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PETROFABRIC ANALYSIS OF A QUARTZITE FROM THE BERGSDALEN QUADRANGLE, WESTERN NORWAY

BY

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10 figures in the text.

Abstract. In a flattened quartzite the two symmetrical slip planes are very unequally developed in the biotite (34 and 3 percent) and muscovite (33.5 and 0.5 percent) fabric diagrams. In the quartz diagram a maximum with the remarkable concentration of 37.5 percent lies 38° from the major slip plane. All diagrams have monoclinic symmetry with the line of intersection between the slip planes as the B axis. Field evidence points to this direction as he a axis. Muscovite a axes show strong concentration in this direction, and the position of the quartz maximum proves it to be maximum III, both facts confirming the set-up of fabric axes as determined in the field.

The conclusion must be that the symmetry of fabric diagrams is not always a reliable indicator of the direction of tectonic transport.

During my structural investigations in the Bergsdalen quadrangle east of Bergen I have found in a quartzite a fabric of a very unusual character, so that it deserves a special description.

In the central southern part of the quadrangle, troughout an area of about 8 by 15 km, the rocks have been subjected to very strong deformation. The rocks occurring are quartzite, mica schist, altered rhyolite, dacite and basalt, and granodiorite. The deformation has resulted in a considerable stretching, which is visible in every hand specimen as well as in the landscape. The direction of stretching is in the middle part of this area due east, in the northern part about E 10° N, and in the southern part E 10—15° S. The degree of stretching can be determined by a measurement of the pebbles in quartzite conglomerates, which occur in several localities. In most places the pebbles are shaped like walking sticks and pencils, the dimensions being 1 by 3 by 100 cm etc. A recalculation of the original shape of the pebbles, based on the assumptions that no change in volume has taken place and that the longest diameter was twice the length of the shortest diameter leads to the conclusion that the pebbles in the

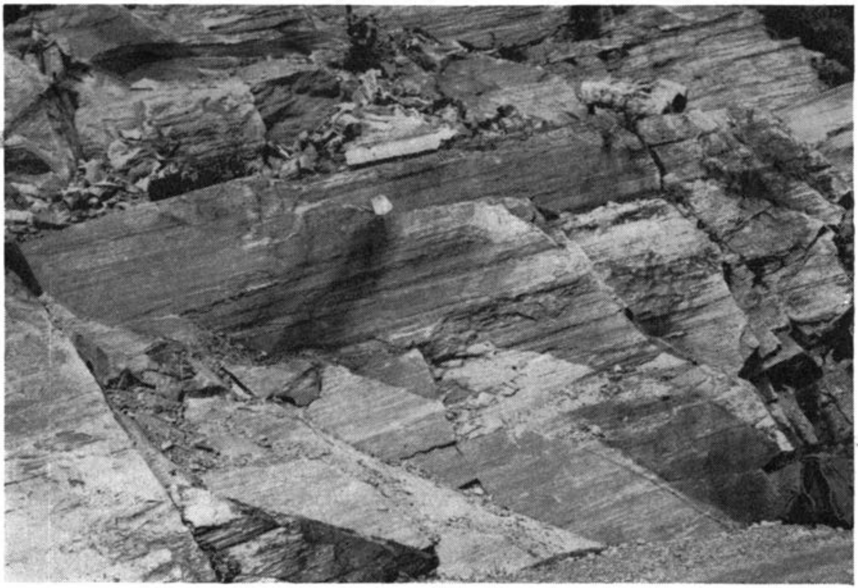

Fig. 1. Quartzite with prominent lineation and cross joints.
Near Grøndalsvatn, Samnanger.

various localities have been stretched from 5 to 10 times their original length. In one locality, near the farm Dyrhovden, lying 1 km west of Grøndalsvatn, which is 30 km east of Bergen, the pebbles are shaped like swords, with the ratio of the medium and the smallest diameters being 5 : 1 to 15 : 1. The ratio of the largest and the medium diameters cannot be determined but is at least 10: 1, possibly up to 20: 1.

The sample of quartzite examined was taken in a roadcut near Grønsdalsvatn, about 1 km from the conglomerate described. Here is no possibility of measuring the degree of lengthening, but the prominent lineation gives an impression of considerable stretching (Fig. 1).

The rock is a massive quartzite with no visible banding. It splits, however, along parallel planes dipping 30° towards S 15° W. On these planes is seen a prominent lineation pitching 9° W. Cross joints strike normal to the lineation, and dip about 75° E, and some less regular, oblique joints strike nearly parallel to the cross joints but dip about 45° E.

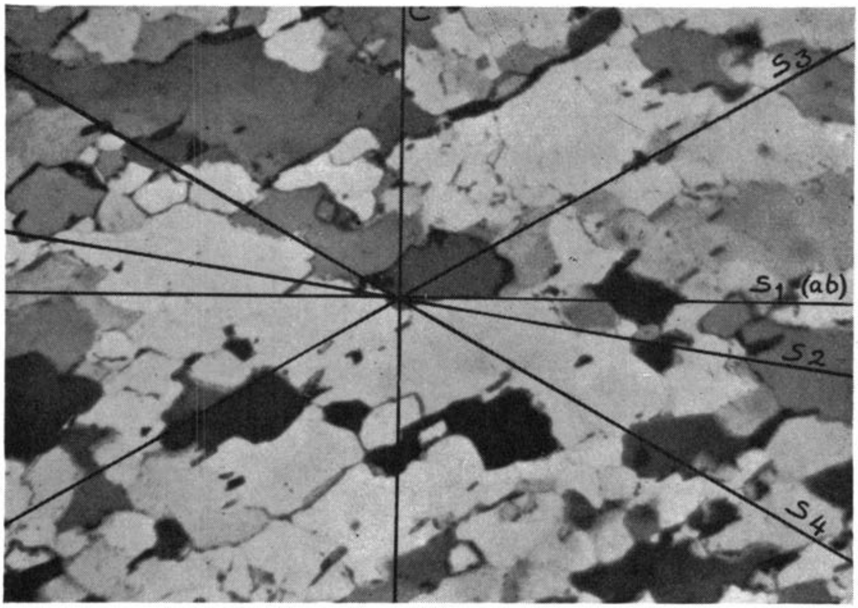

Fig. 2. Section (a) normal to the lineation. 58 × Nicols +.

Description of Thin Sections.

