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STRUCTURAL PETROLOGY OF THE BYGDIN CONGLOMERATE

BY

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With 3 figures in the text and 24 diagrams.

Abstract. The Bygdin conglomerate, a quartzite conglomerate in the Valdres Sparagmite, was deformed by an overriding thrust-sheet of igneous rocks moving towards SE. The boulders of the conglomerate were drawn out in a NW—SE direction. Accompanying this deformation there is folding on NW—SE axes, both stretching direction and axes of folding pitching commonly 10—20° NW. The fabric patterns of quartz and sericite in the deformed boulders are girdles with a direction NE—SW. The folding and the production of the girdles are interpreted as produced simultaneously with the mass transport towards SE, caused by a triaxial deformation by which shearing stresses operated on planes striking NW—SE as well as on planes striking NE—SW.

The Bygdin conglomerate, a brief name for it not intended to be introduced as a new stratigraphical term, is the quartzite conglomerate in the Valdres Sparagmite as exposed near the road at the eastern end of Lake Bygdin, about 1100 metres a. s. l., district of Valdres, Southern Norway, geographical position about 61° 19′ N, 8° 50′ E (see map Fig. 1). For further topographical orientation the map Slidre (E 31 aust) of the Ordnance Survey of Norway may be used, the same sheet is at present in preparation for publication as a geological map by the Geological Survey of Norway.

In the region at the eastern end of Lake Bygdin and environs the following rock units are recognized, of which only 3. and 4. occur in the area of map Fig. 1:

1. Archaean rocks forming the basement are exposed in a window of erosion about 10 km to the south.

2. The sedimentary cover of this basement is made out of phyllites with some intercalated beds of quartzite, being marine deposits of Cambrian and Ordovician age.

3. Resting upon these marine deposits is the Valdres Sparagmite, of which the Bygdin conglomerate is the upper member preserved in this tract. The Valdres Sparagmite consists for the greater part

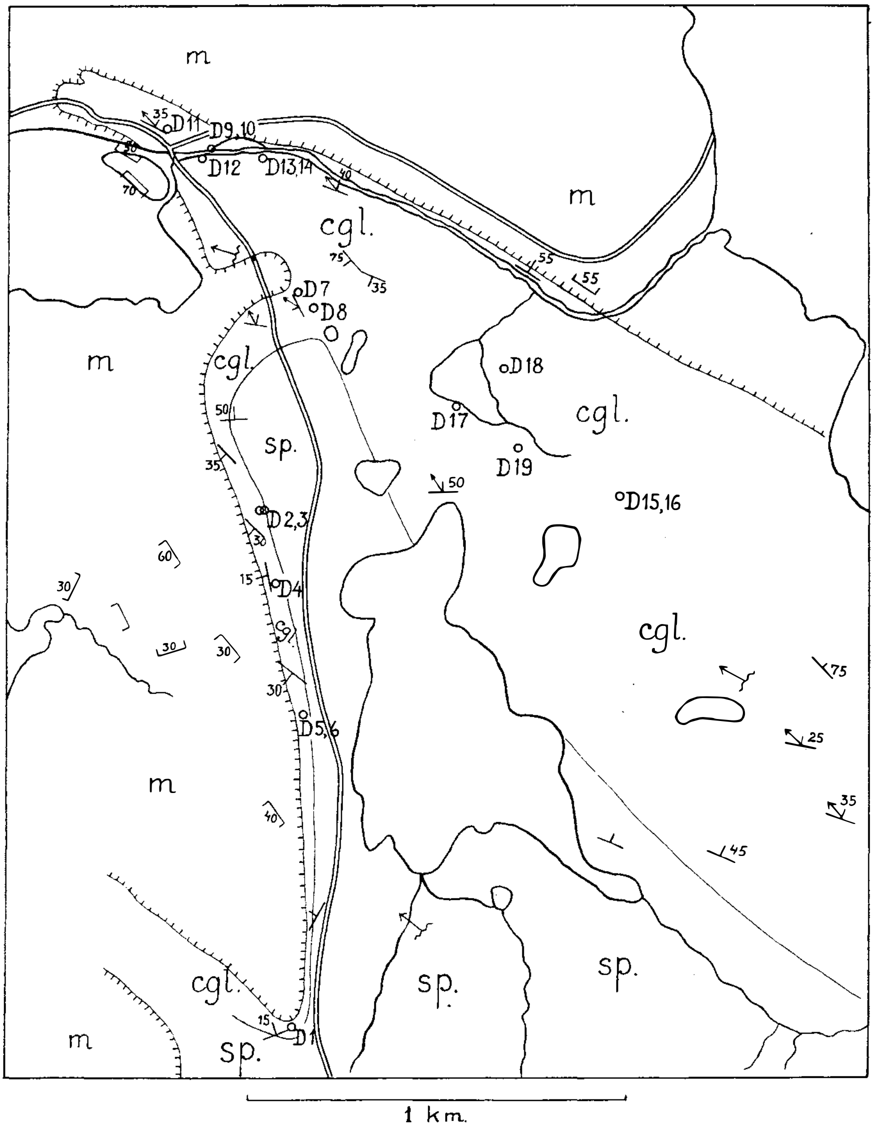

Fig. 1. Geological sketch-map of the quartzite conglomerate at the eastern end of Lake Bygdin (in the upper left corner). sp. = sparagmite, cgl. = quartzite conglomerate, m = mylonites. Arrows indicate pitch of the stretching direction or axes of small-scale folding (wavy lines). Rings indicate localities from which the specimens yielding the diagrams were collected.

of feldspathic arkoses, petrographically similar to the Eocambrian sparagmites. As has been definitely shown by Goldschmidt, however, it is of Caledonian age and is to be considered as a Caledonian flysch, or, perhaps better, molasse deposit (see Goldschmidt 1916 a, Strand 1939).

