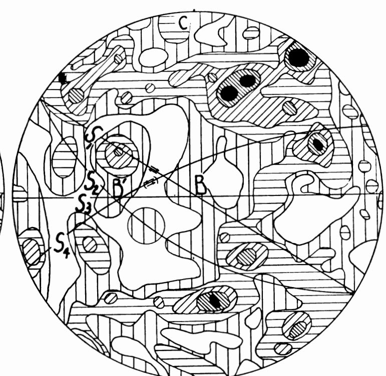

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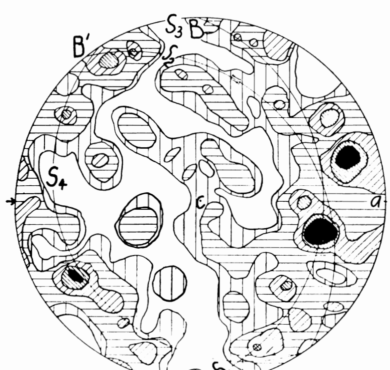

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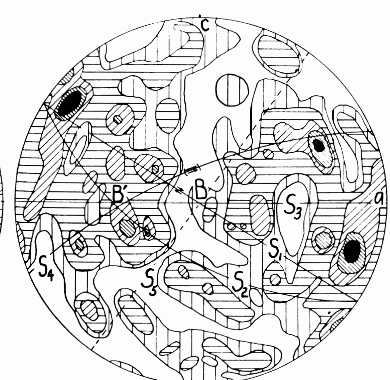

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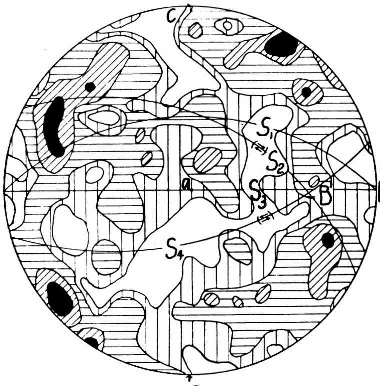
Fig. 13. 146 quartz axes from the area of S::, section b.
Fig. 14. 300 quartz axes from the area of S::, section b.
Fig. 15. 193 quartz axes measured from the b′ section.
Fig. 16. The diagram of Fig. 15 rotated to the position of the b section.
Fig. 17. 200 quartz axes measured from the c section.
Fig. 18. The diagram of Fig. 17 rotated to the position of the b section.

the S_3 maximum from its diagram indicates that the section was probably cut between two planes of motion so that the quartz in this particular section is unoriented with respect to S_3. Another section cut parallel to the *c* face might show the S_3 maximum very strongly developed. That the mica in the c section is partly oriented with respect to S_3 may be due to the fact that S_3 was the original set of s-planes and controlled the growth of all of the micas at first.

The quartz diagram from the *a* section, Fig. 19, cannot be correlated directly with those from the other sections. It is impossible to say, unless the diagram is rotated, what it means in terms of the complex fabric of the rock. Rotation to the position of the *b* section, Fig. 20, makes the diagram even more puzzling, because there is absolutely no correspondence between the rotated diagram and the one measured from the *b* section. The fact that the quartz is more completely oriented with respect to the B′-axis suggests that the diagrams from sections *a* and *b′* be compared by rotation. Fig. 21 shows the diagram from section *b′* rotated to the position of the *a* section. This rotated diagram is very similar to the one measured from the *a* section. The maxima are not quite as strong in the diagram from section *a* (3 to 4% as against 4 to 5% for the maxima in the diagram from section *b′*), but the positions of the maxima in the two diagrams correspond remarkably well. It must be remembered that with maxima of 3 to 5% in diagrams of 200 grains the positions of the maxima are not rigidly fixed. Analogous diagrams from different parts of the same thin section will show the same maxima, but they may vary in position several degrees. In correlating quartz maxima from such diagrams, therefore, two maxima that are within 10° or 15° of each other may be correlated with a fair degree of certainty, and maxima even farther apart may be (less definitely) correlated in a rock with highly inhomogeneous fabric. As the number of grains measured, or the intensity of the maxima, increases, less variation is permissible. The interpretation of the *a* diagram is, therefore, that the grains from which it was made lie largely in the slip planes that are characteristic of the B′-axis. That is logical, because section *a* makes an angle of only 50° with section *b′*, but is normal to section *b*.