Of this quartzite were prepared three thin sections mutually perpendicular to each other; (a) normal to the lineation, (b) parallel to the lineation and normal to the planar structure, and (c) parallel to the planar structure.

a. In the thin section cut normal to the lineation the rock is homogeneous, consisting of quartz grains of various size with tiny flakes of brown biotite and of muscovite, evenly distributed throughout the rock (Fig. 2). The amount of muscovite is at least three times that of biotite. Parallel intergrowths of the two minerals are seen in some grains. The biotite is in some places altered to chlorite. In small quantities occur garnet, zircon, tourmaline, and iron ore. It is worthy of notice that part of the tourmaline is arranged in rows parallel to the main mica *s* plane (s_3). No segregation in layers of larger and smaller grains can be seen.

The quartz grains range in length from 0.08 to 1 mm and in width from 0.05 to 0.5 mm. The small grains are more or less equidimensional, while the medium grains are commonly elongated, the ratio

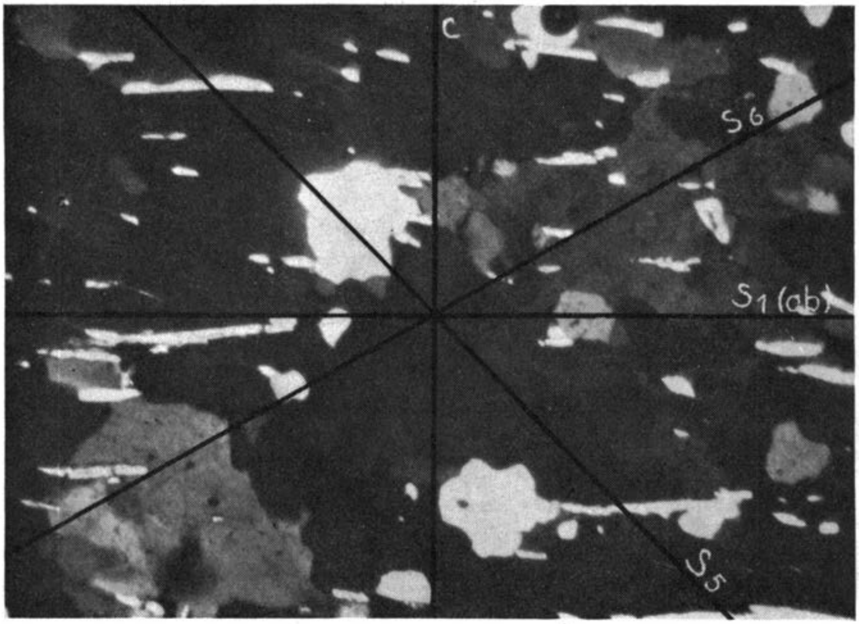

Fig. 3. Section (b) parallel to the lineation and normal to the foliation. 58 × Nicols +.

between the longest and the shortest diameters usually being 3 : 1 or 4 : 1. Many of these grains have parallel outlines, thus marking an *s* plane (s_2), which forms an angle averaging 8° with the macroscopic *s* plane (s_1). The larger grains are irregular in shape, but are invariably broken into rods along lines parallel to s_2, which in this way is strongly emphasized. The rods have slightly varying extinction.

Another *s* plane (s_3) is marked by the outlines of several quartz grains. This plane forms an angle of about 30° with s_1 and of 38° with s_2.

A third *s* plane (s_4) is followed by the outline of some quartz grains, which are partly broken into needles parallel to the plane. Also s_4 makes an angle of 30° with s_1, which thus bisects the angle between s_3 and s_4.

Under crossed nicols nearly all quartz grains extinct simultaneously, proving an unusually good orientation.

The biotite and the muscovite occur as tiny grains of a fairly even size, being 0.08—0.15 mm long and 0.015—0.030 mm thick. They

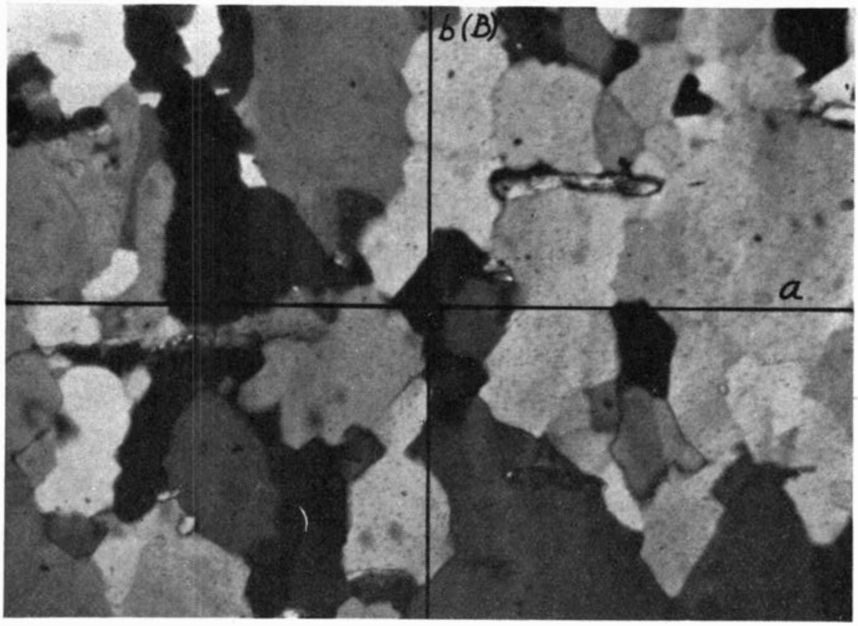

Fig. 4. Section (c) parallel to the foliation.
58 × Nicols +.

lie between the quartz grains and are oriented after s_3 with some spreading apparently caused by the variations in direction in the outline of the quartz grains.

