THE STRUCTURE OF THE SKIDDAW SLATES

IN THE

NORTH-WEST LAKE DISTRICT

by

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ABSTRACT

In an area of complex folding, few fossils and no marker-horizons, classical methods of analysing structures have limited use. The area studied was divided into 64 sub-areas, and the attitude of bedding plotted on β-diagrams to give a statistical trend and plunge for the fold-axes in each sub-area. The trend and plunge of the axes of 117 small folds were measured, and the orientations of lineations formed by the intersection of bedding and cleavage were noted at over 200 localities. All these structures suggest that there is a weakly developed axis of large scale folding trending N240°E and plunging 15°. This axis is statistically accurate only for the area as a whole; and it is thought to be locally affected by the emplacement of the Ennerdale Granophyre. There is a low degree of mutual parallelism of the axes of folding which may indicate repeated deformation; but it is thought more likely to be caused by limited deformation of incompetent rocks at shallow depth. A tectonic profile constructed for the south-western part of the area gives an indication of the large scale structure of the slates.

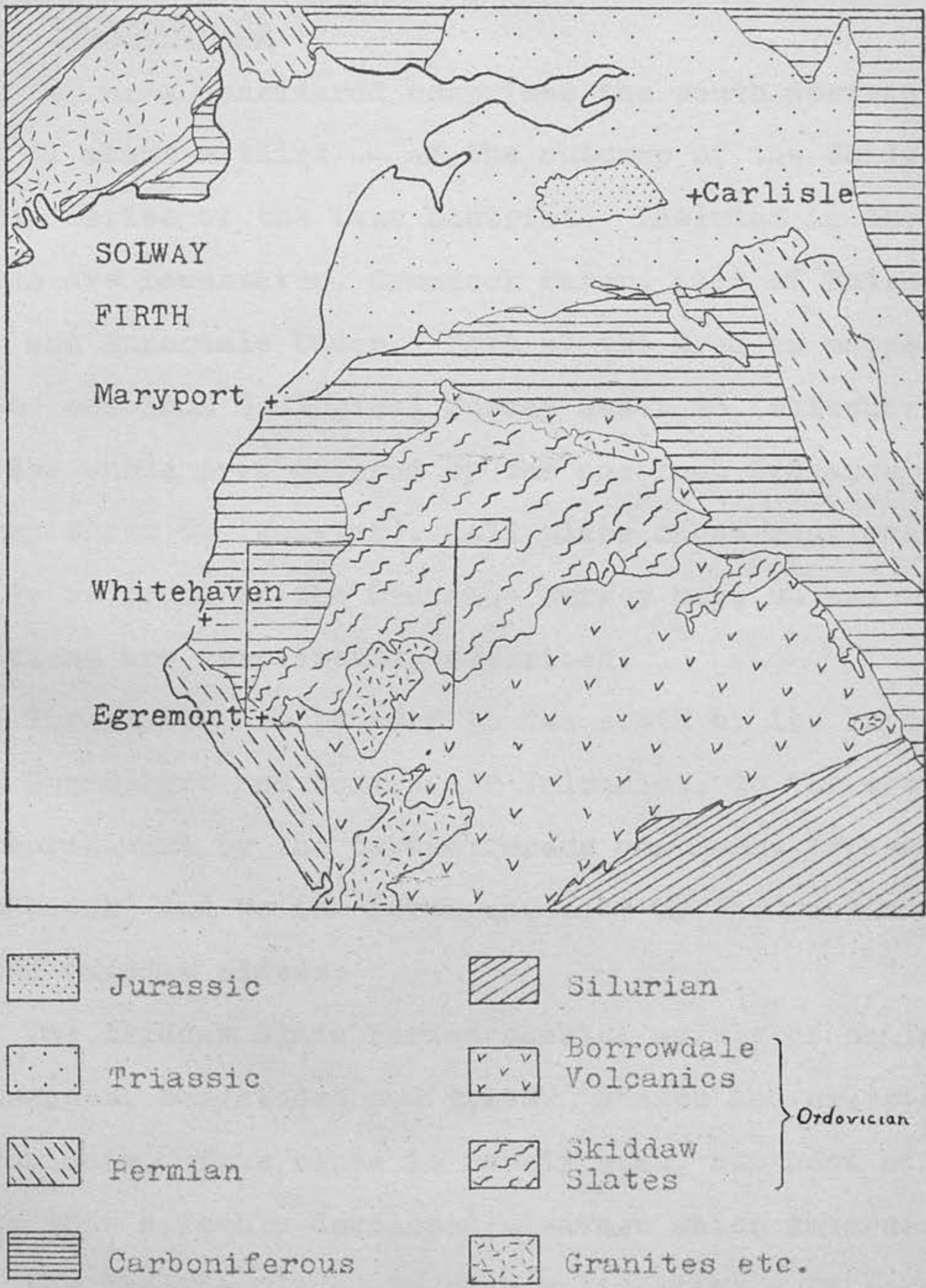


Fig. 1. Location of the Skiddaw Slates studied in relation to the surrounding geology.

I INTRODUCTION

The area considered comprises the south-western part -- about a third -- of the outcrop of the Skiddaw Slates Series of the Lake District. Included in the region are Loweswater, Crummock Water, part of Buttermere and Ennerdale Water. Part of the area is mapped on the one-inch Geological Survey Sheet 28 (Whitehaven), and the whole area covered by the one-inch Ordnance Survey Sheet 82 (Keswick). All place names mentioned are to be found on the Ordnance Survey map, unless their locations are specifically described.

The slates are bounded to the south by the Ennerdale Granophyre and Borrowdale Volcanics, to the west and north-west by the Carboniferous ans Permo-Triassic formations, and to the north and east by the continuation of the Skiddaw Slates.

The Skiddaw Slate Series consist mainly of shales, siltstones, sandstones and grits. Shales and siltstones predominate. True slate is rarely seen, but most of the rocks show a feebly developed cleavage which intersects with the bedding planes to give a lineation. In some rocks a well developed cleavage can be measured even when the bedding survives.

The shales have a general north-east -- south-west strike, but this is complicated in certain areas where the strike rapidly changes direction.

The base of the Skiddaw Slates is never seen. The highest beds of the series are represented in this area by the Latterbarrow Sandstone (sub-area 1 on all maps) and the Watch Hill Grit (to the north-east of Cockermouth.

The shales are intruded by the Ennerdale Granophyre in the south, and cut by lamprophyre dykes, especially in the region of Dent. The Borrowdale Volcanics overlie the shales unconformably, as also do the Carboniferous Limestones and Coal Measures, and the Permian and Triassic limestones and sandstones.

The Pliocene river systems have been considerably deepened by glacial action, and the whole region is covered with thick deposits of peat and glacial and fluvio-glacial drift.

The purpose of this work is to analyse in detail the structure of the Skiddaw Slates of this area. The area was chosen as a north-easterly extension from the region of Dent and Latterbarrow which were mapped as part of a thesis for the degree of B.Sc. It was the encouraging results obtained from this earlier work that gave rise to its extension in detail. The data obtained from this earlier mapping have since been revised, and further detail added.

II SUMMARY OF PUBLISHED DATA

It has long been realised by previous workers that the structure of the Skiddaw Slates is "the outcome of a series of earth-movements, and of succeeding or accompanying phases of sedimentation, igneous intrusion or denudation that have affected the area at intervals" from the Caledonian to the Alpine orogenies. The earth movements are summarised in Table I.

Both the Skiddaw Slates and Borrowdale Volcanics are described as having been subjected to compressional uplift about an axis trending north-east through Skiddaw. The early stages were foreshadowed by crustal disturbances indicated by the unconformity at the base of the Latterbarrow Sandstone. These disturbances reached their greatest intensity in post Silurian times when the warping already initiated attained full amplitude, whilst countless minor folds and puckerings were superimposed on the major structures and cleavage was impressed in the softer shales. The slates were known to form a denuded anticline trending north-east, complicated by flanking anticlines and minor folds. (Geol. Survey Memoir, 1931. pp 12 - 16).

There are problems associated with the zoning of the Skiddaw Slates. Marker-horizons are absent in the shales. Palaeontological evidence is of doubtful value for indic-

Table I

Earth Movements affecting the Skiddaw Slates

Earth Movements	Geol. Age	Denudation Period
		Stripping off of all 'soil' formations deposited since St. Bees Sdst. Sculpture of all formations.
Late Hercynian & / or Alpine	Post St. Bees possibly post-Cretaceous	
		Great unconformity at base of N. Red Sdst. Series.
Hercynian	Post Carboniferous	
		Unconformity at base of Whitehaven Sdst. Series.
Precursors	Intra-Coal Measures	
		Probable unconformity of Millstone Grit on Hensingham Group.
of	Mid Carb.	
		Potholes and channels in limestones.
Hercynian	Intra-Carb. Lst. Series	
		Great unconformity at local base of Carb. with lava flow (Cockermouth).
Caledonian	Post Silurian (culminating in cleavage and igneous intrusions, the latter apparently both before & after cleavage).	
		Unconformity at base of Coniston Lst Series S. side of Lake Dist.
Caledonian Precursor	Post Borrowdale Volcanics.	

From Geol. Survey Memoir. Whitehaven & Workington Dist. 1931.

ating different horizons. Fossils -- almost entirely graptolites -- are abundant in only a few isolated localities. G.L. Elles considers that the Skiddaw Slates Series include rocks which range in age from Arenig to Llanvirn. This view (arising from her work on the Welsh succession) rests upon the assumption that attenuation of the shales must have taken place since graptolites of apparently widely differing zones are found in close proximity to each other. (Elles 1898. pp. 463-539).

The Survey favour a correlation of the Skiddaw Slates with the Levis Shales of North America. Their grounds for this correlation are, the similarities between the two faunal assemblages, and their failure to find signs of attenuation of the shales. Their preference is supported by the correlation of the Upper Durness Limestones of the North-West Highlands of Scotland with the Beekmantown Limestone of North America, and the world-wide distribution of the American graptolites as compared with the restricted distribution of the Welsh fauna.
It has been suggested that Marr's term 'Skiddavian' be used in preference to Arenig or Llanvirn. (Marr 1905, pp. 81-83).

The Ennerdale Granophyre has been dated as Caledonian (Geol. Survey. 1931). It is considered to be a stock, the outcrop of which is almost completely interrupted north of Ennerdale by remnants of its roof. The granophyre is said to have been intruded by stoping, for "it has replaced an equivalent amount of the stratified rocks without arching up the beds" (Geol. Memoir, 1931. p. 51).

III FIELD WORK

The region was mapped in detail, and over 3000 attitudes of bedding were recorded. The orientations of the axes of 117 small folds were measured, and lineations, formed by the intersection of bedding and cleavage, were noted at over 200 localities.

Over seven months were spent in the field. The first half of the field work consisted of preparing a structural map to the scale of six inches to one mile in as great a detail as the nature of the exposures would permit. After considering the best methods of handling the data so obtained, the remainder of the time in the field was spent in completing the six-inch map, and mapping in greater detail a few selected localities.

From the data of the original mapping, a structural picture was obtained which was largely confirmed by the later work.

For the purposes of this work, 'small folds' consist of those recognisable folds which vary in amplitude from a yard or so, to folds whose curved surfaces can only be recognised by measuring the attitudes of their bedding by walking or climbing five or ten yards. Their axial orientations may, or may not, be visible. (See photographs 1, 2 and 3 for typical small folds).