4. Overlying the Valdres Sparagmite with tectonical contacts is an overthrust massif of igneous rocks, out of which the Jotunheim mountains to the north of our area have been carved. For an account of these rocks, known as the Bergen—Jotun kindred, see Goldschmidt 1916 b. In the area of map Fig. 1 they are present as mylonites near the thrust-plane.

The Bygdin conglomerate was described in considerable detail by V. M. Goldschmidt in a well known paper (Goldschmidt 1916 a), in which was paid a special attention to the deformation of the conglomerate. A number of large specimens of the conglomerate collected by Goldschmidt are exhibited in the Geological Museum in Oslo and photographs are reproduced in Pl.s 2 and 3 in Goldschmidt's paper.

H. Cloos in his text-book "Einführung in die Geologie" has published a couple of photographs from the Bygdin area, one of which is of the deformed conglomerate.

The present writer collected a number of orientated specimens of the conglomerate in the area of map Fig. 1 and made rather detailed observations of the tectonics of the same area during visits in the summers of 1936, 1938, and 1939. The measurement in the laboratory of the quartz and sericite orientation was performed by a Leitz universal stage. The working out of the diagrams of the finely granulated quartz boulders was made possible by the use of special high power objectives for the universal stage from the firm Leitz (magnification 20 and 30 diametres). For the determination of the position of quartz axes the method of Tsuboi was used and found very convenient.[1] The diagrams were counted by means of 1 per cent circles. All diagrams here presented have been rotated into the horizontal plane. This procedure greatly facilitates the orientation for the reader and ought to be followed by all writers dealing with petrofabrics in connection with regional tectonics.

[1] The method has been described in the Jap. Journ. of Geol. and Geogr., but volume and page of the publication can not be given due to the inaccessibility of the library of the Geological Survey during the present circumstances.

In the area of map Fig. 1 the structure is dominated by an anticline with axis trending NW, and pitching in the same direction. Erosion has brought up Valdres Sparagmite in the midst of the anticline with the overlying quartzite conglomerate at the sides, which is again overlain by overthrust mylonitized igneous rocks. As will appear from a glance at the map, the anticline is far from symmetrical, as the conglomerate occupies a wider space at the northeastern than at the southwestern side. At the southwestern side the conglomerate occupies a thin zone between sparagmite and overlying mylonites, commonly with a gentle dip in a western direction, while at the northeastern side it occupies a wide area, mostly with rather steep dips to the northeast. A calculation of the thickness from dip and extension across the strike would here give a great thickness, several hundred metres, for the conglomerate. From observations in regions farther east it is shown that the thickness of the conglomerate is less (about one hundred metres). The schistosity of the conglomerate, determined by the plane of the two greater dimensions of the deformed boulders, is here apparently not coincident with the stratification. This is directly seen in some outcrops showing the boundary between conglomerate and sparagmite with traces of stratification. Possibly the conglomerate is here also repeated by isoclinal folds.

The main features of the tectonics are seen from the map and from D 23, in which poles of bedding (and schistosity) planes in sparagmite and conglomerate have been plotted down together with the stretching directions (directions of elongation in the deformed boulders). As will appear from the diagram the poles of the bedding planes gather on a great circle, the pole of which coincides with the most common direction for the stretching, *i. e.* the stretching direction is coincident with the axis of folding. Another feature apparent in the diagram is the strong prevalence of northeasterly dip, the folds are commonly overturned to the southwest. In some localities one can also observe folding on a small scale with the same northwest axial pitch, which is quite symmetrical, with a sinus-curve shape of the folds. On cross-joints (normal to the stretching direction) in deformed conglomerates an other type of small scale folding can be observed in some places. In this case the boulders are bent and twisted about the stretching direction as an axis. The two minor dimensions of the boulders have no common orientation and the conglomerate has no schistosity (Fig. 2). This is clearly a shear folding (Scherfaltung,

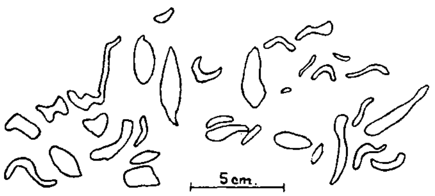

Fig. 2. Sections of deformed boulders on a cross-joint, showing shear-folding. Drawn from field sketches and a photograph.

Cloos) and must be caused by shearing stresses acting on planes parallel to the stretching direction.

In D 24 measurements of joints are represented by the poles of joints-planes. The joints fall on three groups. In the SE and also in the NW quadrant, near the horizontal plane, there are cross-joints or tension-joints normal to the stretching direction, often represented by two sets intersecting at a small angle. These are the commonest and most conspicuous of all joints, but they may be represented by relatively few measurements in the diagram. N—S striking joints with a steep dip to E, with their poles in the E quadrant, are interpreted as vertical shear-joints. Corresponding E—W striking joints, as demanded by symmetry, have not been observed. Finally, there are WNW—ESE striking joints, with the poles situated on a great circle, with a maximum concentration near the horizontal plane, representing steeply dipping planes. Also this group is interpreted as representing shear-joints.