In this section are seen some cracks, most of which go through several grains. Some of the cracks are normal to s_1, others dip northward forming angles with s_1 ranging from 10° to 80° with a maximum around 55°—60°. Only few cracks dip southward, their angles with s_1 being 45°—55°.

b. In the section cut parallel to the lineation and normal to the macroscopic *s* plane (Fig. 3) the smaller quartz grains (0.1—0.2 mm) are round or polygonal. In several grains is seen a tendency to a hexagonal outline with angles of 55°—60° between adjoining sides. Many of the larger grains (0.3—0.5 mm by 0.15—0.2 mm) are generally parallel oriented with their longest dimension parallel to the trace of s_1. Other grains have a very irregular outline and are broken into smaller grains with slightly varying orientation along lines which are irregular and show no parallelism. In the outlines of several quartz

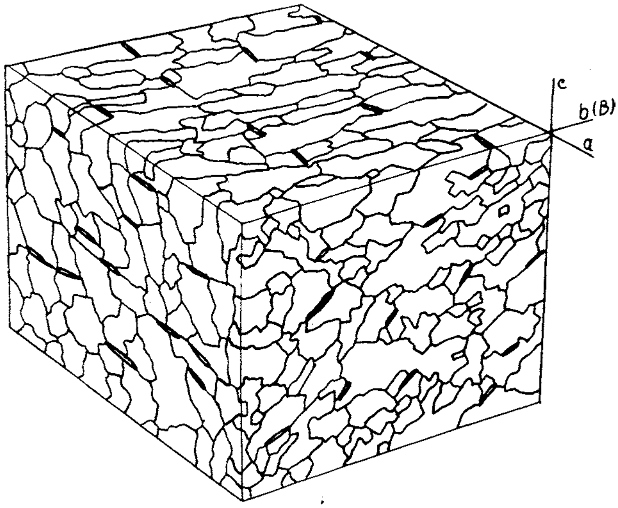

Fig. 5 a. Block diagram composed of drawings of the three thin sections.

grains are seen two other directions, s_5, which makes about 45° with s_1 and dips eastward, and the weaker s_6, which makes about 30° with s_1 and dips westward.

Under crossed nicols most quartz grains are dark throughout the rotation of the table, showing that a great majority of the grains have their c axes nearly normal to the sections, and in good accordance with the tendency to a hexagonal outline described above.

The micas are in this section strictly parallel to s_1. They are 0.1—0.4 mm long and 0.01—0.03 mm thick, rarely 0.05 mm. No cracks or joints are seen, a rather surprising fact, as several joints, normal and inclined to the lineation, occur in the outcrop.

c. In the section cut parallel to the macroscopic *s* plane (Fig. 4) (s_1) the smaller quartz grains are nearly equidimensional while the larger grains (0.3—1.5 by 0.2—0.4 mm) show a good parallel orientation with their longest diameters normal to the megascopic lineation. The larger grains are broken into parallel rods, which are 0.08—0.15 mm wide. As many quartz grains are more or less rectangular, the outlines of these grains show a direction parallel to the megascopic lineation.

Under crossed nicols the quartz shows the same good orientation as in the other sections.

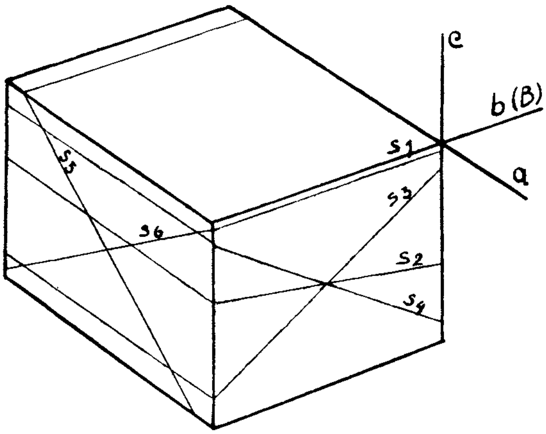

Fig. 5b. The same block showing position of s planes.

The micas are in this section nearly parallel to their base, but the grains are not equidimensional, as might have been expected. They are 0.1—0.4 mm by 0.02—0.05 mm and have their longest diameters parallel to the megascopic lineation.

This is one of the rare cases, where the orientation of the minerals can to a large extent be determined by the ordinary study of oriented thin sections, without the aid of petrofabric diagrams. Fig. 5 is a block diagram of a rectangular specimen with the top surface parallel to the macroscopic s plane and the edge pointing forward (a) parallel to the megascopic lineation. The block diagram was prepared from drawings made in a Reichert Universal-Mikroskop. The drawings were pasted on cardboard sheets which were again pasted together to form a block. This block was photographed, and finally the contours of the photograph were redrawn on translucent paper. (The orientation of the petrofabric axes (a, b, c) is discussed in connection with the petrofabric diagrams.)

The figure shows clearly that the majority of quartz grains are elongated parallel to their optic axes, which are nearly parallel to each other and normal to the macroscopic lineation. Thus this lineation cannot be produced by a parallel arrangement of minerals, the flakes of mica in spite of their good orientation being too small and too few to give any macroscopic impression of lineation. This lineation must be produced by the intersection of s planes, especially of s_2 and s_3 with s_1.

Another remarkable feature of this rock is that no minerals are arranged parallel to the macroscopic *s* plane s_1. This plane, therefore, most likely is a compromise surface between the intersecting *s* planes, notably s_2 and s_3. Such an arrangement of *s* planes reminds of flattening, but the asymmetrical positions of the main *s* planes s_2 and s_3 are unusual. For further information on this and other points we must turn to the fabric diagrams.

Description of Petrofabric Diagrams.

Diagrams of biotite, muscovite, and quartz have been prepared in the section normal to the macroscopic lineation. Following Sander and Schmidt the lower half of the hemisphere has been used, and the readings have been plotted in an equal area net. The number of grains within one percent of the net has been counted for every half centimeter to obtain greater accuracy in the drawing of the contour lines. These lines in all diagrams limit the areas with ½ - 1 - 2 - 5 - 10 - 15 - 20 - 25 - 30 etc. percent concentration. The area within the highest contour line is black, while the location of the exact maximum of concentration is marked as a white spot. This is done to obtain greater accuracy in determining the position of the maxima, a procedure that is justified by the great concentration in the diagrams and by the results discussed below. On each diagram is marked a horizontal line, the bearing of this line in degrees from north eastward, and the angle of dip of the diagram when oriented in nature.

Biotite. Owing to the scarcity of biotite only 100 grains could be measured. (Fig. 6.) The normals to 001 show very good orientation with a maximum of 34 percent. This maximum determines a *s* plane (s_3) which forms 30° with the megascopic *s* plane (s_1). There is, however, a tendency towards a girdle, with the macroscopic lineation as the girdle axis. A weak, but significant sub-maximum of only 3 percent lies 60° from the main maximum, indicating a *s* plane (s_4) which lies symmetrically to s_3 with regard to s_1.