IV TECHNIQUES EMPLOYED

a. Geometry of Simple Folds

Most simple folds approximate to a cylindroidal form (McIntyre 1948). Some complex folds may be described in terms of simpler folds, and have similar geometry. In all cylindroidal folds, the folded surface is everywhere tautozonal about the fold-axis; that is, the axis of a cylindroidal fold will describe a folded surface when movwd parallel to itself (Clark and McIntyre, 1951). Thus the attitude of the folded surface at any point on the fold is a guide to the orientation of the fold-axis. If the fold-axis plunges, then the line of intersection of any two attitudes of the folded surface gives the trend and plunge of the fold-axis. The lowest recorded dip at the surface will not be less than the plunge of the axis of the fold; that is, horizontal bedding will only be found in folds with a horizontal axis, and the strike of the bedding will only be parallel to the trend of the fold-axis when the bedding is vertical (Fig. 2).

b. π-Diagrams

Wegmann (1929) developed the π-diagram to determine the trend and plunge of the axis of folding of a series of s-surfaces (that is, any surface or plane in a deformation fabric). The diagram is prepared by plotting on

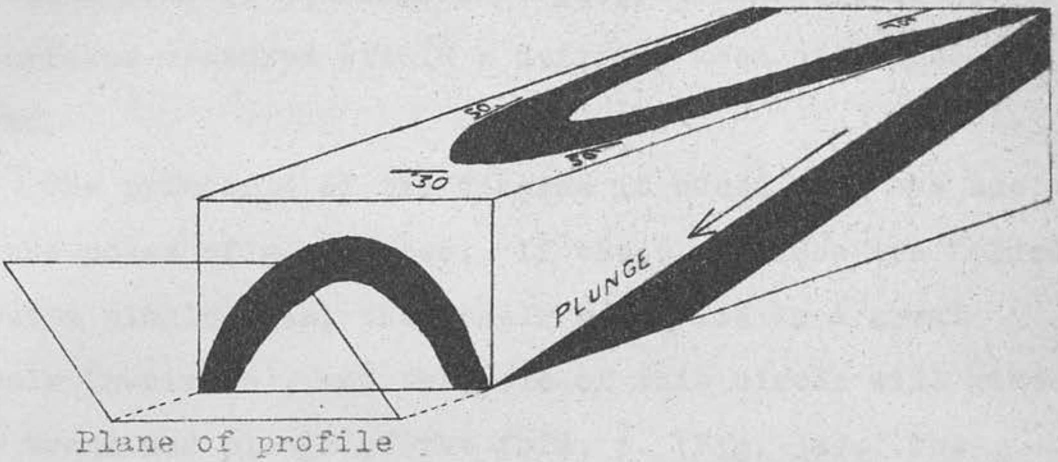


Fig. 2. Block diagram of a plunging anticline showing the essential features of profile construction, and the change in dip and strike of the bedding along its contact with a horizontal plane. See also Section Vf.

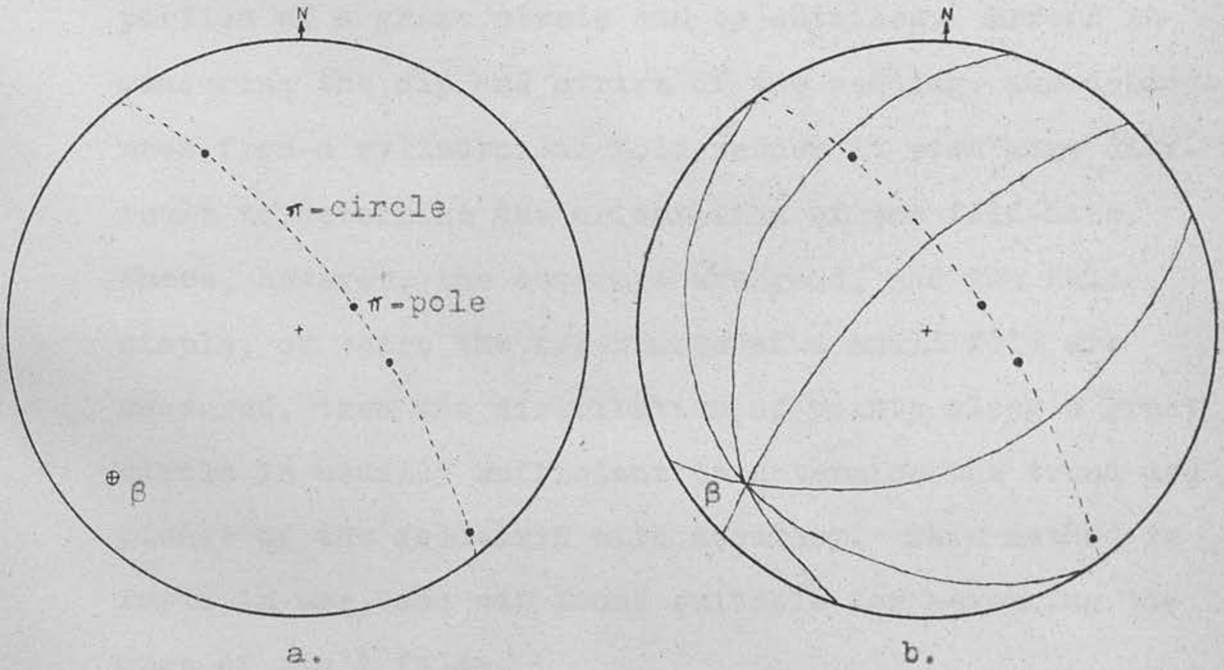


Fig. 3. a. Idealized π-diagram to show the relation between the π-circle and β.
b. Idealized β-diagram to show the relation between the π-circle, great circles of s-surfaces and β.

an equal area or stereographic projection the poles of s-surfaces measured within s definite area of folded rocks.

The principle of the diagram is based upon the use of the poles of s-surfaces. If the s-surfaces are folded about a single axis, then their poles lie on a great circle (π-circle), and the pole of this circle will give the trend and plunge of the fold, β. (Fig. 3a). The degree of conformity to an ideal great circle indicates the degree of approach to a cylindroidal fold.

This diagram has limited application where outcrops are poor, because generally in such areas, only a small portion of a great circle can be obtained. Errors in measuring the dip and strike of the bedding, and departures from a cylindroidal fold render it even more difficult to determine the orientation of the fold-axis. Where, however, the outcrops are good, and the folds simple, or where the s-surfaces of a small fold are measured, then the distribution of points along a great circle is usually sufficient to determine the trend and plunge of the fold-axis with accuracy. This method is rapid in use, and was found suitable for measuring the axes of small folds.

c. β-Diagrams

A more delicate use of the same data was developed by Sander (1948) in the construction of β-diagrams. The great circles of several s-surfaces from a small area are plotted on an equal-area net. Their mutual intersections are then transferred to another diagram. The distribution density of the intersection points is then contoured, and the highest point of the concentration is selected as β. (Fig. 3b). With the s-planes of a simple fold, a strong maximum appears which is the axis of the folding. The degree of concentration of the points indicates the approach to a cylindroidal fold. (Fairbairn, 1949. p.194).

If x is the number of great circles of s-surfaces in a β-diagram, then the number of mutual intersections which they give equals $x(\frac{1}{2}x-1)+\frac{1}{2}x$.

For a β-concentration which can be easily handled, the most convenient number of great circles was found to lie between 11 (55 intersections) and 30 (435 intersections). Anything less than 11 is considered to be of doubtful accuracy, whilst with over 30 great circles it becomes almost impossible to find all their mutual intersections.

It can be seen from the above that β-diagrams are ideally suited for use with relatively few measurements of s-surfaces, whilst the π-diagram is quite capable of dealing with larger numbers.

d. Small Folds

It has been stated that "the degree and direction of the pitch of a fold are often indicated by those of the axes of the minor plications on its sides" (Pumpelly's Rule -- Pumpelly, Wolff and Dale. 1894). His use of the term 'pitch' has now been changed to 'plunge by modern structural usage (Clark and McIntyre, 1951, p. 598). This rule has since been extended by other workers to include most types of minor folds which presumably depend upon the major folding forces. (Hills, 1951, pp 97-8).

Direct measurement of these small folds is not easy, and often inaccurate. The use of the π-diagram, however, gives quick and accurate results for the trend and plunge of their axes. By this method it is also possible to measure the orientation of the axes of folds which are not, at first, visible to the eye. A series of measurements of the attitude of the bedding over a small area will often give a very good great circle.

e. B-Lineations

Lineation has been defined as "any kind of linear structure within or on a rock". Since this term includes structures of widely diverse origin, it is necessary to explain the type of lineation referred to in each case. The importance of lineation lies in the evidence it affords to the direction of movement. In slickensides, for example, the lineation is parallel to the movement in a given plane. The lines representing the intersection of cleavage and bedding are parallel to the axes of the folds, that is, they are B-lineations.(Hills, p.112). It is this B-lineation which has been made use of in interpreting the structure of the Skiddaw Slates. In common with small folds, B-lineations are a quide to the trend and plunge of the major structures.

Whereas π- and β-diagrams are used to describe structures on the largest scale, small folds and B-lineations describe structures on the intermediate and smallest scales respectively.

V INTERPRETATION OF THE STRUCTURAL DATA

a. General Features

The contoured π-diagram Figure 4A shows a broad girdle giving a general axial plunge for the whole area of 10^{o} - 20^{o} to the south-west. The girdle is too broad for the area to be completely homoaxial, although this condition is statistically approached.

Since the π-diagram was not considered to give an accurate picture of the axial trend and plunge on a scale smaller than that of the whole area, it was found necessary to sub-divide the whole area into sub-areas which were essentially homogeneous, and construct a β-diagram for each sub-area.

Figure 4B shows exactly the same data as in 4A, plotted in the form of a synoptic diagram of β-maxima taken from 64 β-diagrams representing 64 sub-areas into which the whole area was divided. It shows far more clearly than the π-diagram the variations in trend and plunge. The maximum is at about 10^{o} to N240^{o}E, but the general range varies from N200^{o}E to N260^{o}E in trend, and from 0^{o} to 30^{o} in plunge. Over 60 per cent of the sub-areas have β-maxima in the south-west quadrant, indicating the direction of the axial plunge of the major structure. The 18 per cent which have β-maxima in the

Figure 4

A A contoured π-diagram built up from the attitudes of 1400 bedding planes measured from the whole area. Contours at intervals of 1, 2, 3 and 4% per one per cent area.

B Contoured synoptic diagram of β-maxima from the β-diagrams for the 64 sub-areas.
Contours at intervals of 5, 7·5 and 10% per one per cent area.

C Contoured synoptic diagram of the trend and plunge of 117 axes of small folds measured over the whole area.
Contours at intervals of 2·5, 5 and 7·5 % per one per cent area.

D Contoured synoptic diagram of the orientation of B-lineations taken from the whole area.
Contours at intervals of 2·5, 5 and 7·5% per one per cent area.

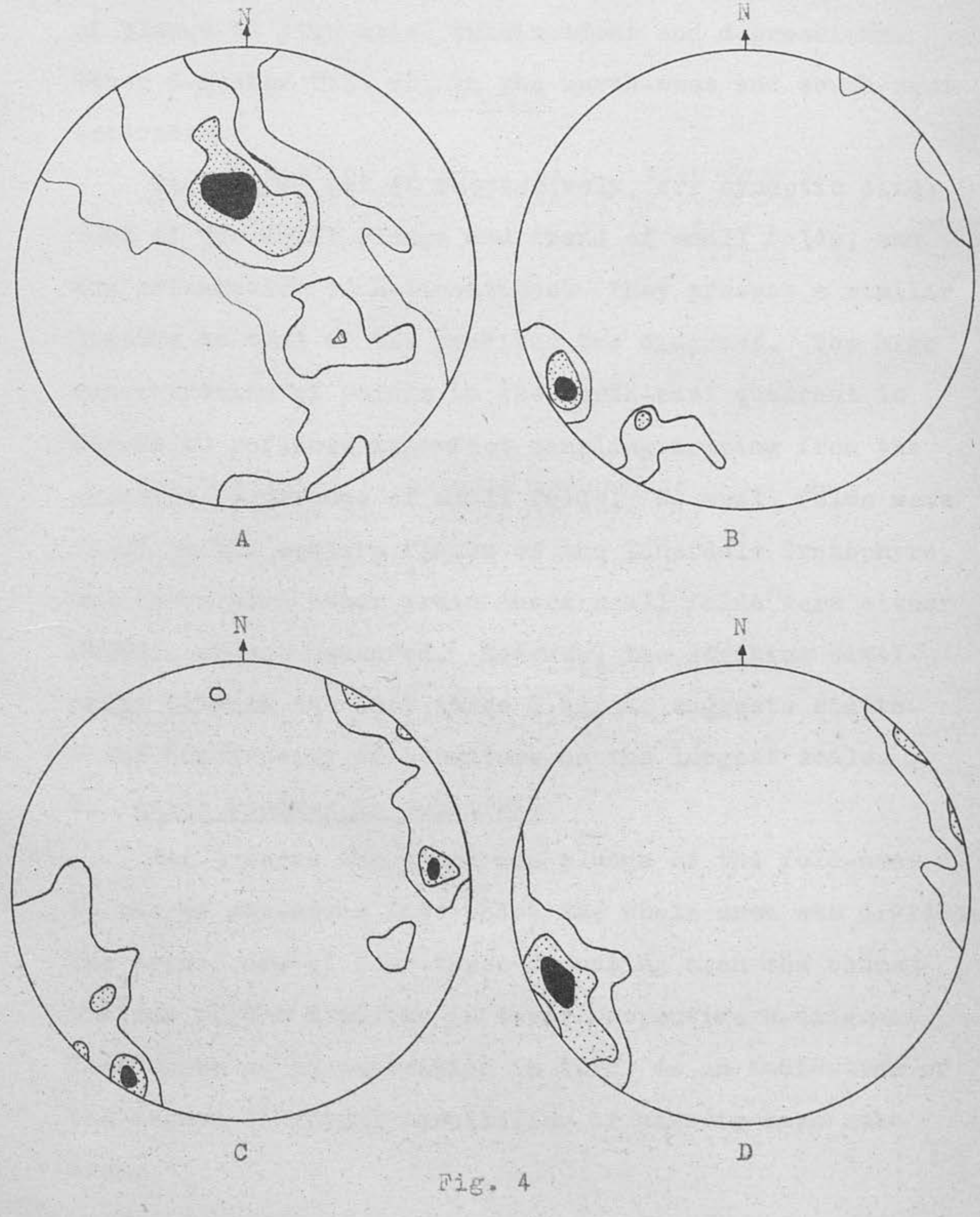


Fig. 4

north-east quadrant represent a reversal of the direction of plunge to give axial culminations and depressions. Other β-maxima fall within the north-west and south-east quadrants.