Passing to the petrography of the conglomerate, the boulders are almost exclusively of fine-grained, flinty quartzites, with a grey colour of a greenish or sometimes reddish hue. Observations on undeformed conglomerates in other localities (Goldschmidt) show that the boulders were of sandstone with a well preserved clastic structure at the embedding in the conglomerate, so that their present structure is wholly a product of the deformation. Microscopically the structure of the boulders is characterized by very fine grain, the grains with irregular boundaries and marked undulous extinction. The matrix in the conglomerate is in most cases sparagmitic. According to Goldschmidt the matrix is remarkably less deformd than the boulders, showing clastic grains of feldspar in the microscope.

The appearance of the conglomerate is seen from Fig. 3. The form of the deformed boulders may be rod-like in extreme cases, but is generally as a triaxial ellipsoid. It may be remarked that the cross-section is more lenticular than elliptical. It is never possible to measure all three dimensions in one boulder, by combination of measurements of the major and medial axes on schistosity planes with measurements of the medial and minor axes on cross-joints, the following figures for the dimensions of boulders (in cm) were found by the author from the top of Svarthammeren east of Bygdin:

a	b	c	a : b : c	$d = \sqrt[3]{abc}$
39	12	7	5.6 : 1.7 : 1	14.9
37	9	6	6.2 : 1.5 : 1	12.6
28	9	6	4.7 : 1.5 : 1	11.5
18	8	5	3.6 : 1.6 : 1	9.0
15	4	1	15.0 : 4.0 : 1	3.9
13	4	1	13.0 : 4.0 : 1	3.7

Calculations of the original diameter, $\sqrt[3]{abc}$, of the boulders give an approximate measure of the changes which have taken place in the three dimensions, assuming a subspherical shape of the original boulders. Observations on undeformed conglomerate (in the locality Grønnsennknipa, Goldschmidt 1916a, p. 30) show that the boulders are really well rounded. The figures given above ought to indicate a diminuation of both the lesser axes, b and c, of the boulders, except for the smaller ones, in which b ought to be practically equal to the original diameter. The type of deformation characterized above is the common one, generally found in the area of map Fig. 1 as well as in other occurrences of the same conglomerate. For the Bygdin area Goldschmidt states the most frequent proportion of a : b : c as 6 : 2 : 1 (the mean of the above measurements is 5.8 : 1.8 : 1). In some cases the lengthening may be extreme, according to the same author up to 80 : 1.5 : 1.

A different type of deformation is represented by the so called "kvartskakelag" ("quartz-cake layers"), in which the boulders are extremely flattened, but where the difference between the two major dimensions is not extreme. Measurements of the two minor axes, b and c, from a conglomerate deformed in that manner from the area of map Fig. 1 are (in cm): 15—1, 11—0.8, 11.5—0.6, 9—0.4. Measurements of the corresponding major axes, a, could not be undertaken, but in this case there has certainly been a considerable widening of the dimensions b. The dimensions a are not so large as they would have been, if no such widening had taken place.

The orientation of quartz and sericite in the deformed quartzite boulders of the conglomerate will appear from the diagrams (D 1—20).

D 1—6 are from boulders deformed to "quartz-cakes" as described above.

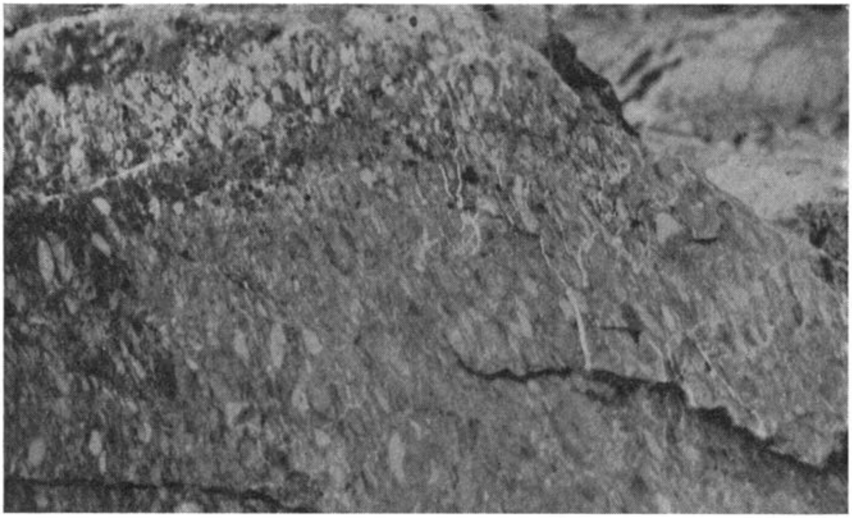

Fig. 3. Surface of a cross-joint in the conglomerate, locality of D 12.

D 1 is quite unique in showing a well defined girdle with two maxima in the direction NW—SE. The specimen yielding the diagram was taken from the very contact between conglomerate and overlying mylonitic igneous rocks.

D 2, 3, 5 show distinct girdles with the direction NE—SW, as is the normal condition in the area. The girdles have two maxima, which in D 3 are bent down towards the horizontal plane and thus united into one. D 4 is quite atypical, if an error in the orientation of the section has not taken place.

D 6 shows a very distinct girdle orientation of the poles of sericite flakes, which is quite in accordance with the orientation of quartz axes. The same is the case with D 10, 14, 16.

D 7—19 are from quartzite boulders deformed in the common manner with a proportion between the two smaller dimensions about 2 : 1.

In D 7, 8 the girdles are asymmetric with a strong maximum in the NE part. D 9, 11 ,12 show less distinct girdles with asymmetry in the development of the maxima, and there is a tendency, apparent in D 11, of the strong maximum wandering towards the N quadrant. In D 13, 15, 17, 18 there are girdles, in which the two maxima apparent in other diagrams are united into one centering about the horizontal plane, while the zenith part of the girdles are sparsely set.