Muscovite. The diagram (Fig. 7), comprising 170 grains, is almost identical with that of biotite. The maximum is 33.5 percent and lies exactly in the same position as the biotite maximum. The tendency towards a girdle is equally strong, but the sub-maximum is missing. Actually there is in this place a concentration of ½ per-

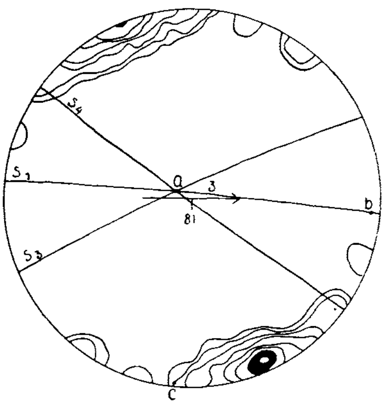

Fig. 6.

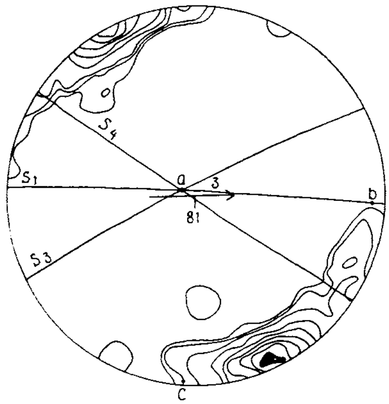

Fig. 7.

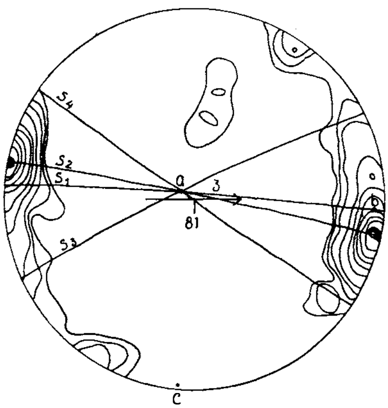

Fig. 8.

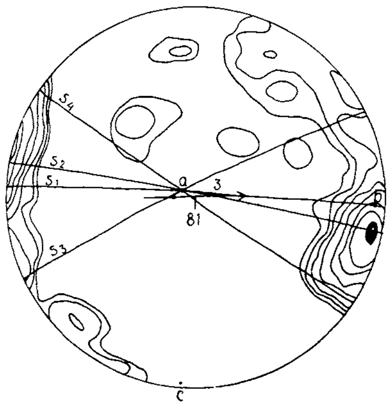

Fig. 9.

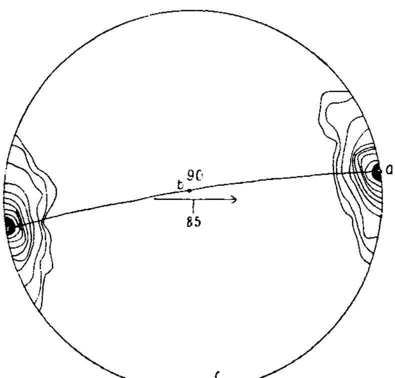

Fig. 10.

Fig. 6. Biotite. Section (a). 100 normals to (001). Contour lines 1-2-5-10-15-20-25-30(black)-34(white) percent.

Fig. 7. Muscovite section (a). 170 normals to (001). Contour lines ½-1-2-5-10-15-20-25-30(black)-33.5(white) percent.

Fig. 8. Quartz section (a). 200 axes. Contour lines ½-1-2-5-10-15-20-25-30-35 (black)-37.5(white) percent.

Fig. 9. Quartz section (b) rotated to (a). 200 axes. Contour lines ½-1-2-5-10-15-20-25(black)-27(white) percent.

Fig. 10. Muscovite section (b). 200 normals to axial planes.

Contour lines 1-2-5-10-15-20-25-30-35-40(black)-45(white) per cent.

cent, while the rest of the girdle is unoccupied. How much significance should be ascribed to the difference in concentration in this place by muscovite and biotite is difficult to decide. The biotite diagram covers a greater portion of the thin section than does the muscovite diagram. With so small figures it is not unlikely, that if the two diagrams had covered exactly the same area, the difference in density in the sub-maximum would have been reduced. We, therefore, are justified in saying that there is no noteworthy difference in the orientation of the micas.

Quartz. Mica diagrams with concentrations of more than 30 percent are rare, but not unknown. Quartz diagrams with that high concentration have, as far as I know, never been described. Actually this diagram (Fig. 8), which comprises 200 grains, has a maximum concentration of 37.5 percent. The maximum lies in the "girdle" formed by the micas, and makes an angle of 52° with the mica maximum. Of the 200 grains measured 189 are concentrated around this maximum, which is drawn out in the mica "girdle". Of the remaining 11 grains 8 form a sub-maximum of 3 percent also in the "girdle" and 65° from the main maximum, which means that it lies symmetrically to the main maximum with regard to the main mica s plane (s_3). The remaining 3 grains lie about halfway between the centre of the diagram and the biotite sub-maximum, and are thus near Sander's maximum II or III with regard to this sub-maximum. Consequently not a single quartz grain in this diagram is unoriented. So high degree of orientation is rather astonishing and must be caused by a very intense deformation. The only comparable diagrams which I have seen, are Sander's diagrams from certain shear zones (Harnisch-mylonite). There the quartz grains are concentrated around a single maximum, which in his D 24 reaches 25 percent. These diagrams are, however, made from narrow zones, D 24 is thus made from a layer with a thickness of 5 to 10 grains. In the quartzite near Grønsdalsvatn the orientation is equally strong throughout the rock.

In shape and size the concentrations around the quartz and muscovite maxima are almost identical, with a steep side towards the normal to s_1 and a gentle slope towards s_1. This fact is in good agreement with the observation in the thin section that the spreading in direction of the micas is caused by variations in direction in the outline of the quartz grains.

Homogeneity of the fabric. For control of the homogeneity a quartz diagram was prepared from the section parallel to the lineation and normal to s_1. The diagram was then rotated to the same position as the others (Fig. 9). The most important features of the two quartz diagrams are the same. The main maxima are in exactly the same position, but the concentration in the rotated diagram is only 27 percent against 37.5 percent in the first diagram. The girdle has the same length in both diagrams, but in the rotated diagram it is a little wider, especially around the sub-maximum, which has split in two concentrations of only two per cent lying 25° apart. Further altogether seven grains occur outside the girdle in scattered positions which seem to have no relation to the common quartz maxima. The differences between the diagrams are explained by the fact that, when most quartz axes are nearly normal to the plane of a thin section, they remain dark throughout the rotation of the table and can only with difficulty be separated during a traverse of the section. The grains whose axes are inclined or nearly parallel to the section stand out with a bright interference colour and are likely to be over-represented in the diagram. Considering these facts we may safely assume the fabric of the quartzite to be homogeneous.