Figures 4C and 4D respectively, are synoptic diagrams of the axial plunge and trend of small folds, and the orientation of B-lineations. They present a similar picture to that of the previous two diagrams. The high concentration of points in the north-east quadrant in Figure 4C reflects imperfect sampling arising from the sporadic occurrence of small folds. No small folds were found on the western flanks of the Ennerdale Granophyre, and there were other areas where small folds were either absent, or not measured. However, the striking similarity between the last three diagrams suggests statistical homogeneity of structure on the largest scale.

b. Axial Plunges in Sub-Areas

Map 3 shows the trend and plunge of the fold-axes in the 64 sub-areas into which the whole area was divided. The arrows are of four types depending upon the concentration of the β-maxima in their respective β-diagrams. The degree of concentration in turn, is an indication of the degree of mutual parallelism of axes in each sub-area.

Figure 4E

Contoured β-diagrams (1 - 64) for the 64 sub-areas into which the whole area was divided. Contours are at intervals of 7·5, 10, 15 and 20% per one per cent area. All β-diagrams are directly comparable. 20% shaded black. Over 15% dotted. 7·5 and 10% contours are left plain. Concentrations of less than 5% are considered to have little value.

Sub-area	No.π.	No. Intersections.	Sub-area	No.π.	No. Intersections.
1	18	153	33	28	378
2	17	136	34	21	210
3	11	55	35	24	276
4	23	253	36	24	276
5	19	171	37	28	378
6	24	276	38	24	276
7	23	253	39	19	171
8	22	231	40	28	378
9	32	496	41	23	253
10	23	253	42	22	231
11	20	190	43	23	253
12	16	120	44	20	190
13	20	190	45	18	153
14	22	231	46	24	276
15	11	55	47	26	325
16	22	231	48	29	435
17	28	378	49	27	351
18	30	465	50	22	231
19	18	153	51	24	276
20	17	136	52	23	253
21	19	171	53	17	136
22	20	190	54	21	210
23	19	171	55	18	153
24	21	210	56	19	171
25	20	190	57	18	153
26	22	231	58	19	171
27	17	136	59	25	300
28	16	120	60	11	55
29	24	276	61	18	153
30	24	276	62	18	153
31	24	276	63	21	210
32	29	406	64	13	78

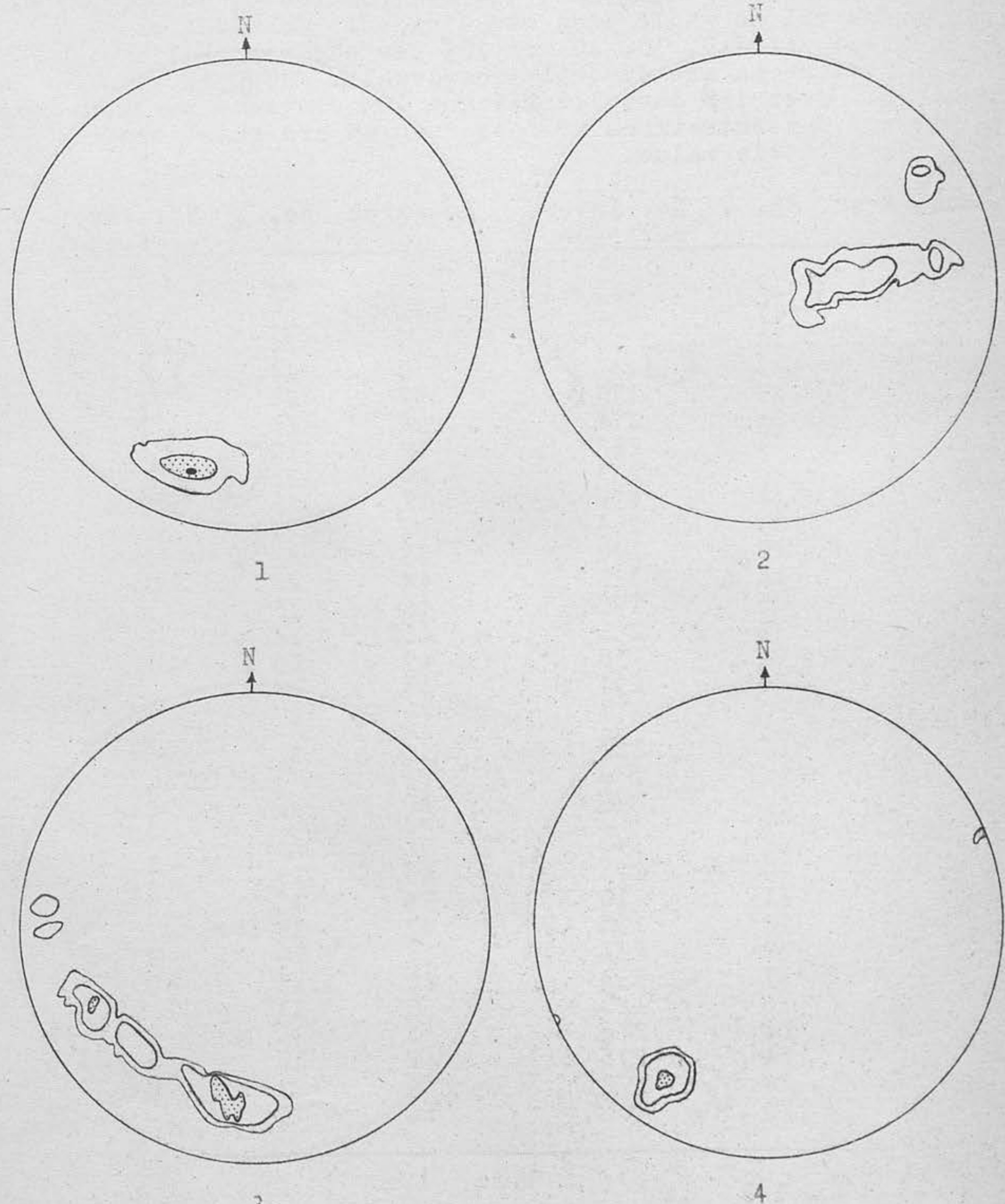
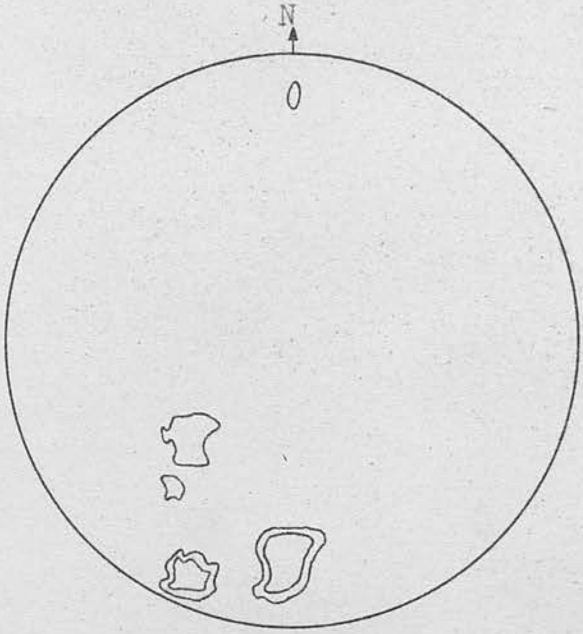


Fig. 4E



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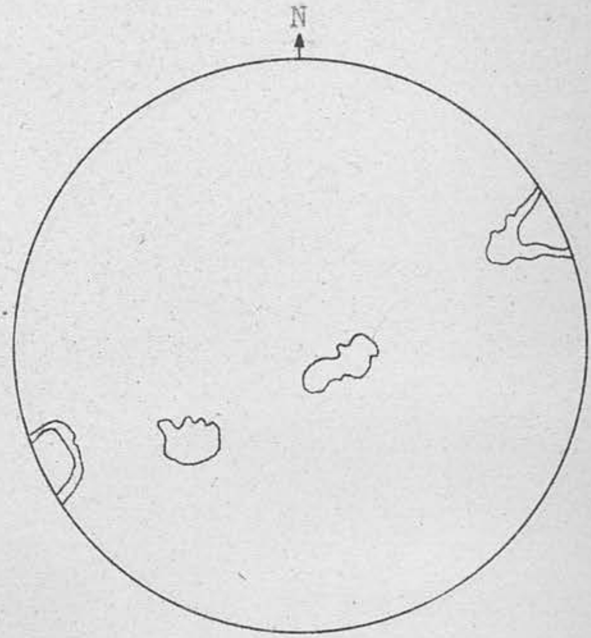

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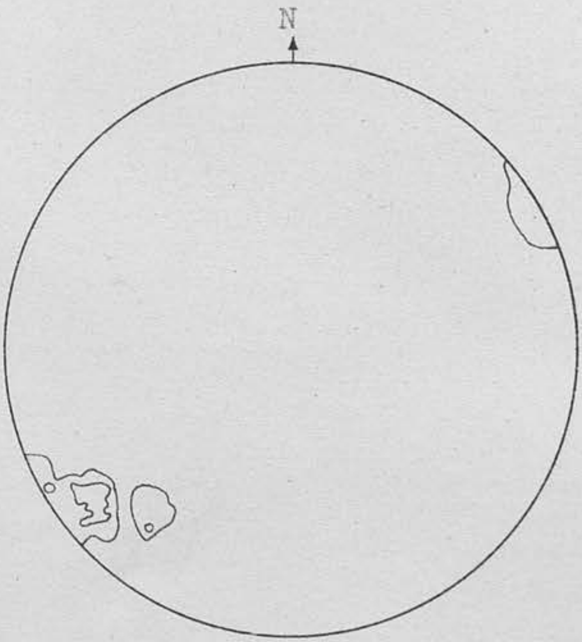

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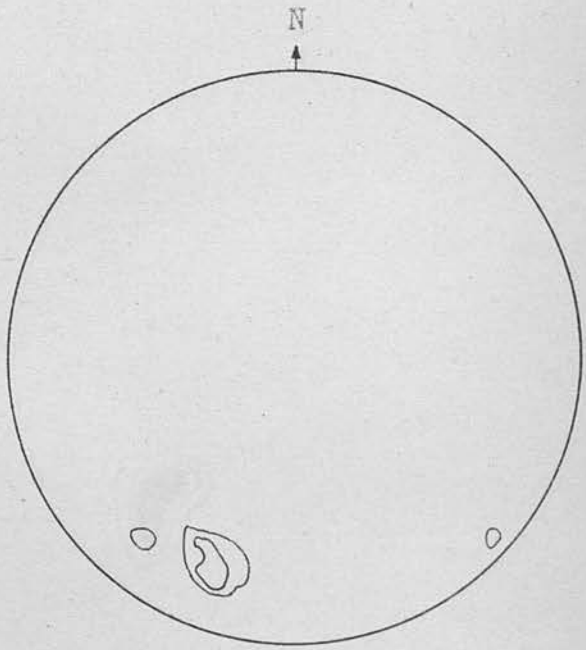

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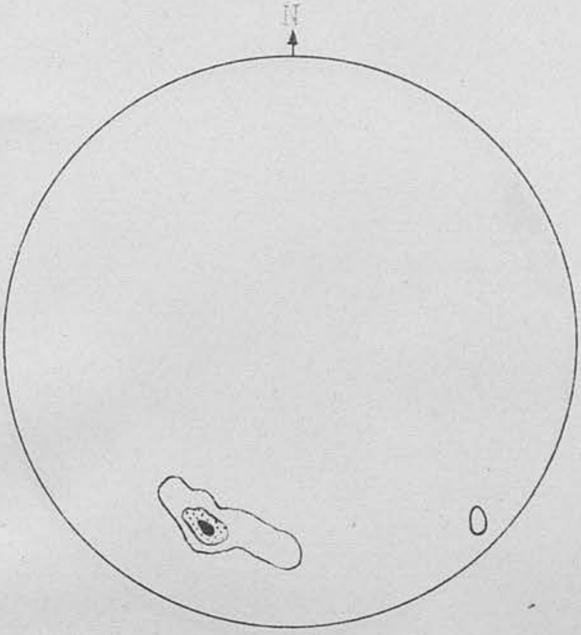