The maxima are also widened and drawn out in a horizontal direction. This has gone still further in D 19, where a horizontal girdle may said to be present. The stretching direction has here an uncommonly steep pitch.

D 20—22 are from sparagmites south of the area of map Fig. 1. These are reproduced to show that the orientation is much less sharp in these rocks, in which quartz is relatively subordinate to feldspar, mica and other minerals. They show the influence of "fabric neighbours" (Gefügegenossen) to lessen the effect of the orientation of quartz.

The salient feature in all diagrams, except of D 1, is the presence of a girdle with direction NE—SW, the axis of which, directed NW — SE, is parallel to the stretching direction of the boulders. In all diagrams there are maxima situated at a distance of 30° or less from the horizontal plane, while the zenith part of the girdles are always more or less sparsely set with quartz axez. The two maxima may have nearly symmetrical strength and position, giving the fabric a plane of symmetry, but the symmetry is never perfect and in many cases asymmetry is marked.

It is a noteworthy fact that the fabric patterns have a constant position in space, relative to the geographical coordinates, and that they, on the other hand, are independent of the s-planes. A fact worth attention is also the uniformity of diagrams taken from near-seated localities with the same type of deformation. This is seen from D 2—6 and from D 9—12.

No discussion of the mechanism active in the production of fabric patterns of the type presented will be taken up here. As long as the orientation mechanism of quartz is not more precisely known, such discussion will be of little value for the special problems here considered. So much is clear, however, that the girdles have been produced by partial movements in the rocks caused by shearing stresses, the partial movements as well as the stresses acting on planes situated in a zone, the axis of which is coincident with the axis of the girdle.

If the tectonics of the present area were to be interpreted from the facts presented above only, the result would most probably be the conception of a compression of the area in a NE—SW direction, in accordance with the trend of folding axes and the direction of the fabric girdles. Yet, in the areas of the Caledonian zone of deformation, of which the present area forms a small part, the direction of tectonical transport has been towards SE, thus the overthrust massif of igneous rocks above the deformed quartzite conglomerate has moved in this direction. We accordingly have folding axes in the direction of tectonical transport, and this is by no means particular of the present area. From many parts of the Caledonian mountain-chain of Scandinavia transverse folding (cross-folding) with an axial direction NW — SE to W—E has been noticed and often referred to in the literature. This folding commonly occurs together with "normal" folding with an axial direction NE—SW to N—S, a fine example is afforded by the Tysfjord area (Foslie 1941 with map), or it may be dominating over relatively large areas. Th. Vogt (1927, p. 167) also refers to a stretching structure with the direction W—E, coincident with the direction of thrust movement, from the Sulitelma area.

The transverse folding will necessarily have to be interpreted in one of two ways. Either it belongs to a separate act of deformation, older or younger than the normal folding, or both sets of folding are essentially simultaneous, and are expressions of one set of movement and deformation. The writer will emphasize two reasons against the first alternative. Firstly, from *a priori* considerations, it may be deemed wholly improbable that a mountain-making process should also produce active movements in a direction normal to the chief direction of mass transport. Experience shows, quite contrary, that foldings in the same area separated in time tend to follow the same trend-lines. Secondly, as the writer can testify from his own field experience, the two types of folding are intimately connected and can supersede each other within the narrowest limits. An example: On a bedding surface dipping NW and thus affected by the normal folding there may be quite small folds with axes pitching NW, representing the transverse folding. Then some metres away, the folds with NW-pitching axes have increased in dimension to a width, say, of one metre. The NW folding is then dominating and has obliterated the other folding.

It is accepted that rock deformation is generally biaxial or plane, that is the partial movements take place in the plane containing the direction of tectonical transport, the ac-plane of Sander. Normal to this plane, in the direction of tectonical strike, there is no movement, and any dimension in this direction remains unchanged. From a kinematical point of view this is simply ascribed to the fact that a rock mass has no freedom to move in the strike direction. Dynamically the matter is less simple, because this type of deformation requires a definite adjustment of the stresses. In this case shearing stresses will operate only on planes in a zone with the tectonical strike, b, as axis. The dynamical point of view in the treatment of rock deformation has been used by Walter Schmidt in his "Tektonik und Verformungslehre", in which some useful conceptions from technical mechanics are introduced into the discussion of rock deformation. Schmidt devotes a chapter in his book to the discussion of triaxial deformation (pp. 60—72), and arrives at the result that this type of deformation may be realized in some folding zones, in which movement in the general direction of strike has taken place. In this case the special adjustment of stresses leading to plane (biaxial) deformation has not taken place and shearing stresses will operate also on planes outside the zone of b. To take the area here dealt with as an example, there will be shearing stresses not only on planes striking NE—SW, but also on planes striking NW—SE.

The writer interpretes the folding with NW axes in the present area as due to a triaxial deformation of the rocks. From the above description of conglomerate deformed to "quartz-cake layers" it follows that in some cases elongation in the direction b has taken place. (The medial axis of the boulders, b, is in most cases coincident with the tectonical strike direction) Of course it is not possible for a rock mass as a whole to undergo any elongation in the main direction of strike, and an elongation that takes place in this direction in some parts of the mass must be compensated by folding and possibly also by deformation with shortening in the same direction in other parts of the mass. The transverse folding thus produced ought to be symmetrical, a condition which is not always fullfilled in our area, as the folds are often overturned to the SW, that is to the right of the direction of movement. The same is the case in the Tysfjord area, where an overturning of the transverse W—E striking folds, when present, always takes place to the south (Foslie 1941, p. 54). The Coriolis force might give an explanation of this circumstance, provided it should be of any concern at the very small velocities in rock deformation.