Bedding and *s* planes. The bedding cannot be determined with certainty in the hand specimen. In the thin section normal to the lineation rows of tourmaline are visible parallel to the main mica slip plane s_3. This indicates that s_3 is parallel to the original bedding plane, which partly explains why practically all mica is oriented in this plane and not in the symmetrical slip plane. Mica flakes that are oriented in or near a slip plane cannot easily be rotated out of this plane as long as the slip plane is active. Sander's explanation of unequally developed slip planes, namely that a one-sided lateral displacement was combined with the flattening, may also be partly responsible for the difference between the slip planes.

Discussion of the Diagrams.

Fabric axes and symmetry. To interpret the diagrams we must first determine the petrofabric axes *abc,* where *a* is the direction of tectonic transport, *b* is the normal to *a* in the most prominent *s* plane, and *c* is the normal to the *ab* plane.

In the described quartzite the *s* plane visible in the hand specimen is naturally chosen as the *ab* plane, and the position of the *c* axis is thereby fixed. The determination of the other axes presents some difficulties. Usually, if the rock has a lineation, this lineation will be parallel to the *b* axis. If this *b* axis represents the line of intersection of two or more slip planes which were formed during the same act of deformation, or if it is an axis of external rotation producing a bending movement in the rock, the axis is called a *B* axis and the rock is a *B*-tectonite. Fabric diagrams of a *B*-tectonite show a marked tendency to developing a girdle around the *B* axis. Another criterium for the determination of the *a* and *b* axes is the symmetry of the diagram. If only one plane of symmetry can be laid through the diagram (monoclinic symmetry), this plane will contain the direction of tectonic transport *a*.

All these criteria are fulfilled by the direction parallel to the megascopic lineation. It is the line of intersection of the slip planes s_3 and s_4, which lie symmetrically to the megascopic *s* plane, and of which there is no reason to believe that they were formed in different phases of deformation. Both the quartz and the mica diagrams show a clear tendency to a girdle around this axis. It is evident that only one plane of symmetry can be laid, viz. normal to the supposed *B* axis, and that with respect to this plane the symmetry is as perfect as one can expect to find in a fabric diagram.

Thus all the usual criteria determine the megascopic lineation as the *B* axis. Consequently the direction of tectonic transport should be normal to the lineation. As the lineation strikes exactly east-west, the tectonic transport should have taken place in the north-south direction.

This conclusion is, however, in strong contrast with the evidence gathered by structural investigations in the field. For details must be referred to a monograph on the quadrangle, which will be published in Bergens Museums Årbok. Here shall only be mentioned that the field observations show, in my opinion with absolute certainty, that the whole complex to which the quartzite belongs has been thrust eastward parallel to the lineation, and that the lineation was formed during the thrusting. The immense stretching of the rocks, with elongation of conglomerate pebbles as much as 5 to 10 times their original length, is in itself a proof of considerable tectonic transport parallel to the lineation.

We are thus forced to reject the results of the preliminary determination of *a* and *b* axes. Another criterium that has been used for determination of the fabric axes is that by lattice orientation the muscovite a axis is probably arranged parallel to the fabric *a* axis. Sander (p. 215) finds support for this assumption in fabric diagrams, but holds that further investigations are needed to bring conclusive evidence. Fairbairn (1937, p. 35) states it as a fact without giving any evidence. Knoph and Ingerson (1938, pp. 166 and 176) on this point only refer to Mügge (1898, pp. 101—108) who by experiments produced translation in muscovite with the directions of the percussion-figure as probable directions of translation. Mügge, however, also (p. 108) considered the directions of the pressure-figure as probable directions of translation, thus giving six directions of gliding in (001). Ingerson (1936, pp. 184—85), finding a maximum of normals to the axial planes of muscovite parallel to the fabric *B* axis, concluded that gliding had taken place normal to the *B* axis. He thus seemed to suppose that the muscovite a axes were oriented normal to the direction of movement.

Thus the problem is not settled at present. This is not the place for a thorough discussion, but as the directions of gliding in crystals commonly are the directions of closest atomic packing (see f. inst. Fairbairn 1937, p. 132 et sq.), it should be noted that the crystal structure of muscovite has perfect hexagonal symmetry in (001) and that the lines of the percussion figure have the closest packing. Thus the crystal structure gives no preference to any of the three directions, nevertheless the percussion line parallel to the a axis is always more prominent than the others, indicating this line as the favoured line of gliding. In Fig. 10 is given a diagram of the normals to the axial planes of 200 muscovite grains, measured in the section parallel to the lineation and perpendicular to the *ab* plane. This diagram has a greater concentration than any of the others, with a maximum of 45 percent parallel to the megascopic lineation.

This diagram gives evidence that (1) there is only one direction of gliding in muscovite, (2) this direction is the crystallographic a axis, (3) the muscovite in this rock is not oriented by growth, but by lattice orientation. Further the diagram supports the field determination of the fabric axes.

F l a t t e n i n g. To obtain a better understanding of this seeming controversy we must consider the question of flattening of the rock. As mentioned above the conglomerate 1 km to the west of the locality has been flattened to a considerable degree, the proportion between the medium and the smallest axes being 5: 1 to 15: 1. Such direct proofs of flattening cannot be found near the outcrop where the specimen was taken, and other criteria must be used.

Flattening is characterized by the occurrence of slip planes which are symmetrical with regard to the macroscopic *s* plane, in which no gliding has taken place (Sander, p. 220). Further the fabric elements, especially quartz grains, are elongated parallel to the macroscopic *s* plane.

In the mica diagrams Figs. 6 and 7 one *s* plane (s_3) is completely dominating. In the biotite diagram there is, however, a sub-maximum of 3 percent, which lies 30° from the *c* axis and 60° from the main maximum. This sub-maximum proves the existence of a second slip plane (s_4) lying symmetrical to the s_3 with regard to the macroscopic *s* plane (s_1). In the muscovite diagram the sub-maximum, however, shows only one half percent.

Elongation of quartz grains in the macroscopic *s* plane was described above. The elongation, however, is not strictly parallel to the *s* plane but makes an angle of about 8° with it, thus determining an *s* plane (s_2) which makes an angle of around 38° with the main slip plane (s_3). The interpretation of this fact will be dealt with below. Fairbairn (1937, p. 82) mentions that rod-like elements by flattening tend to arrange themselves with their longest dimensions parallel to the *B* axis. In the description of the thin section was shown that the quartz grains are elongated normal to the lineation.