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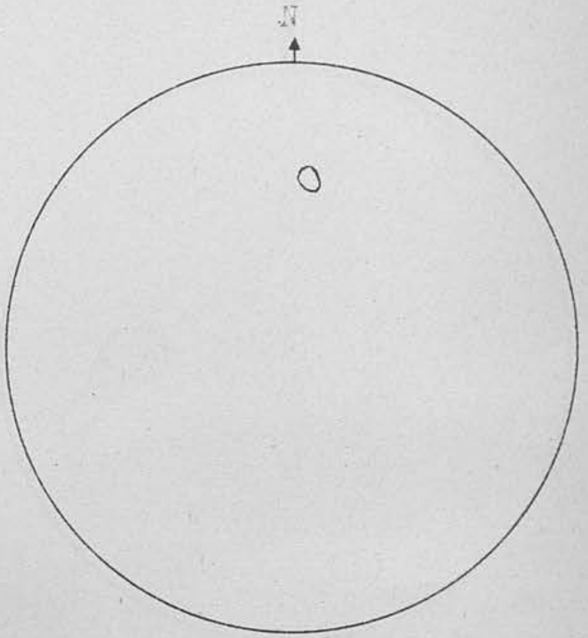

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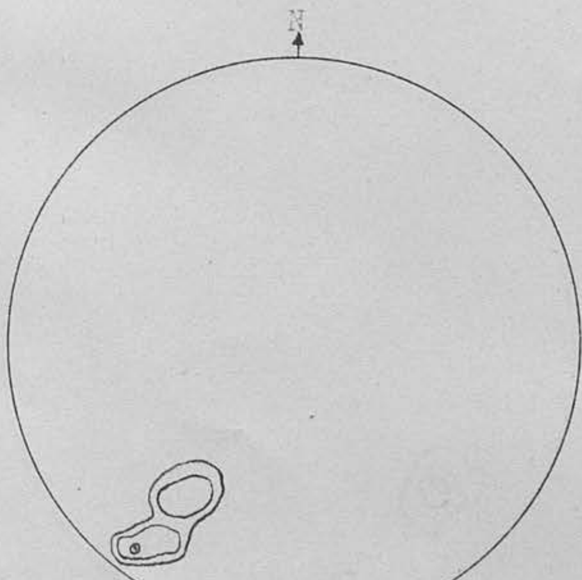

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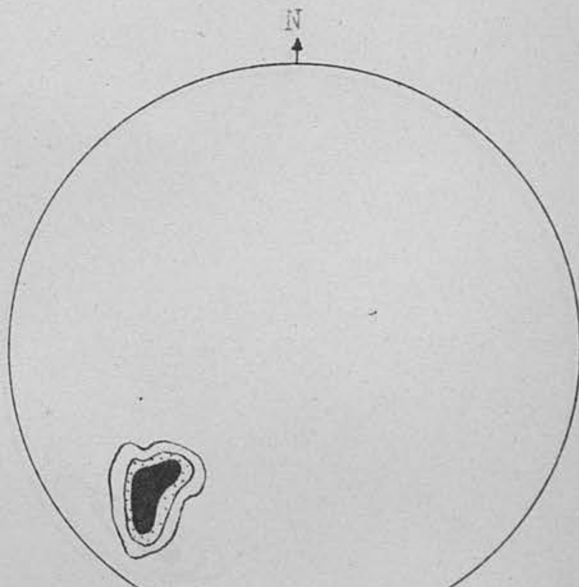

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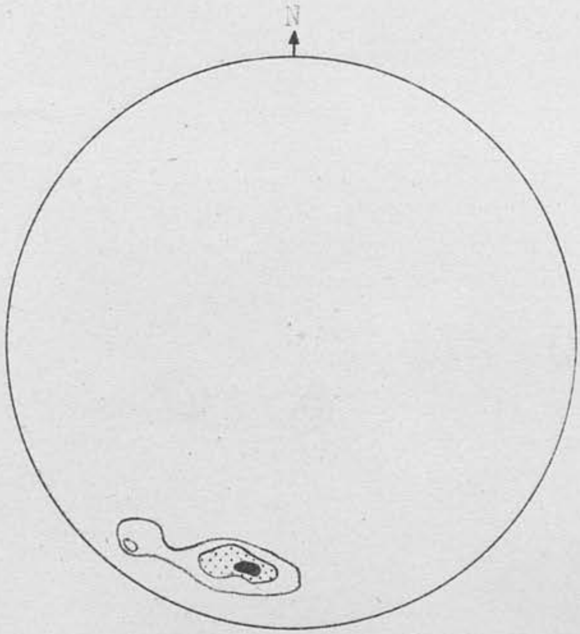

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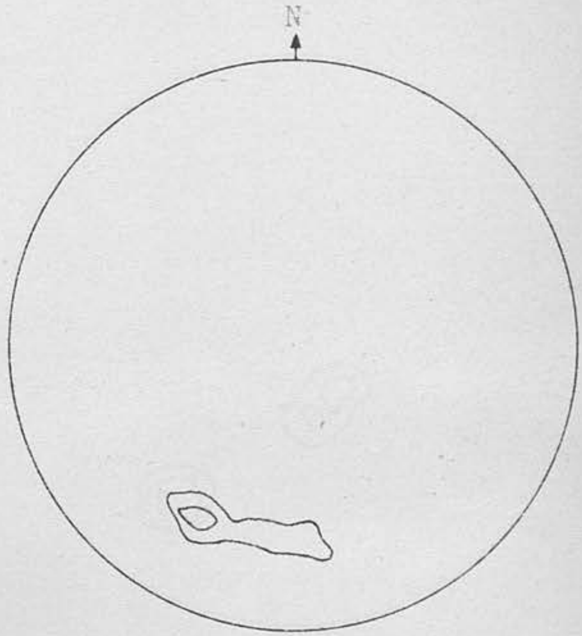

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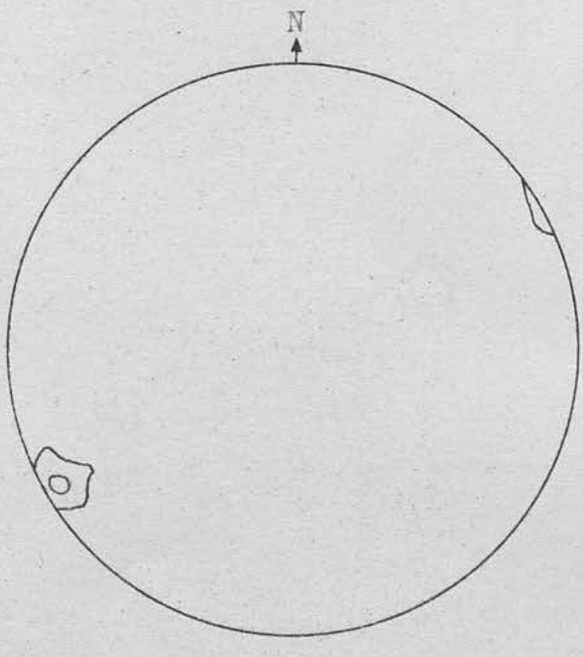

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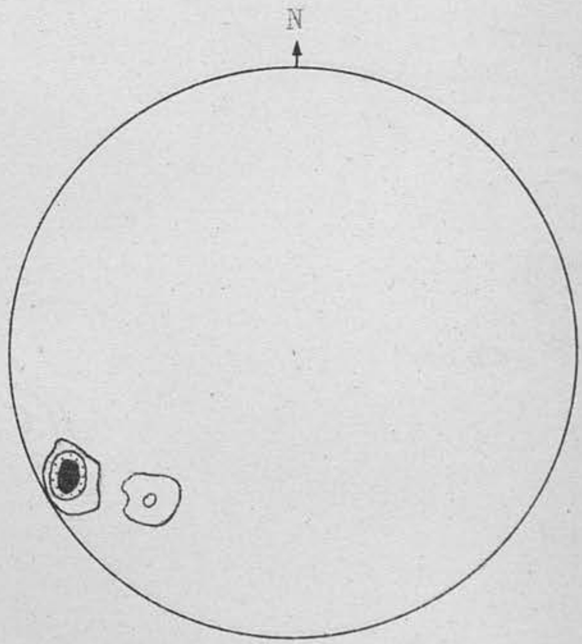

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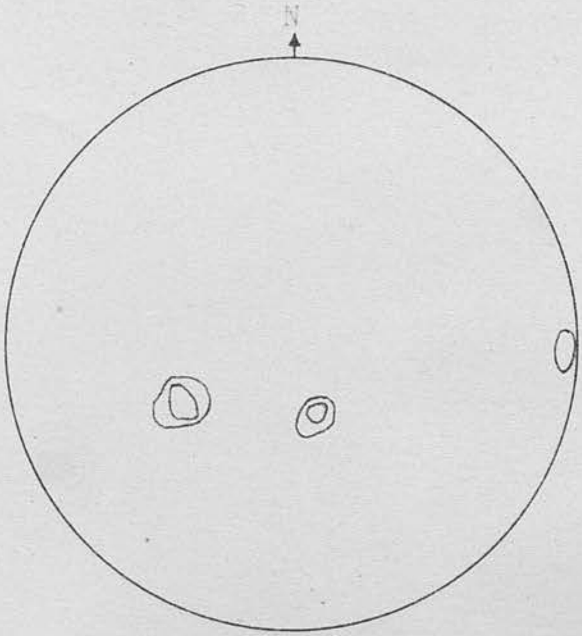

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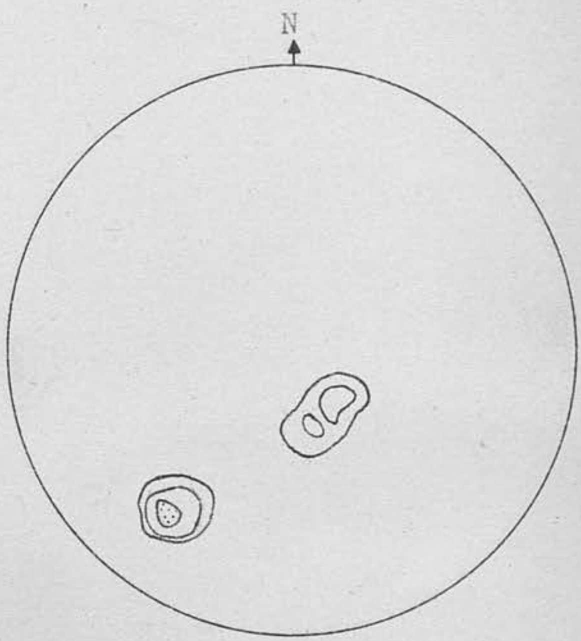

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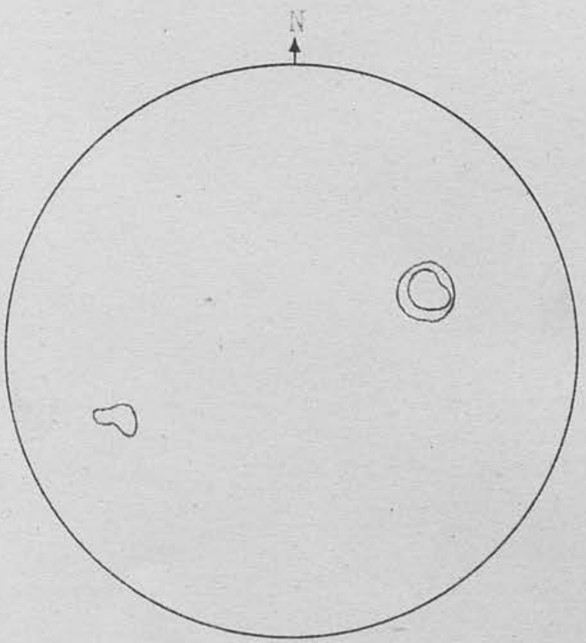