An example in miniature of folding with axes in the direction of the thrust movement has been described by Balk (1936, p. 738) in a thrust-faulted block of gneiss. The folds are subordinate features, but may attain several feet in length. There is some analogy between the miniature example described by Balk and the transverse folding in the Scandinavian Caledonian. The latter region is, indeed, built up of a series of very large thrust blocks, moving towards the foreland on a peneplained surface with a cover consisting mostly of argillaceous, incompetent rocks. It seems that these are the conditions in favour of transverse folding. On the other hand, a thrust sheet is not supposed to be deformed or folded in a direction transverse to the direction of transport, as long as it is on its way upwards and is still inclosed in the depths of the earth (Schmidt 1932, p. 63).

The chief movement and deformation in the present area has taken place in the direction NW to SE, but in the particular area here considered, there is no folding with axes normal to this direction. Possibly the deformation producing elongation of boulders and pitch of the stretching direction and axes of folding commonly 10—20° NW was brought about by shearing on a single set of planes (einscharige Gleitung of Schmidt). Under the assumption of horizontal shearing planes, the pitch of the longer axis of the deformed boulders may be calculated from the axial ratio of the strain ellipsoid, as represented by the deformed boulders, by using the formulas of Becker (1893, p. 25) for this type of deformation. With the ratio 6 : 2 : 1 for the dimensions of the boulders, the direction of elongation of the boulders should make an angle of about 20° with the horizontal plane. With increasing deformation this angle will decrease. It is seen that this hypothesis is so far in accordance with observations. It may, however, also be argued that the regular girdle in D 1 indicates the simultaneous activity of both directions of maximum shearing stress in the ac-plane. In this case the strain should be essentially an irrotational one, and the axes of the deformed boulders should be coincident with the three principal stresses.

The prevailing fabric pattern in our area is correlated to the folding on NW—SE axes, parallel to the axes of the girdles. This folding, as well as the production of the girdles in the fabric patterns, was certainly brought about by shearing stresses acting on at least two planes normal to each other (mehrscharige Gleitung of Schmidt). The production of the girdles is so far easily interpreted. It is more remarkable that the partial movements in the plane of mass transport (the ac-plane) have left no records in most fabric patterns. (Such movement is recorded only in D 1.) It may be that the orientation produced by this movement was an unstable one in relation to the prevailing orientation on NE—SW girdles, or these girdles were formed in the last phase of the deformation and have thus been preserved in the record.

The chief feature of the diagrams here presented is the presence of girdles in a direction normal to the chief direction of movement, and, as interpreted by the writer, the partial movements producing the girdles and the main mass transport were integral parts of the same act of deformation. A similar case was recorded by H. Martin (1935) in diagrams from fault planes, in which the direction of movement was determined from field evidence. Sander refused to accept the correlation of the production of a girdle to a movement in a direction parallel to its axis, as shown by a citation from his polemics with Martin (1936): "Daß etwa, zuordenbar einer Verschiebung parallel einer Richtung n, Gürtel $\perp$ n entstehen können, sozusagen als ein neuer Tektonit-Typus unter bisher nicht begegneten Bedingungen, — — —, das ist an Hand der von Martin vorgelegten Daten nicht wahrscheinlich zu machen." The present writer must agree with Martin that girdles are generally ambiguous as to the determination of the direction of movement.[1]

Thus in Sander's opinion a girdle is always a testimony of a separate act of deformation with a direction parallel to the girdle (normal to its axis). F. C. Phillips accepted this view in the interpretation of the fabric patterns of the Moine schists of Scotland worked out by him (1937). In the Moine schists, SE of the great Moine thrust, he showed the presence in the fabric pattern of quartz and mica of girdles with the direction NE—SW. The axes of the girdles are coincident with a lineation or stretching structure with the direction about NW—SE and the pitch SE. As the Moine thrust is directed towards NW, there is consequently a full analogy with the area here described, the opposite direction of pitch being in accordance with the opposite direction of movement. In the interpretation by Phillips the lineation structure and fabric girdles had their origin in a deformation act with a compression in the direction NE—SW prior to the Caledonian thrust movement towards NW. The fabric patterns are thus brought in as evidence in the controversy on the age of the Moine schists in favour of a Pre-Caledonian (Pre-Cambrian) age of this group of rocks. A comparison with the Bygdin area will at once annihilate this argument, even with the rejection of the interpretation of similar structures here presented. In the case of the Bygdin area the possibility of a Pre-Caledonian age of the rocks involved (con-

[1] The same opinion as to the significance of girdles has been expressed by Kvale (1941, p. 197).

glomerates in the Valdres Sparagmite) is excluded, nor can there thus be any Pre-Caledonian deformation.

The structural analogy between the Moine schists and the rocks here studied is of great interest as an indication of a regularity in structures, including those of petrofabric patterns, resulting from similar tectonical conditions. As sufficient material accumulates, structural petrology may prove of value for the interpretation of tectonical structures, perhaps especially in old zones of deformation.

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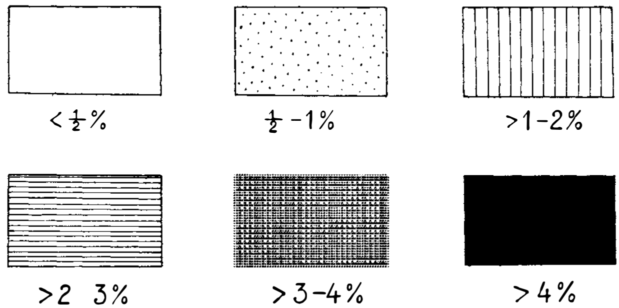
To the diagrams.