We may thus take it for proved that the rock has been flattened, but with a very unequal development of the slip planes. Sander's explanation of this structure is that the flattening has been combined with a lateral displacement (Knoph and Ingerson 1938, p. 148).

By pure flattening the macroscopic *s* plane, which is also the *ab* plane, is normal to the direction of greatest pressure, whereas by other types of deformation the *ab* plane is inclined to this direction. Accordingly the three axes of the strain ellipsoid ABC are parallel to the fabric axes *abc,* whereas by other types of deformation only the fabric axis *b* is parallel to the corresponding strain axis *B*. By flattening the maximum elongation occurs in A (or *a*) while by other types of deformation the greatest elongation usually is parallel to B. This is one more proof that the *a* axis is parallel to the lineation, which we know is parallel to the maximum of elongation.

Rotation. Flattening may be combined with rotation. If a rotation occurred around the *B* axis, it would tend to rotate those elongated quartz grains that were not parallel to *B*. We should then expect to find two quartz maxima symmetrical around *B*. No such maxima occur, however, and the only possible sign of a rotation is that the maximum is somewhat pulled out on the "other" side of *B*. A rotation around *B* should also show itself in the mica diagrams as a widening of the maxima. A weak half percent widening of the muscovite diagram, caused by two grains in a deviating position, is the only sign of such rotation. Although grains that have been oriented in a slip plane, only with difficulty can be rotated out of this position as long as the set-up of strain is not radically changed, there can be no doubt that the rotation around *B* has been insignificant.

The only possible sign of rotation around the *c* axis is the spreading of the *a* axes in muscovite, but this spreading is more likely due to imperfect orientation.

Rotation around the *a* axis is on the other hand evident in all diagrams. The extension of the maxima is in the *bc* girdle more than twice the extension normal to it. Also in the thin section is clearly seen the contrast between the straight parallelism of mica in the sections normal to *b* and *c* and the numerous deviations normal to *a*. In this quartzite, which has been flattened, we might suppose that the spreading of the maxima was caused by a pressing of the slip planes closer to the *ab* plane as the deformation continued. We should then expect to find a younger set of slip planes making greater angles with *ab* (Knoph and Ingerson 1938, p. 143). Such a rotation of the dip planes may be partly responsible for the spreading, but no indication of more than one set of planes can be found.

The field observations give the same picture of the rotation. Small-scale folding with axes parallel to the lineation is relatively common, while folding with axis normal to the lineation has not been observed. Where cross-folding occurs, the second set of folds can be proved to belong to a different phase of deformation.

Remarks on the Orientation Mechanism of Quartz.

The problem how quartz grains achieve a preferred orientation in tectonites is not yet settled, and any information bearing on that problem may therefore be of value. Diagrams with few maxima and good concentrations may be especially informative.

As very few papers on structural geology have reached me since 1940, the following brief summary of current opinions may not be quite up to date.

Three main theories have been set forward on the orientation mechanism of quartz.

Sander (1930) holds that two processes are important: 1) The orientation of the crystallographic c axis in the slip direction (fabric axis *a*) and 2) the orientation of the plane of the Böhm lamellae (a flat rhombohedron) in the slip plane. The various maxima encountered are eexplained by orientation in various slip planes (*h0l*) (*0kl*) etc., partly produced by a rotation of the strain axes.

Schmidt (1932) assumes that there is only one plane of slip in *s*-tectonites, and refers the maxima to the orientation of various slip directions in quartz parallel to the fabric axis *a* and various crystallographic planes in the fabric plane *ab*.

Griggs and Bell (1938) on the basis of experiments, believe that quartz grains under the combined effect of pressure, heat, and solution break up in needles bounded by 1) irregular surfaces parallel to the *c* axis, 2) rhombohedral cleavage planes, 3) the basal separation, or a combination of two of these surfaces. They assume that the elongation of the needles will be parallel to the direction of gliding.

In the diagram described the elongation of the quartz grains is normal to the direction of gliding as found in the muscovites. If we apply the theory of Griggs and Bell to the described quartzite we must assume that the direction of gliding which determined the orientation of quartz was normal to that which determined the orientation of mica. Later is shown that if we apply Sander's strain ellipsoid theory to this rock, we must assume two rhythmically alternating ellipsoids E and E′ whose axes were at right angles to each other. The planes s_3 and s_4 were formed as slip planes in E′, while the muscovite was later reoriented in E, leaving no trace of the original direction of gliding. Adopting this scheme we many assume that the quartz needles were oriented with their elongation in the direction of gliding determined by E′, and that they were not — as were the muscovite grains — reoriented by E.

The maximum occurring lies in the *bc* girdle and is thus Sander's maximum III. Sander explained this as the result of gliding in a (*0kl*) plane by either of the two possible grain mechanisms. Schmidt explains it as an orientation of the rhombohedron $(10\bar{1}1)$ in the slip plane (usually *ab*) and the base-rhombohedron edge [$2\bar{1}\bar{1}0$] in the direction of slip. The theoretical angle between the quartz axis and the slip plane would then be 38° 13′. If the first assumption of petrofabric axes in the rock had been correct, the maximum would have been Sander's II lying on the *ac* girdle. This maximum Schmidt explains as the orientation in the slip plane of the rhombohedrons ($2\bar{1}\bar{1}2$) or ($11\bar{2}2$) and the rhombohedron edge [$2\bar{1}\bar{1}3$] in the direction of slip. Sander's explanations do not in either case require a special angle as the ideal one, but he gives 38° and 43° as the average angles for the maxima II and III respectively, while Schmidts empirical angles are 41° and 38°.

ab is no slip plane by flattening. We must therefore compare the quartz maximum with the mica maximum, which determines the slip plane. The angle between the quartz and the mica maxima is 52°, and accordingly the angle between the quartz maximum and the mica slip plane is 38°, or exactly what it should be according to Schmidt's theory. This coincidence between the theoretical figure and the figure determined in the best oriented quartzite ever measured cannot be fortuitous and it gives evidence that the maximum is Sander III and not II, thereby confirming the orientation of the fabric axes as determined from the direction of gliding in muscovite. It also justifies the accuracy in reading angles, which is made possible by marking the spot for the exact maximum of concentration.