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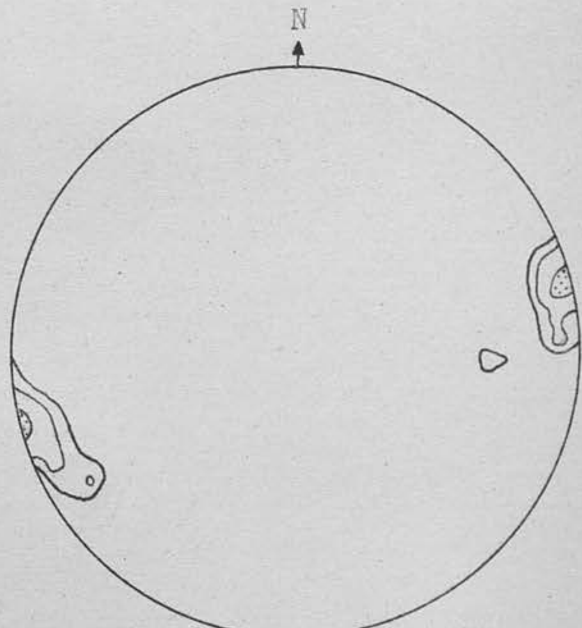

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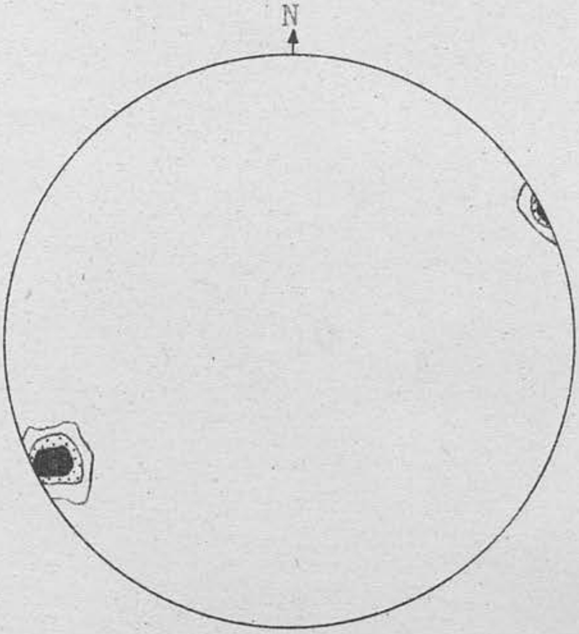

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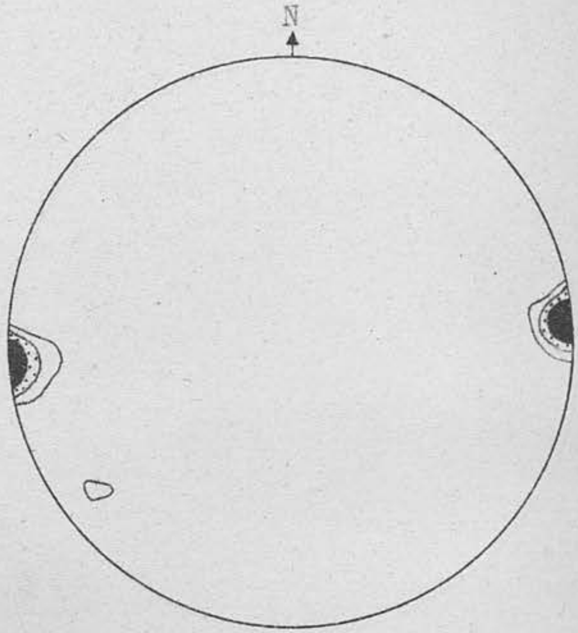

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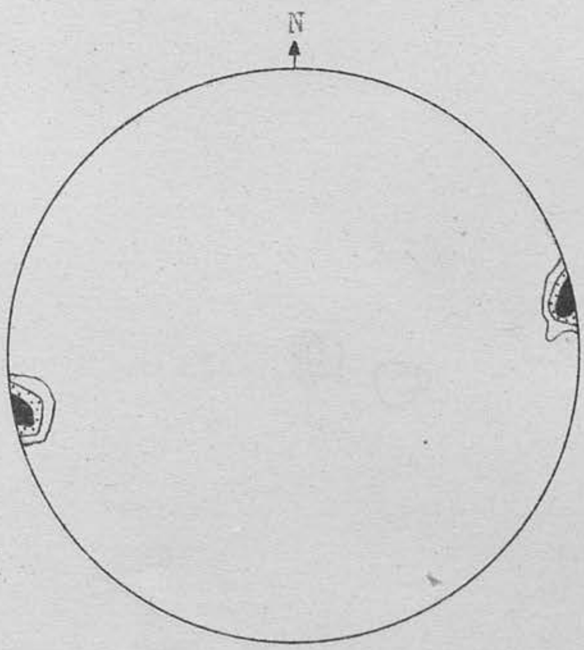

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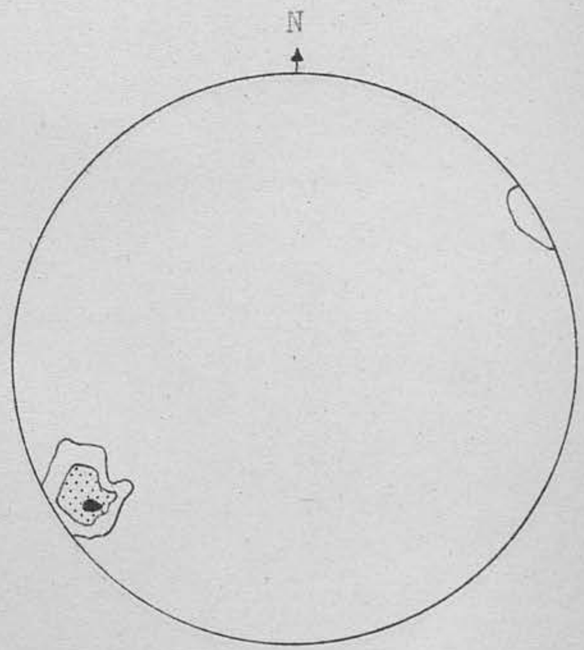

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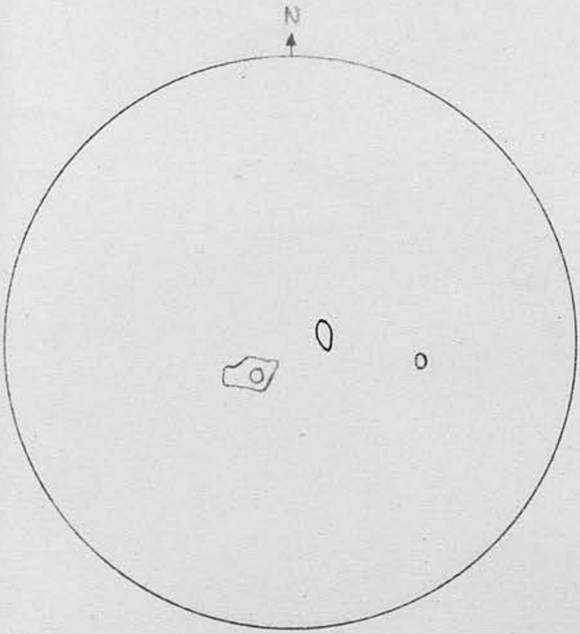

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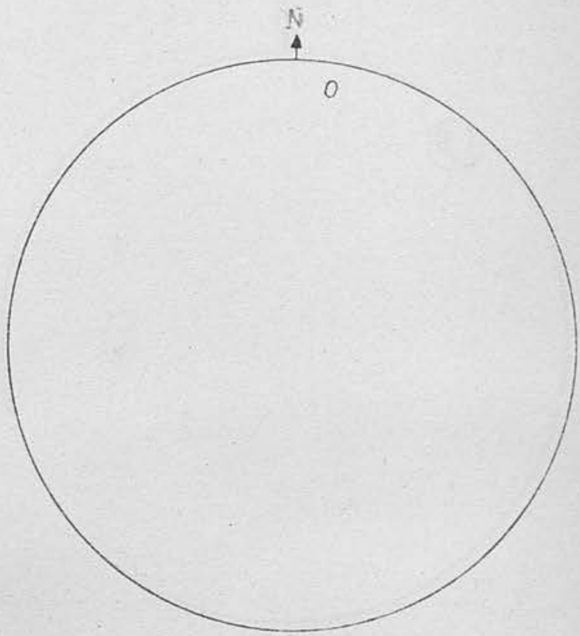

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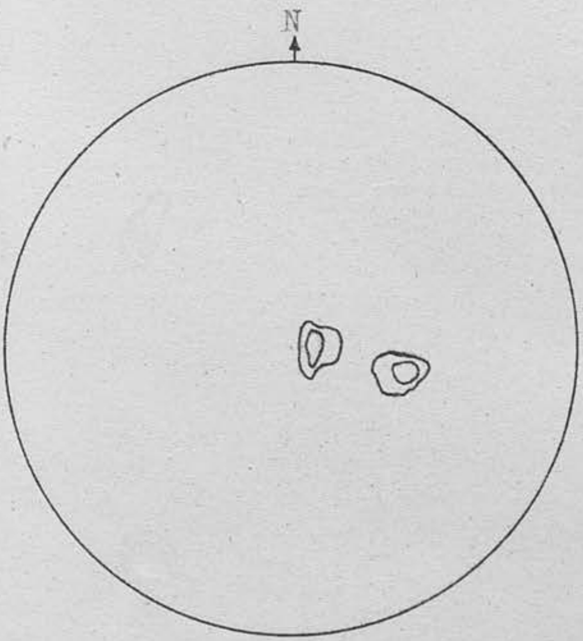

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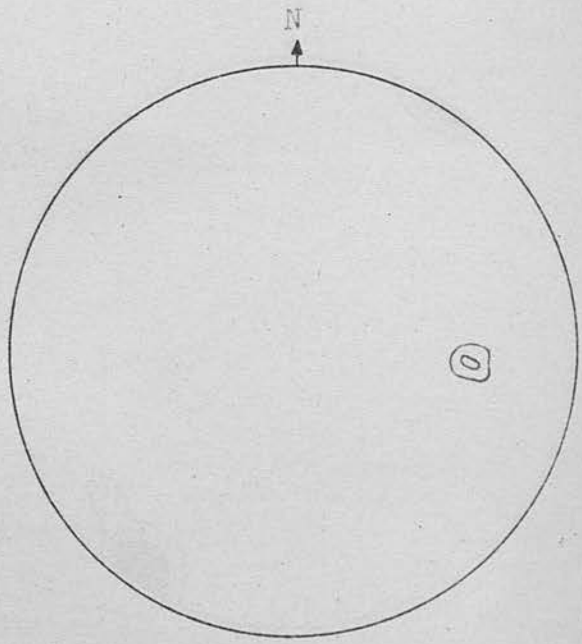

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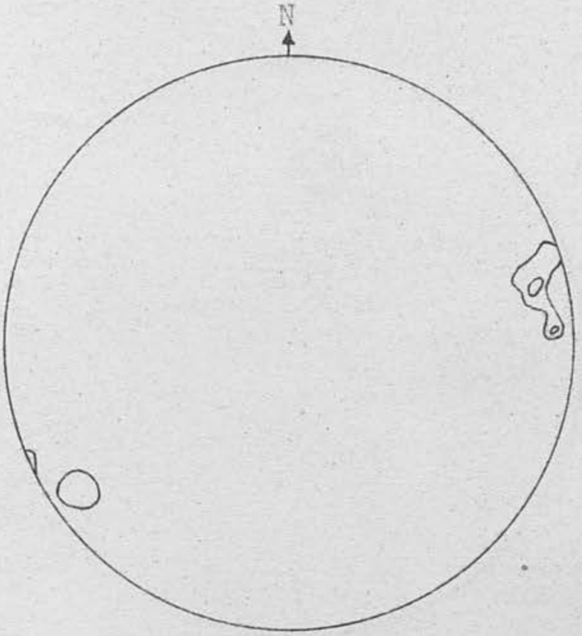

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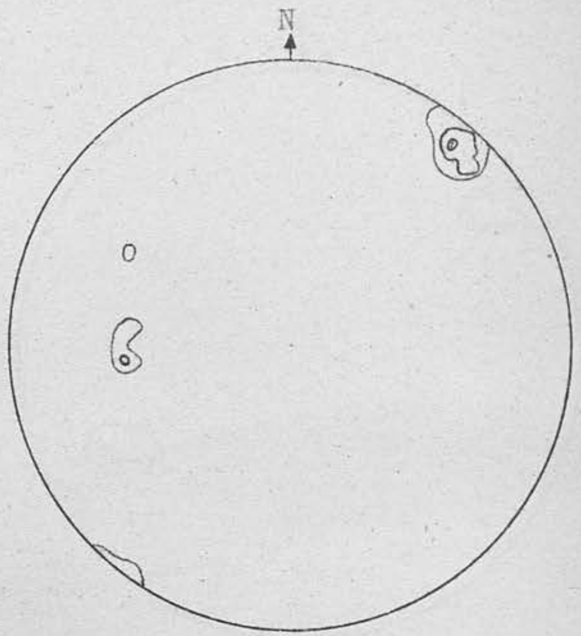