All the diagrams are in equal area projection. They have all been rotated into the horizontal plane and are projected on the *upper* hemisphere. The schistosity (or bedding) planes are marked by semicircles and the stretching directions by rings.

D 1—19 are from deformed quartzite boulders in the conglomerate, the localities of the specimens from which the diagrams were prepared are marked on map fig. 1 (p. 15). D 20—22 are from sparagmites, localities at the road 1—2 km south of the area of map fig. 1. See also text pp. 20—21.

E 31 ø 430 etc. is the number of the specimen from which the diagram was prepared, in the collection of the Geol. Survey of Norway. 200 qu.—200 quartz axes, 110 ser.—110 poles of sericite flakes.

D 1.	E 31 ø 430.	206 qu.		D 12.	E 31 ø 435.	300 qu.
D 2.	E 31 ø 432.	250 qu.		D 13.	E 31 ø 256.	235 qu.
D 3.	E 31 ø 433.	250 qu.		D 14.	E 31 ø 256.	100 ser.
D 4.	E 31 ø 436.	240 qu.		D 15.	E 31 ø 428.	210 qu.
D 5.	E 31 ø 252.	230 qu.		D 16.	E 31 ø 428.	120 ser.
D 6.	E 31 ø 252.	110 ser.		D 17.	E 31 ø 426.	230 qu.
D 7.	E 31 ø 257.	210 qu.		D 18.	E 31 ø 438.	240 qu.
D 8.	E 31 ø 434.	260 qu.		D 19.	E 31 ø 427.	210 qu.
D 9.	E 31 ø 290.	210 qu.		D 20.	E 31 ø 243.	300 qu.
D 10.	E 31 ø 290.	120 ser.		D 21.	E 31 ø 241.	300 qu.
D 11.	E 31 ø 271.	260 qu.		D 22.	E 31 ø 242.	220 qu.

D 23. Poles of bedding and schistosity planes (dots) and stretching directions (rings) from the area of map fig. 1. See text p. 17.

D 24. Poles of joint-planes from the area of map fig. 1. See text p. 18.

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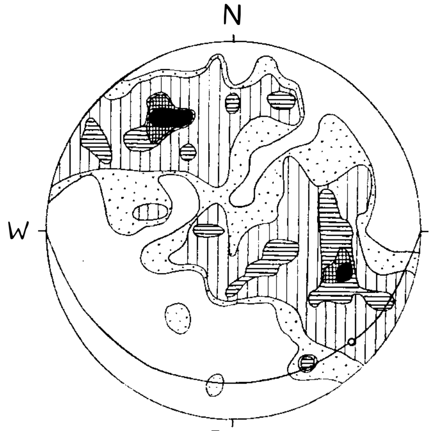
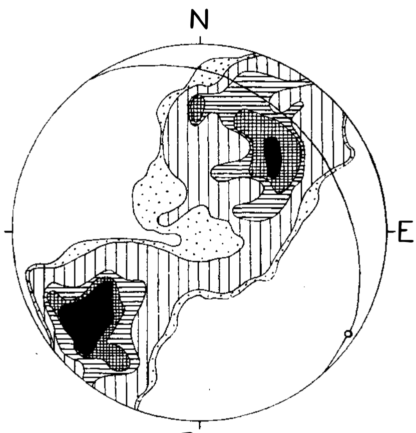
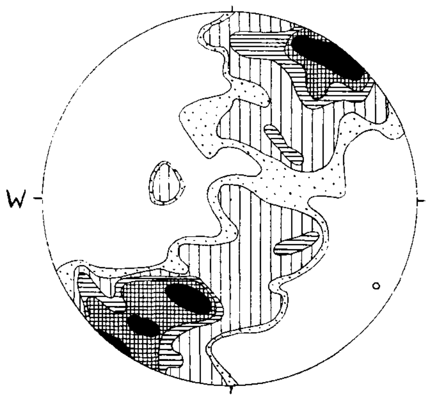


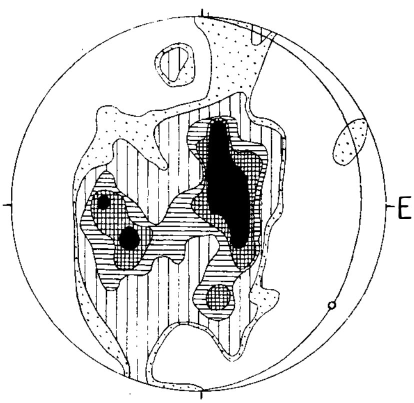
D 1



D 2



D 3



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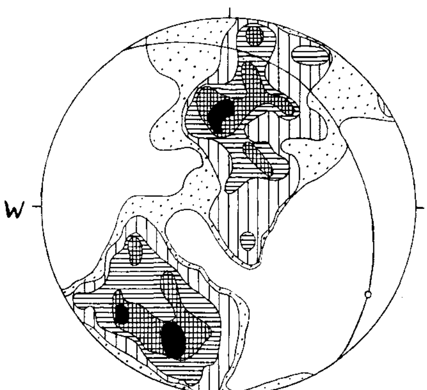

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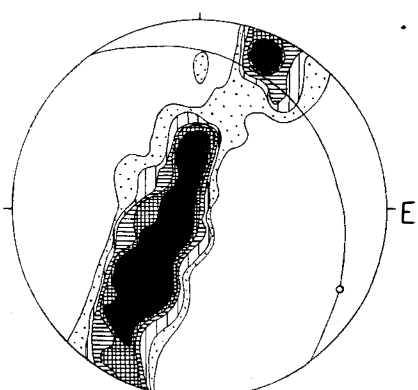