Mica diagrams.—The mica diagrams, Figs. 22-30, also contain much of interest, although they show only one B-axis. They emphasize some of the interpretations suggested above



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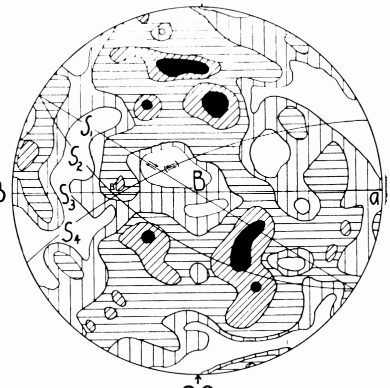

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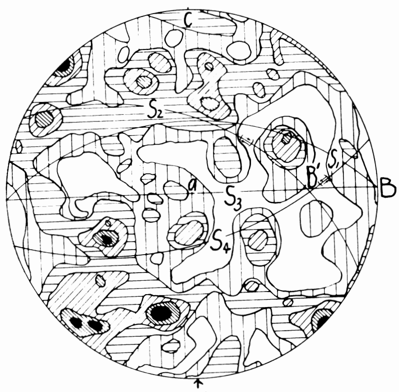

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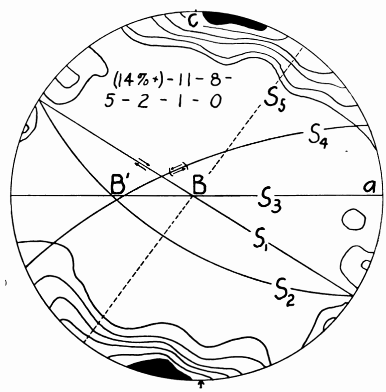

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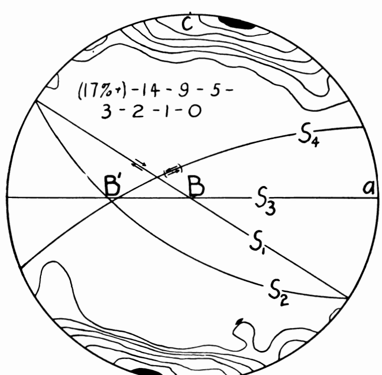

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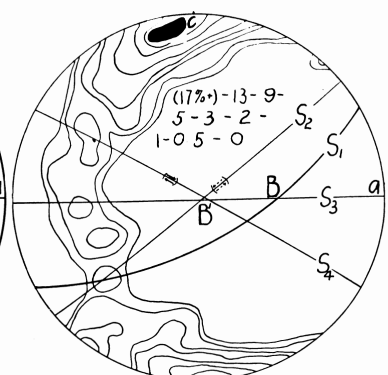

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Fig. 19. 300 quartz axes from the a section. Legend as in Fig. 7, except that the maxima are 3 to 4% instead of 4 to 5%.

Fig. 20. The diagram of Fig. 19 rotated to the position of the b section. Legend as in Fig. 19.

Fig. 21. 193 quartz axes measured from the b′ section (Fig. 15) and rotated to the position of the a section.

Fig. 22. Normals to the cleavage of 216 biotite flakes from the b section.

Fig. 23. Normals to the cleavage of 309 muscovite flakes from the b section.

Fig. 24. Normals to the cleavage of 209 biotite flakes from the b′ section.

and suggest a few additional possibilities. The muscovite diagrams are very much like those of the biotite, but also show interesting points of difference.

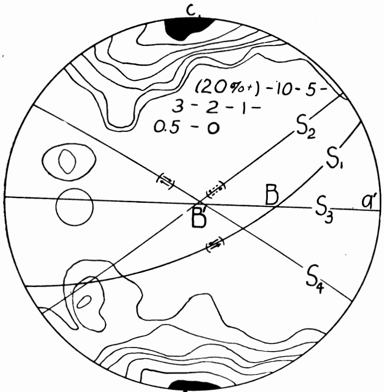
The biotite diagram from the *b* section, Fig. 22, shows a very strong maximum that lies between the normals to S_1 and S_3, indicating that the orientation of the flakes is controlled by both sets of planes. The sub-maximum coinciding with S_1 confirms the presence the hidden slip planes, S_5, as indicated above. The asymmetry of the lines enclosing the principal maximum is to be ascribed to post-crystalline motion in S_1. The asymmetry is in the proper direction to have been produced by the motion as determined from the thin section and recorded in the diagram. The muscovite diagram from section *b*, Fig. 23, does not show this asymmetry. This fact corroborates the observation made from the thin sections that the muscovite is younger than the biotite.

The biotite diagram from section *b′*, Fig. 24, shows the B girdle as clearly as does the one from the *b* section itself. It also shows the complete absence of a mica girdle about the B′-axis. The muscovite diagram from the *b′* section, Fig. 25, is identical except that the girdle is not quite as complete.