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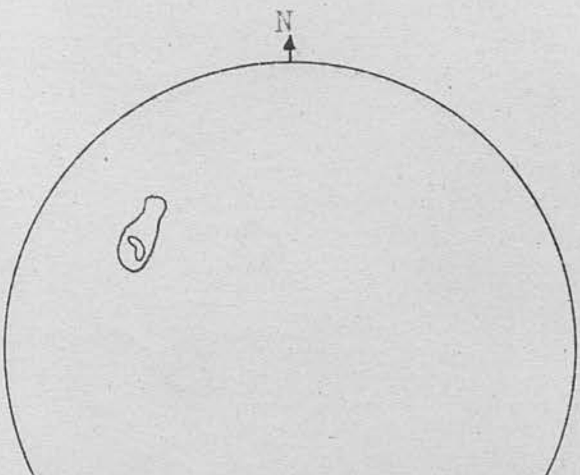

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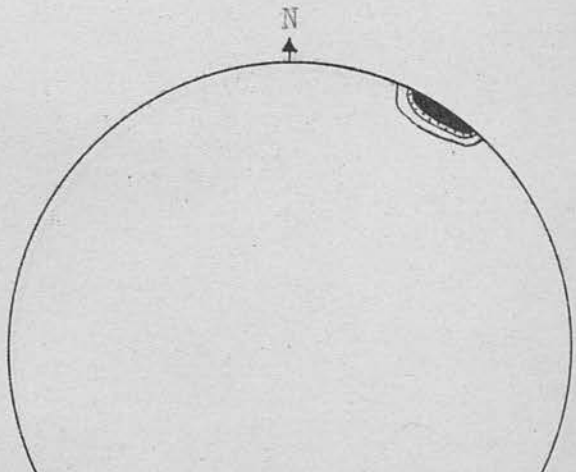

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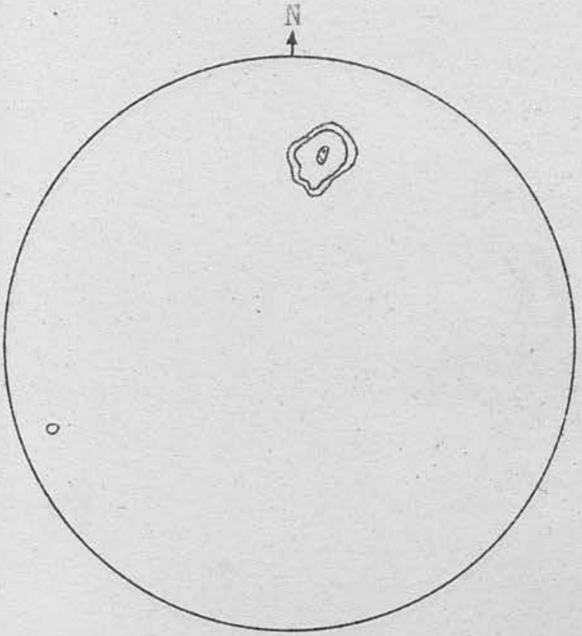

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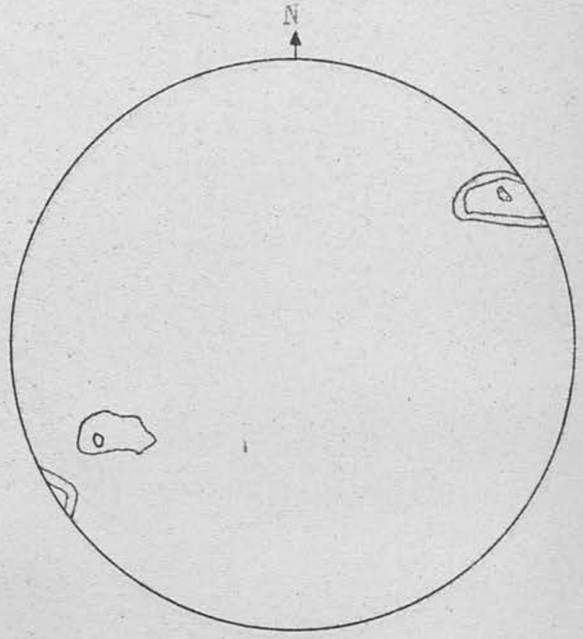

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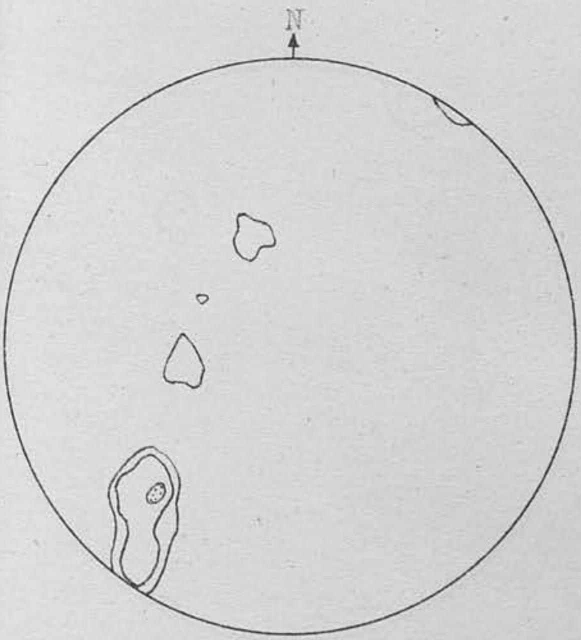

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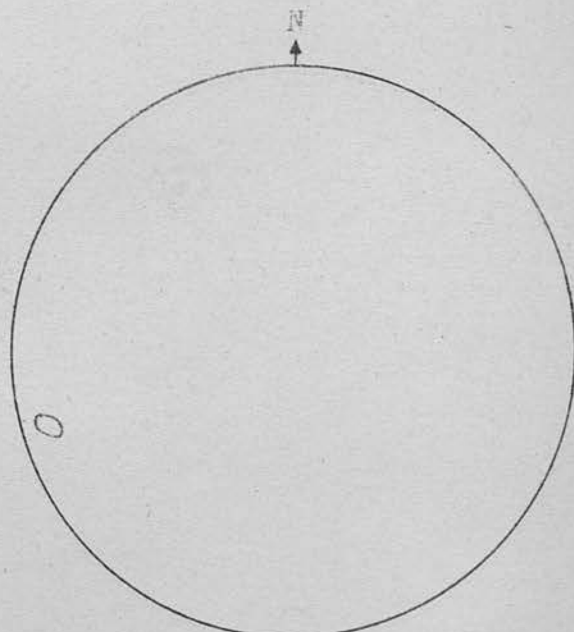

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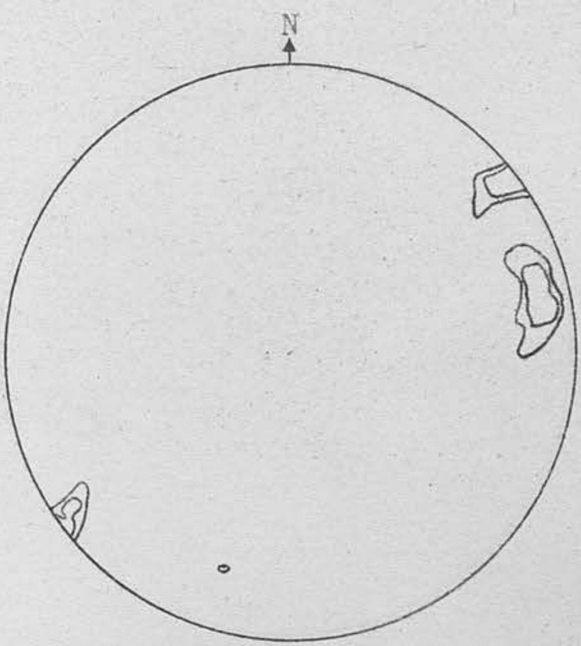

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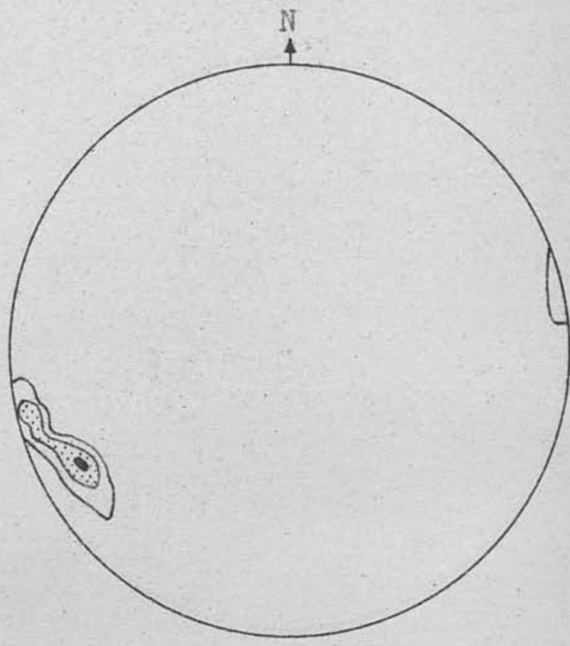

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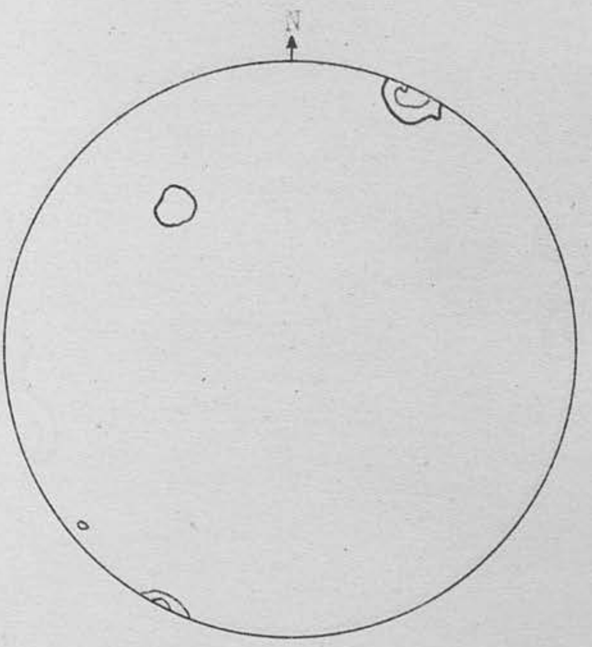

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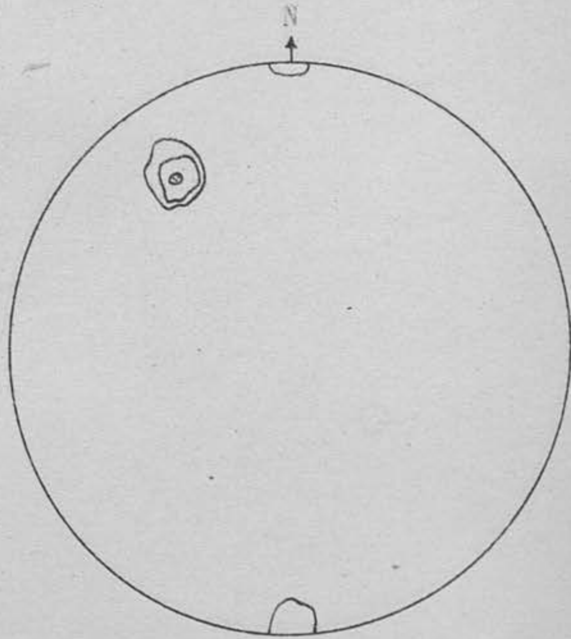

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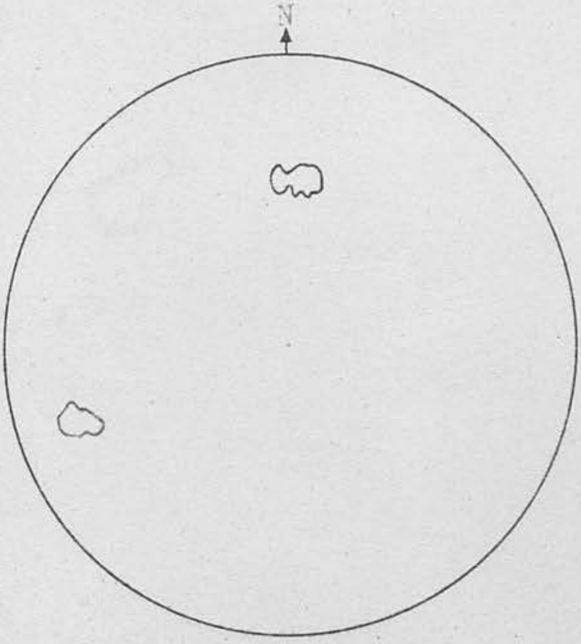