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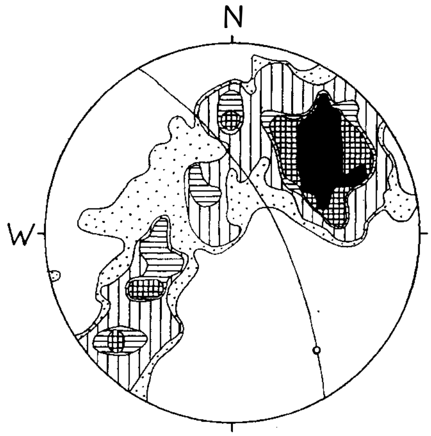

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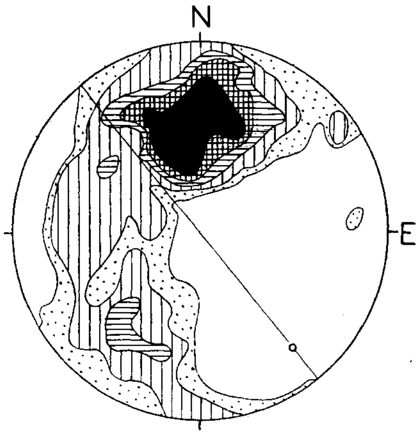

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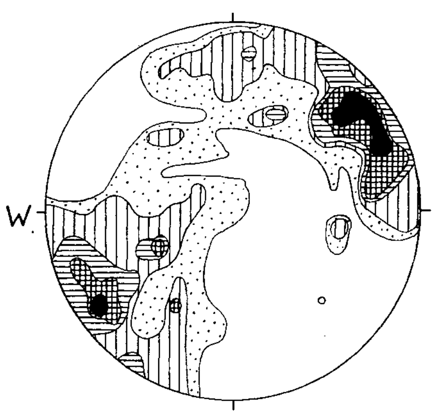

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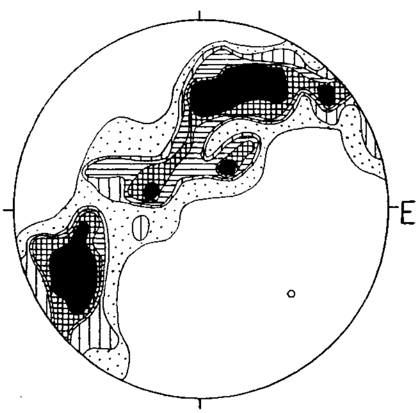

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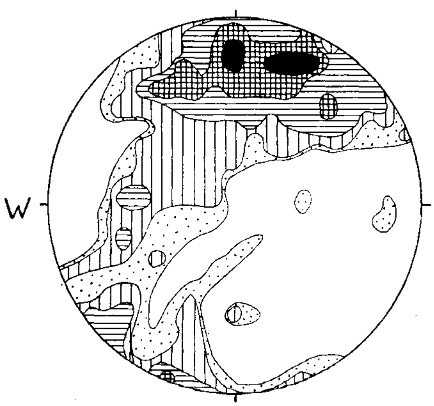

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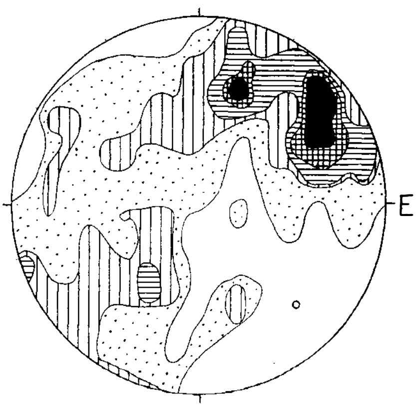

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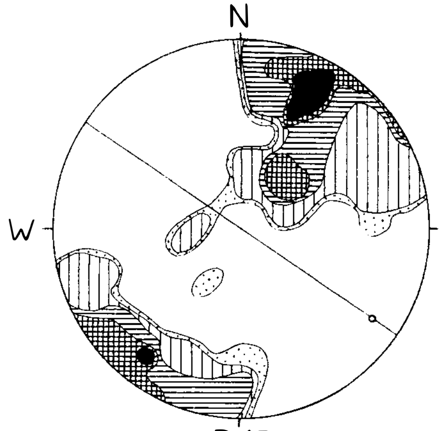

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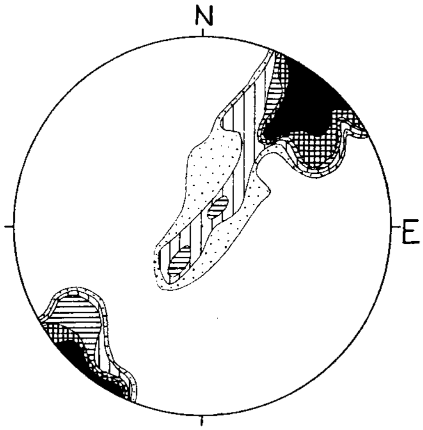

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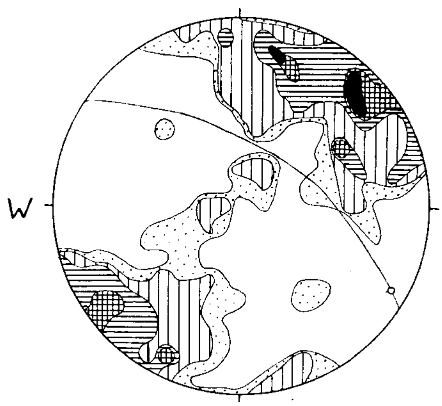