The sub-maximum of 3 percent makes an angle of 57° with the mica maximum, corresponding to 33° between the quartz axes and the slip planes. With so weak a sub-maximum a deviation of 5° from the theoretical angle is not surprising. The reason for the weakness of this maximum must be that the longest dimensions of the quartz grains in this position make an angle of 60°—65° with the surface of flattening *ab*, while the grains in the main maximum are nearly parallel to *ab*.

In my opinion there is no contradiction between Schmidt's theory of slip in more than one direction and in more than one lattice plane and Sander's assumption of more than one plane of slip, an assumption for which Sander has given sufficient evidence.

The maxima occurring in this diagram may be explained according to Schmidt's theory as well as to that of Griggs and Bell, as both theories demand the same theoretical angles. If we apply the former theory, the direction of gliding recorded by quartz is the same as that recorded by muscovite. If we apply the latter theory the two minerals have recorded directions of gliding that are at right angles to each other.

Application of the Strain Ellipsoid.

Sander's explanation of the fabric elements and their mutual relations is based upon the strain ellipsoid theory, mainly in the form given by Becker 1893. According to this theory, shear surfaces can only be formed as $(h0l)$ planes, parallel to the B axis of the strain ellipsoid. $(0kl)$ planes are explained by the assumption of crossed strain. Besides the strain ellipsoid E with axes ABC and corresponding fabric axes a $(b = B) c$ occurs the ellipsoid E' with axes $A'B'C'$ and fabric axes $a'b'c'$ where $b' \perp B = a$. Sander p. 58 holds that the influence of these two ellipsoids may alternate rhythmically, possibly in the way that as soon as the pressure causing the original set-up of strain axes is partly released by shearing along $(h0l)$ planes, the axes relation $A > B > C$ is changed to $B > A > C$, whereby $(0kl)$ planes can be produced. The fabric is called a $B \perp B'$ fabric.

According to Sander (1930, p. 239) the symmetry of this fabric depends upon the symmetry of the two strain ellipsoids. If both have a monoclinic symmetry (unequally developed shear planes), the resultant fabric has triclinic symmetry; if one ellipsoid has orthorhombic symmetry (equally developed shear planes) the fabric retains the monoclinic symmetry.

If we apply the strain ellipsoid theory to the quartzite studied, we must assume an interchange of the a and B axes. The muscovite s planes s_3 and s_4 must be formed when the present a axis was the B axis, but the orientation of the muscovites within the plane is connected with the present set-up of axes. The spreading of the micas in a bc girdle may be due to imperfect orientation, but on account of the close relationship between the quartz and the mica orientation described above it is more likely due to the rotation around the a axis, which in this case must have been a B axis. The orientation of the longest dimensions of the quartz grains nearly parallel to the B axis is common by flattening (Fairbairn 1937, p. 80) and may thus be the result of the present set-up of axes. If we accept the quartz maximum as III and use Schmidt's explanation, the orientation of the glide lines in *a* must also be ascribed to the present set-up of axes, while according to Griggs and Bell it must be related to *E'*.

To the strain ellipsoids *E* (*aBc*) and *E'* (*a'B'c'*) can thus be ascribed the formation of the following fabric elements.

E (*aBc*)	*E'* (*a'B'c'*)
Production of (h0l) planes s_5 and s_6. Re-orientation of micas with musc. a ∥ *a*. (Re-orientation of quartz with [2$\bar{1}\bar{1}$0] ∥ *a*?) No rotation around the *B* axis. Orthorhombic symmetry of *E*.	Production of (0kl) planes s_3 and s_4 with orientation of mica in them, predominantly in s_3. Orientation of quartz (10$\bar{1}$1) in s_3. Some rotation around the *B'* axis. Monoclinic symmetry of *E'*.

This conception of the orienting processes presents some difficulties, especially regarding muscovite. It seems unlikely that in one phase all muscovite grains should be oriented in s_3 — probably with a majority of a axes in the *bc* plane — and in another phase all grains rotated approximately 90 degrees, bringing the crystallographic a axes parallel to the fabric *a* axis. Moreover, such a rotation would rather tend to bring the glide lines (the a axes) in the (*h0l*) surfaces than parallel to *a*.

Schmidt (1932, pp. 60—72) from a dynamical point of view deduced that by triaxial deformation tensions arise which cannot be released by shearing along planes intersecting in the *B* axis, and which therefore result in shearing along planes intersecting in *a*. He believes to have proved that this is the only possible set-up of shear planes by triaxial deformation, and he therefore considers this deduction more satisfying than Sander's assumption of two plane deformations acting at right angles to each other. He does not discuss whether the movements in the two sets of shear planes may take place simultaneously or alternating.

Schmidt's explanation seems to me to be more satisfying than the other one. No doubt triaxial deformation is the normal case in nature, but lateral resistance prohibits any noticeable movements in the *Bc* plane, and the (*0kl*) planes are therefore generally insignificant. When occurring they prove that movements in the *Bc* plane were possible (cf. the dimensions of the conglomerate pebbles). In this particular case we may assume that movements took place in the *Bc* plane as well as in the *ac* plane, the latter movements being on a larger scale, and that by interference the glide directions in muscovite were not oriented in any of the shear planes but parallel to the fabric *a* axis.

Another possibility would be that the rock contains hidden (*Okl*) planes whose angles with *ab* are close to zero. Fairbairn (1937 p. 50) held that also by triaxial deformation shearing is likely to occur along the circular sections, as they contain the lines of maximum resolved shear. The angle ν between the *a* axis of the strain ellipsoid and the circular sections is determined by the formula

$$\tan \nu = \pm \frac{c\sqrt{a^2 - b^2}}{a\sqrt{b^2 - c^2}}$$

When *a* is large, the angle is determined by the ratio $b : c$. As examples we take the extreme values found in the conglomerate mentioned.

$$b : c = 5 : 1 \qquad \nu = 11^\circ$$
$$b : c = 15 : 1 \qquad \nu = 3^\circ{,}8$$

Further, when

$$b : c = 30 : 1 \qquad \nu = 1^\circ{,}9$$

Thus, if Fairbairn's assumption is correct, and if we may take the conglomerate pebbles to represent strain ellipsoids — by such extreme deformation this is probably justified — the angles between the circular sections and the *ab* plane may by triaxial deformation become so small that they can not be recognized in a diagram. However, even by using the ratio 15 : 1 the a axes of muscovite ought to occur in two maxima 8 degrees apart and lying symmetrical to the *a* axis, while the diagram actually has one sharp maximum exactly in the position of the *a* axis.

Although the above explanation does not seem unlikely, we have so far no proof of it.