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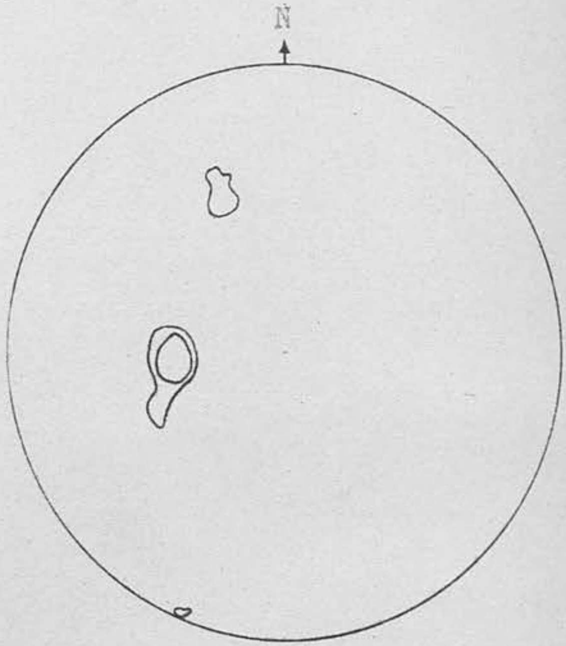

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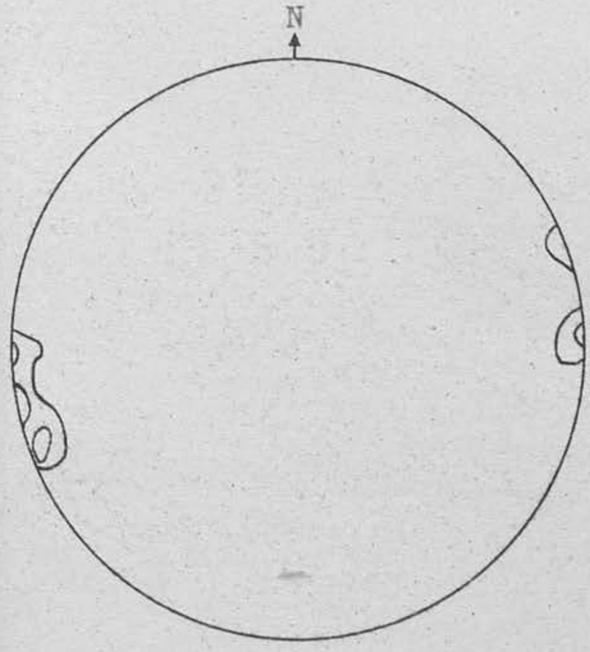

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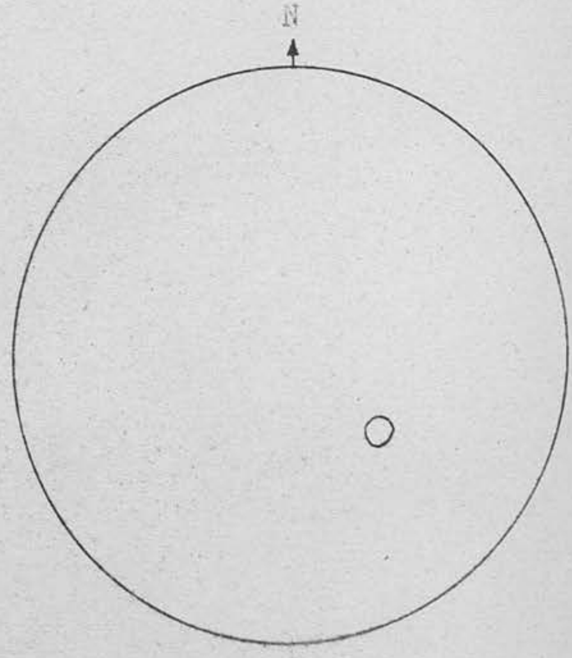

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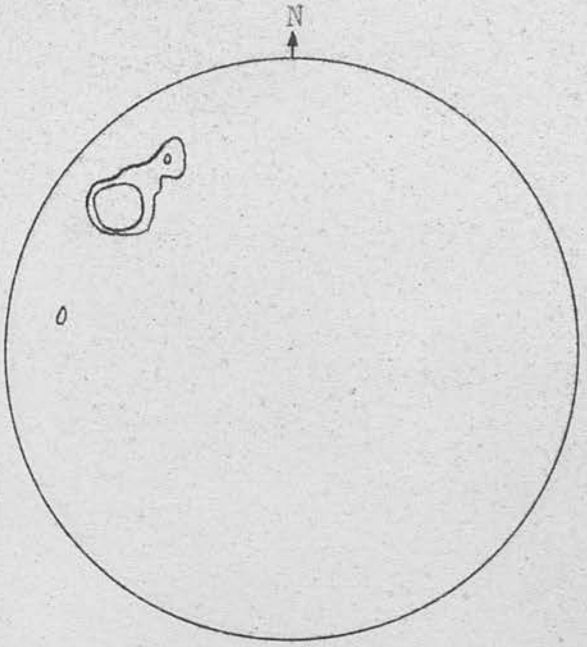

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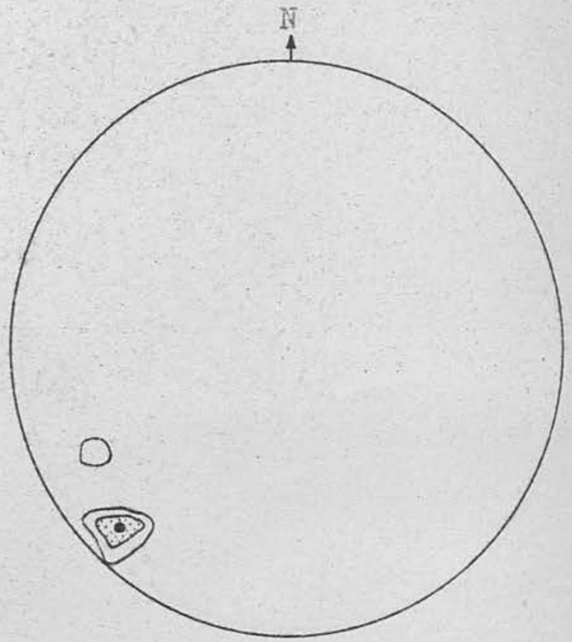

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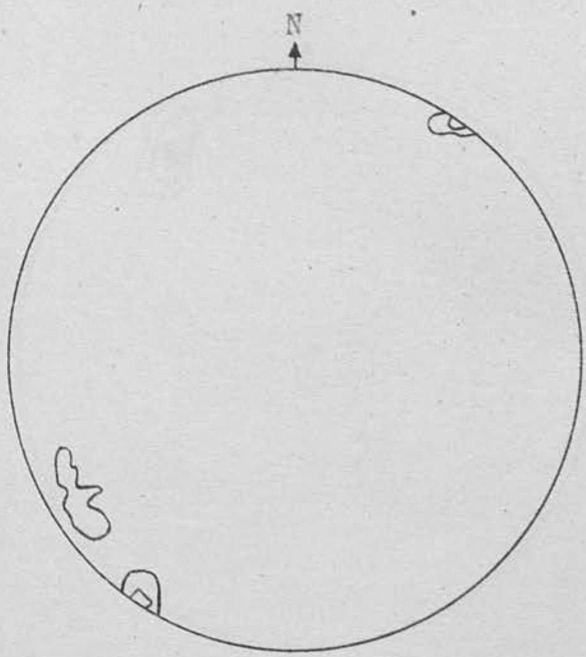

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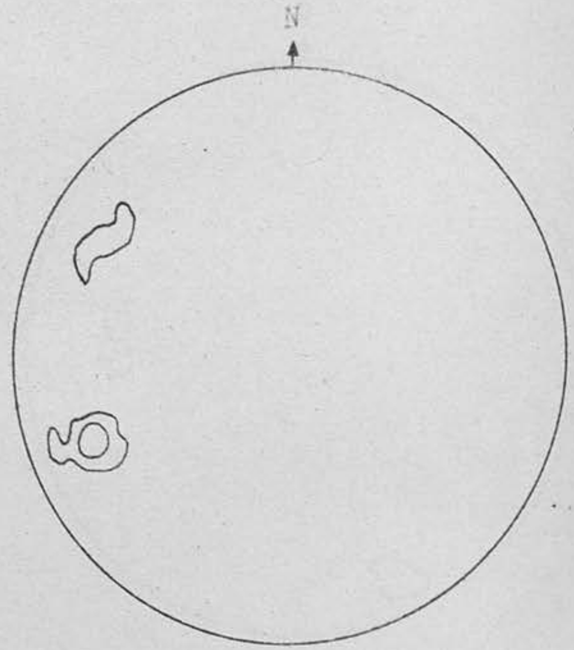

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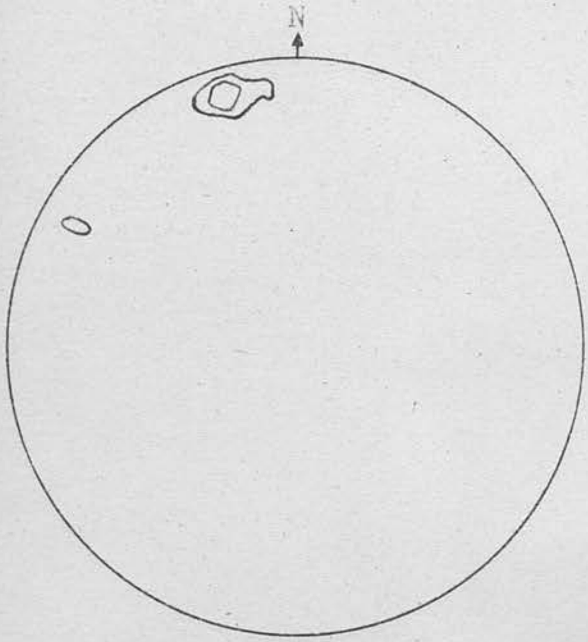

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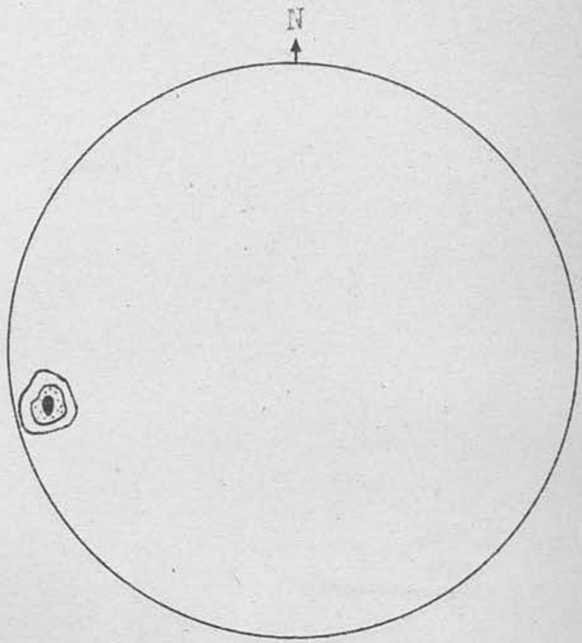

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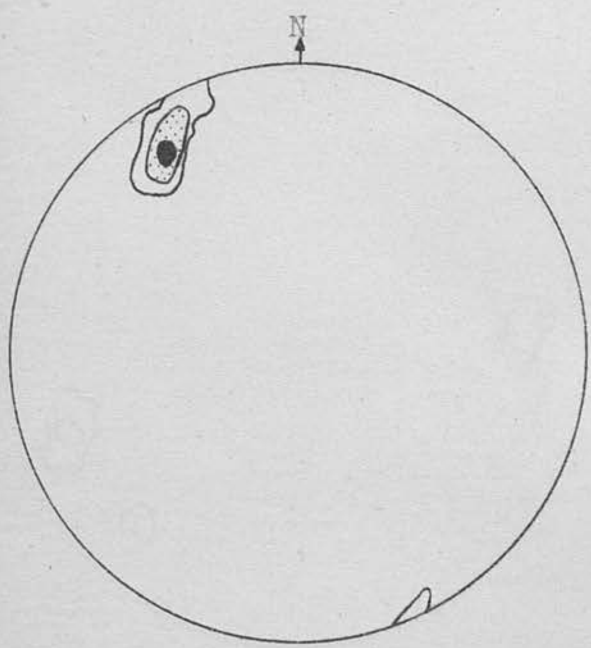