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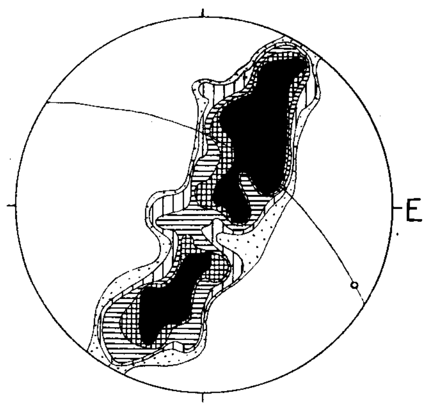

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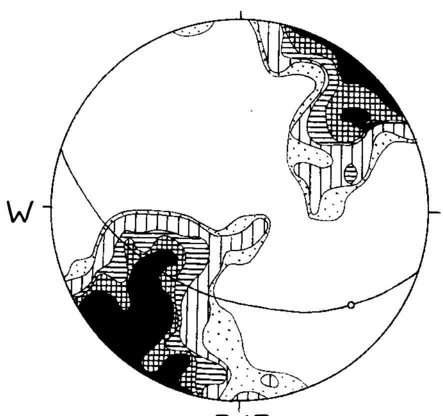

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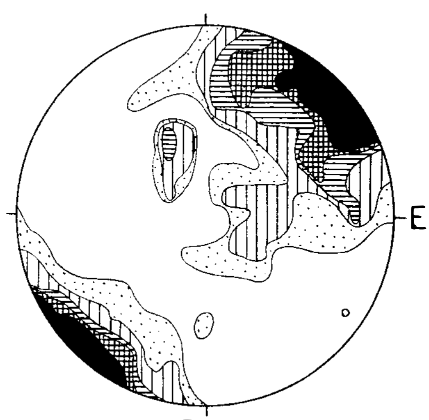

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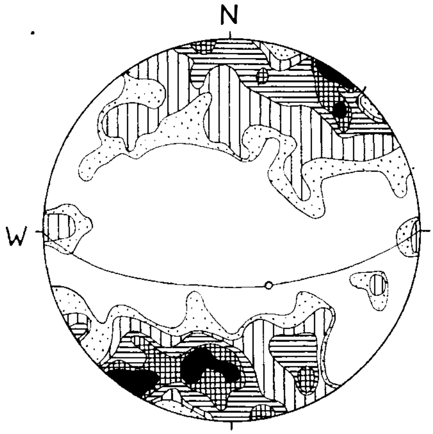

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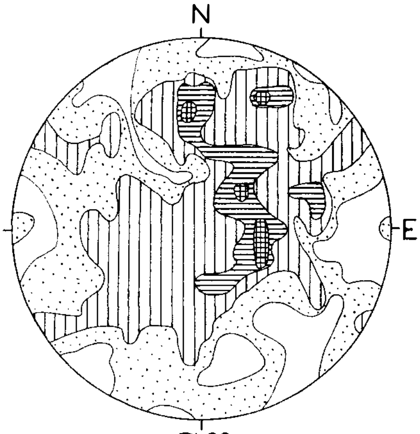

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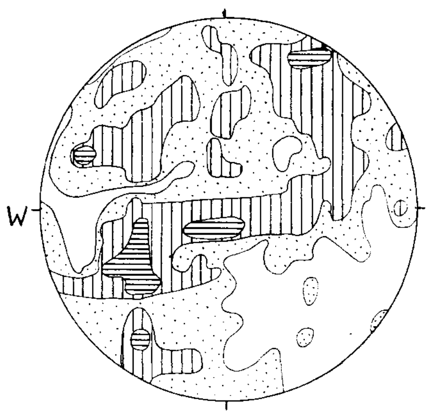

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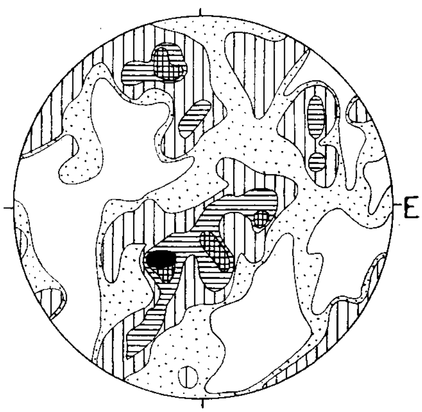

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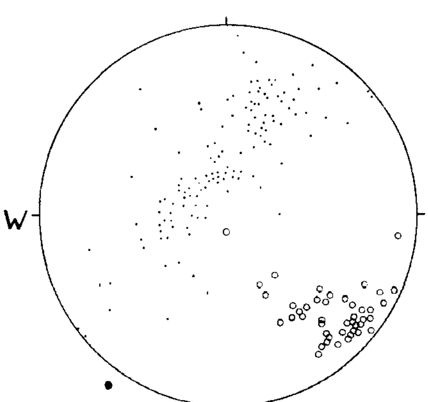

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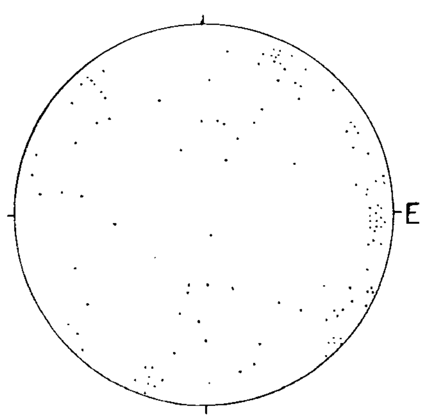

D 24
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