All features of the diagrams can be ascribed to one and the same period of deformation. This is very interesting, as the rock most likely is a pre-Cambrian quartzite and has been subjected to pre-Cambrian as well as to Caledonian deformation. As no trace of the earlier deformation is left, every single grain in the rock has been reoriented under the Caledonian deformation. It may be noted that no sign of accompanying changes in the chemical composition of the rock can be found.

The reasons for the unusual concentration in the quartz diagram must be:

1. The intensity of deformation.

2. The predominance of quartz over mica, prohibiting intergranular rotation and thus speeding up the rate of deformation.

3. The effect of flattening which prohibits the orientation of quartz in the second possible maximum III connected with the main mica slip plane s_3.

CONCLUSIONS

The described type of a tectonite is characterized by the following properties (specific data for the sample investigated in parentheses):

1. $B \perp B'$ tectonite with a tendency to *bc* girdle.
2. *bc* is a plane of symmetry, which is perfect monoclinic.
3. *a* is the line of intersection of (*0kl*) slip planes which are symmetrically arranged with regard to *ab* (angles 30°) and unequally developed (max. in biotite 34 percent and 3 percent, in muscovite 33.5 percent and 0.5 percent).
4. The direction of gliding in (*0kl*) slip planes is || *a*.
5. *bc* joints and (*0kl*) joints (relatively few). No *ac* joints.
6. Two weak (*h0l*) planes (No proof of slip).
7. Flattening in *ab* || *b* and (enormous) stretching in *a*. Elongation of quartz grains || *b*.
8. Quartz max. III with regard to mica slip planes. (Angle quartz max. $\wedge$ mica max. 52°). Elongated quartz grains nearly || *ab*.
9. Quartz concentration equals mica concentration (37.5 percent).
10. Paracrystalline deformation.
11. Quartz, biotite, and muscovite fabric.
12. Homotactic and homoaxial. (Biotite and muscovite max. identical).
13. Rotation around *a*. No or insignificant rotation around *b*. No rotation around *c*.

RESYMÉ

I dette arbeidet er beskrevet mineralkornenes orientering i en sterkt presset kvartsit ved Grøndalsvatn i Samnanger øst for Bergen. Bergarten består helt overveiende av kvarts med små korn av biotit og muskovit. Dette har sammen med den sterke deformasjon gitt mineralene en usedvanlig god orientering. Fig. 5 viser orienteringen som den er funnet i tre tynnslip som står loddrett på hverandre (fig.

2—4). Den samme orientering gjenfinnes i strukturdiagrammene, hvor fig. 6 og 7 viser konsentrasjonen av normalen til (001) hos biotit og muskovit, mens fig. 8 viser konsentrasjonen av kvartsakser. Alle tre diagrammer er fra tynnslip a (loddrett strekningen). For å kontrollere bergartens homogenitet blev målt et kvartsdiagram i tynnslip b og rotert til a (fig. 9). Da fig. 8 og 9 er praktisk talt identiske, er bergarten homogen.

Diagrammene viser at den overveiende del av glimmerne er ordnet i et plan s_3, som danner 30° med den makroskopiske kløvretning s_1. Noen få glimmerkorn, spesielt biotit, ligger i et annet plan, s_4, som også danner 30° med s_1. Kvartsdiagrammet viser usedvanlig god konsentrasjon, med et maksimum på 37.5 % 52° fra glimmernes maksimum. Det betyr at nesten alle kvartskorn har en romboederflate $(10\bar{1}1)$ i glimmernes *s*-plan og kanten $[2\bar{1}\bar{1}0]$ parallell strekningsretningen (*a* i diagrammet). Kvartskornenes lengderetning markerer et plan s_2 som danner 8° med s_1, da vinkelen mellem kvartsens akse og romboederflate er 38°. Alle diagrammer har tydelig monoklin symmetri. Efter Sanders opfatning skulde da retningen for tektonisk transport (den tektoniske *a* akse) ligge i symmetriplanet og altså være loddrett strekningsretningen. Nu viser feltundersøkelsene i de tilgrensende strøk med absolutt sikkerhet at transportretningen har vært parallell strekningsretningen. Dette bekreftes av fig 10, som viser at den optiske normal — og dermed den krystallografiske *a* akse — hos muskoviten i slip *b* har et sterkt maksimum parallelt strekningen. Eksperimenter har gjort det sannsynlig at muskovitens *a* akse stiller sig parallelt glideretningen.

De symmetriske *s* plan (s_3 og s_4) viser at bergarten har vært utsatt for betydelig flattrykning. Dette sees også i et konglomerat 1 km lenger vest. At s_3 dominerer over s_4 kan skyldes at flattrykningen har vært kombinert med ensidig lateral bevegelse, men kan også henge sammen med at s_3 representerer lagningen. I s_3 og s_4 har foregått glidning (skjærbevegelser), derimot ikke i s_1, som var loddrett trykkretningen. Da s_3 og s_4 skjærer hverandre i den tektoniske *a* akse i stedet for i *B* aksen, må bergarten ha undergått treakset deformasjon (Schmidt), efter Sanders opfatning med to strainellipsoider som har stått loddrett på hverandre og vekslet rytmisk.

Konklusjonen blir at diagrammenes symmetri alene gir ingen sikker bestemmelse av den tektoniske transportretning. Studiet av diagrammer må alltid kombineres med grundige feltundersøkelser.

LITERATURE

Becker, G. F.: Finite Homogeneous Strain, Flow and Rupture of Rocks. Geol. Soc. America Bull. Vol. 4, pp. 14—90. 1893.

Fairbairn, H. W.: Structural Petrology. Kingston, Canada, 1937.

Griggs, D. and Bell, J. F.: Experiments Bearing on the Orientation of Quartz in deformed Rocks. Geol. Soc. America Bull. Vol. 49, pp. 1723—1746. 1938.

Ingerson, Earl: Fabric Analysis of a Coarsely Crystalline Polymetamorphic Tectonite. Am. Journ. Sci. 5th ser. Vol. 31, pp. 161—187. 1936.

Knoph, E. B. & Ingerson, E.: Structural Petrology. Geol. Soc. America Memoir 6. 1938.

Mügge, O.: Ueber Translationen und verwandte Erscheinungen in Krystallen. Neues Jahrbuch 1898, Bd. I, s. 71—159.

Sander, Bruno: Gefügekunde der Gesteine. J. Springer. Wien 1930.

Schmidt, Walter: Tektonik und Verformungslehre. Gebr. Borntraeger. Berlin 1932.

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