The biotite and muscovite diagrams from section a, Figs. 26 and 27, are included merely for the sake of completeness. They show that the maximum and girdle occur where they would have been predicted from the other diagrams to occur.

The biotite and muscovite diagrams from section *c*, Figs. 28 and 29, also show the maximum and girdle where they are expected. It is interesting to compare the muscovite diagram that was prepared from the acute bisectrices of the flakes, Fig. 29, with a diagram prepared from normals to the axial planes of the muscovite flakes in the same section, Fig. 30. The diagram prepared from the acute bisectrices indicates only the attitude of the flakes, because the acute bisectrix of muscovite is essentially normal to the cleavage. The axial plane of muscovite is normal to the cleavage, hence, the normals to the axial planes (of the flakes represented in Fig. 29) would lie approximately on the margin of the diagram. Where they lie on the margin will be determined by whether there has been motion in S_3, and if there has been, by the amount and direction of that motion.

The diagram from the normals to the axial planes, Fig. 30, shows a strong maximum coinciding with the B-axis. This maximum means that there was motion in S_3 essentially



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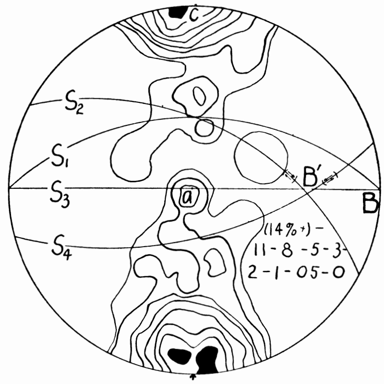

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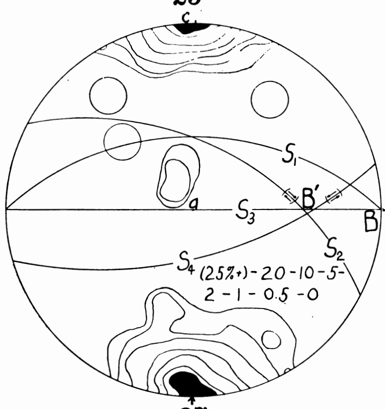

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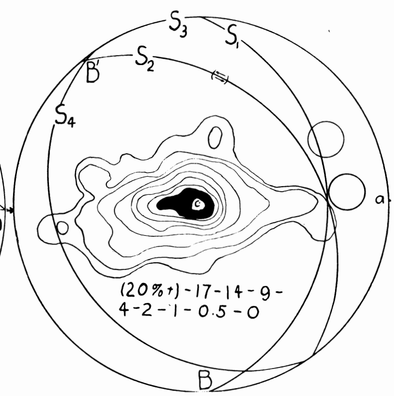

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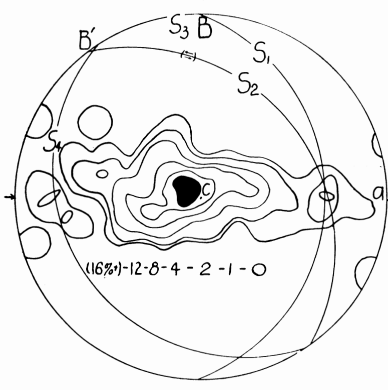

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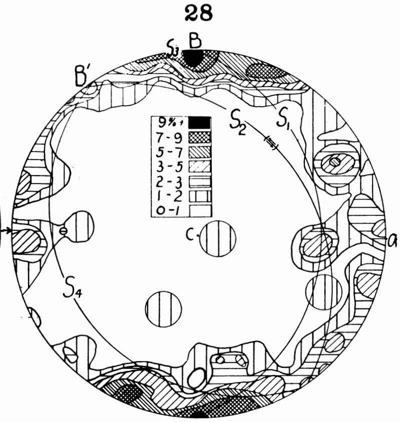

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Fig. 25. Normals to the cleavage of 208 muscovite flakes from the b′ section.
Fig. 26. Normals to the cleavage of 192 biotite flakes from the a section.
Fig. 27. Normals to the cleavage of 205 muscovite flakes from the a section.
Fig. 28. Optic axes of 202 biotite flakes from the c section.
Fig. 29. Acute bisectrices of 104 muscovite flakes from the c section.
Fig. 30. Normals to the axial planes of 100 muscovite flakes from the c section.

normal to the B-axis. Motion in S_3, which could not be detected in the thin sections, is thus established. The direction of the motion as a whole can be told, but not the direction of relative motion of parts of the rock with respect to one another. The S_3 planes may have been the original planes of sedimentation, but they have also served as slip planes. A part of the orientation of the axial planes of the muscovite could have been produced by motion in S_1 normal to the B-axis, but motion in S_3 is also indicated by the fact that many of the quartz diagrams show a maximum normal to S_3.

History of the rock.—The above considerations make it possible to decipher a fairly complete and accurate account of the tectonic history of the Niederthal schist. The mineral composition indicates that it was probably originally an argillaceous sedimentary rock. The oldest s-planes, S_3, very likely represent the original planes of sedimentation. An early metamorphism may have produced an S-tectonite by motion in these planes, perhaps a phyllonite, or a phyllite may have resulted from the growth of minerals in the original s-planes. If either a phyllonite or phyllite was formed its fabric has been completely obliterated by later metamorphisms. The early metamorphism is postulated because of the age and character of the S_3 planes. Neomineralization probably took place during this early metamorphism, with the growth of small mica flakes parallel to S_3.

A second period of metamorphism, with motion normal to the B-axis, produced S_1 and S_5. There was perhaps renewed motion along S_3 at this time. The intersection of these slip planes produced the B-axis and at the close of this period of metamorphism, which was the most intense one to which the rock has been subjected, all of the minerals were probably oriented with respect to the B-axis. Some crystallization of the minerals took place during this metamorphism, biotite before motion had ceased entirely, and muscovite later. The mineral grains in S_1 are decidedly larger than in any of the other slip planes. This may mean that S_1 was the most important set of planes during this metamorphism, or that there was renewed motion and growth of mineral grains in S_1 during the final metamorphism.

The third and final metamorphism was produced by motion that was oblique to the motion that produced the second one. ($B \wedge B' = 38°$) The S_2 and S_4 sets of slip planes were developed during this final metamorphism. It was much weaker than the second one, having no effect on the mica fabric (as far as can be told from the diagrams), and leaving a distinct trace of the B quartz girdle.

NEW RESULTS.

1. This study is a contribution to the regional geology of the Alps, adding to the previously known examples of "B oblique B′" tectonites an excellent one that is sufficiently coarsely crystalline to be studied with the universal stage. It is to be noticed that the character of the last deformation, which is an "overprint," is pre-crystalline.

2. With respect to fabric analysis itself the contribution is an analysis of the fabric of a complex rock in terms of the individual slip planes and the correlation of the partial fabrics with that of the whole rock, which is a B-tectonite fabric. It lends confirmation to the conception expressed in "Gefügekunde der Gesteine" that fabric diagrams from transverse sections of such rocks can be understood only when the mechanics of the behavior of the individual grains and the mechanics of micro-shearing are considered.[10]

3. For those who do not read German the work is a sufficiently complete example of a difficult analysis to serve, together with other papers in English dealing with technique, as a guide for research in fabric analysis.

4. Sander[11] described B-tectonites (B; $B \perp B'$; B oblique B′) formed at slight depth and indicated that similar tectonites formed at greater depth probably had similar fabrics. The above example confirms his prediction and furnishes a third type of such tectonites, which has the following properties (Compare the table[11] which gives the properties of the two types described by Sander):

a. Mica, quartz, and feldspar fabric.
b. Pre-crystalline deformation.
c. The B-axes are essentially the lines of intersection of slip planes.

[10] Compare Sander, Bruno: Fortschritte der Gefügekunde der Gesteine. Anwendung, Ergibnisse, Kritik; Fort. der Min., Krist., und Pet., Bd. 18, pp. 111-170, 1934.

[11] Sander, Bruno: Typisierung von deformierten Tonschiefern mit optischen und röntgenoptischen Mitteln, Zeit. für Krist. (A) Bd. 89, pp. 97-124, 1934. Table giving properties of the two types of tectonites described in the paper on pages 111 and 112.

d. B-axis = girdle axis for mica and quartz.
B′-axis = girdle axis for quartz.
B oblique B′.
B-axis is older than the B′-axis.
e. Overprinting is clearly decipherable.
f. Affine deformation.
g. Tension parallel to the B-axis is indicated by a few *ac* joints (normal to the B-axis).
h. Continuous deformation is dominant.
i. Mica lies in several s-planes; mostly in two.

Conversations concerning fabric analysis held with Drs. Schmidegg, Felkel, and Ladurner, of the Innsbruck Institute, and with Dr. James F. Bell while he was studying at the Institute were most helpful to the writer, especially during the early stages of the study. Constructive suggestions made by Professor and Mrs. Adolph Knopf and by Dr. James Gilluly, of the U. S. Geological Survey, are gratefully acknowledged. Professor Sander's coöperation and aid were invaluable, not only in performing the mechanical part of the study, but also in making interpretations and shaping the manuscript.

Additional Literature.

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