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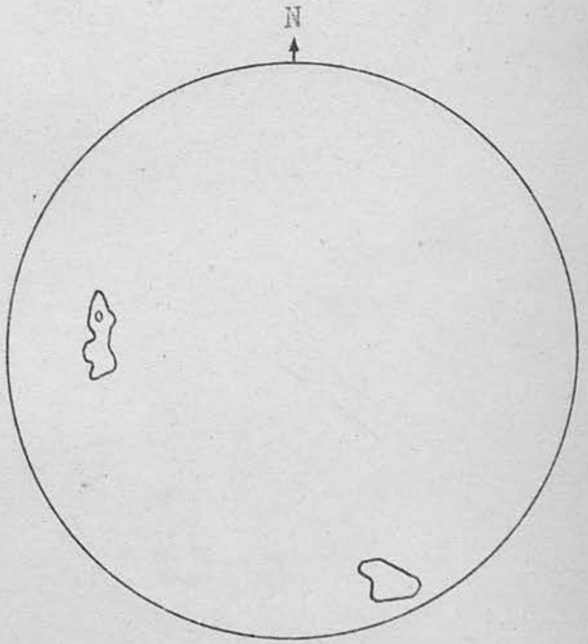

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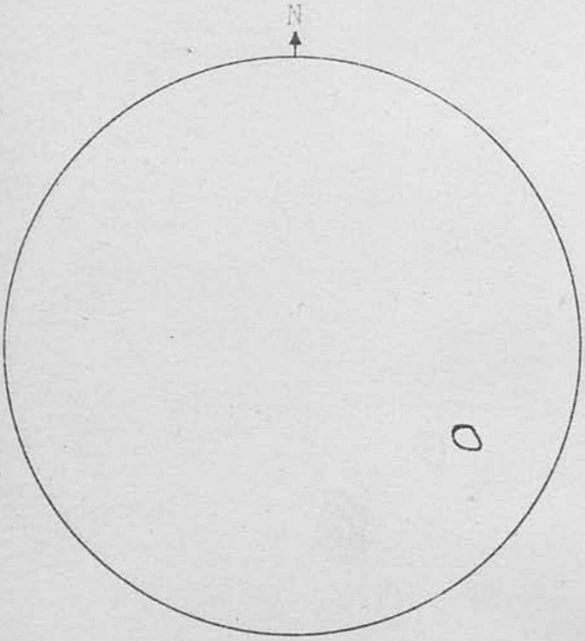

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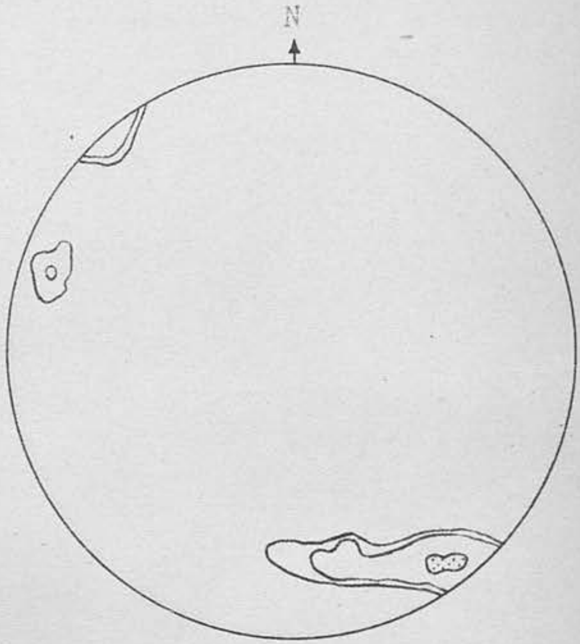

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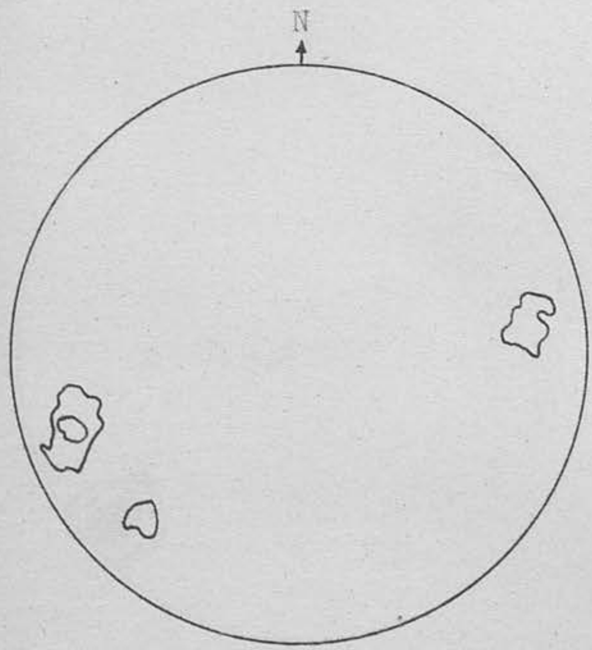

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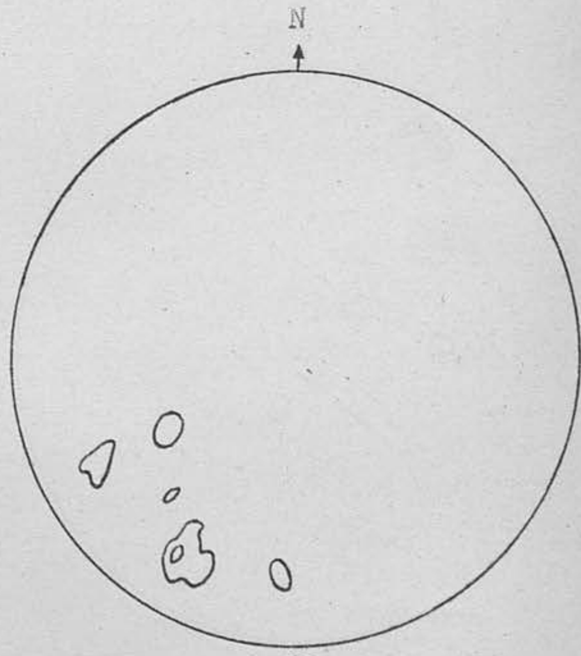

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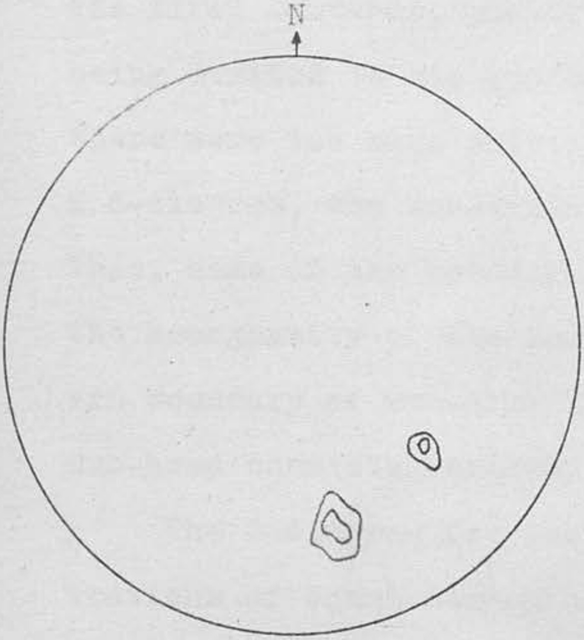

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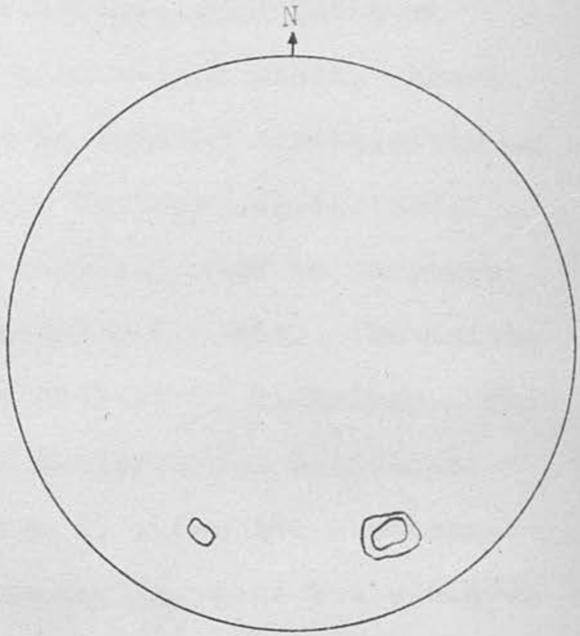

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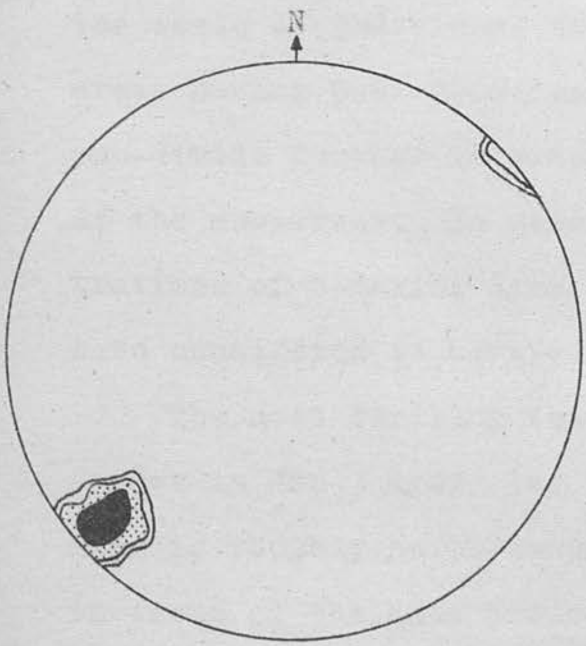

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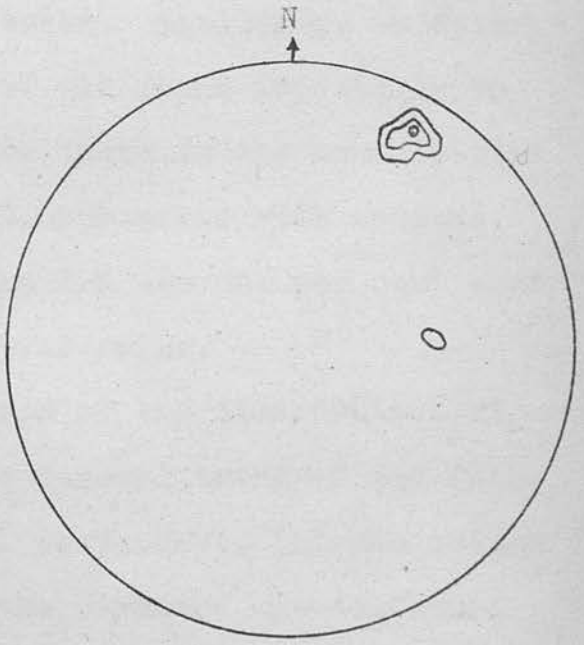

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The choice of boundaries for the sub-areas was, in the first instance, purely arbitrary, each sub-area being limited to one quarter of a 6-inch sheet. Where there were too many points to be handled conveniently on a β-diagram, the sub-areas were further sub-divided. Then, some of the boundaries were adjusted to increase the homogeneity of the individual sub-areas. The northern boundary of sub-area 1 is decided by lithology. This sub-area consists entirely of Latterbarrow Sandstone.

The β-diagram for sub-area 45 shows two β-concentrations of equal strength, suggesting that the sub-area should have been further sub-divided. Sub-division proved impossible, as the area is inhomogeneous above the scale of individual exposures. Similarly, in other areas having poor β-maxima, it was found impossible to sub-divide further in order to increase the homogeneity of the sub-areas. In general, sub-areas with concentrations of β-maxima less than 10% per one per cent area were considered to have doubtful value.

The most striking features of the distribution of arrows in Map 3 are: (a) the general trend of the fold-axes is roughly north-east -- south-west; (b) the change in trend of the axes around the northern and western margins of the Ennerdale Granophyre; (c) the north-west -

south-east trend of the axes in, and to the west of, the valley of the River Cocker.

The general north-east -- south-west axial trend is the main structural pattern throughout the area considered, and possibly throughout the whole extent of the Skiddaw Slates. Figure 6 shows the variation in the statistical trend and plunge of the axes along the line A-A on Map 3. Map 3 shows a major axial depression in the region of Crummock Water, and a culmination further to the west.

The change in axial trend around the Ennerdale Granophyre is taken as strong evidence that when the emplacement of the granophyre took place, there was a struggle for space which resulted in the shales being pushed outwards along the line of contact.

The question of the north-west -- south-east trends is dealt with in greater detail in section Vd.

c. <u>Plunge of the axes of Small Folds</u>

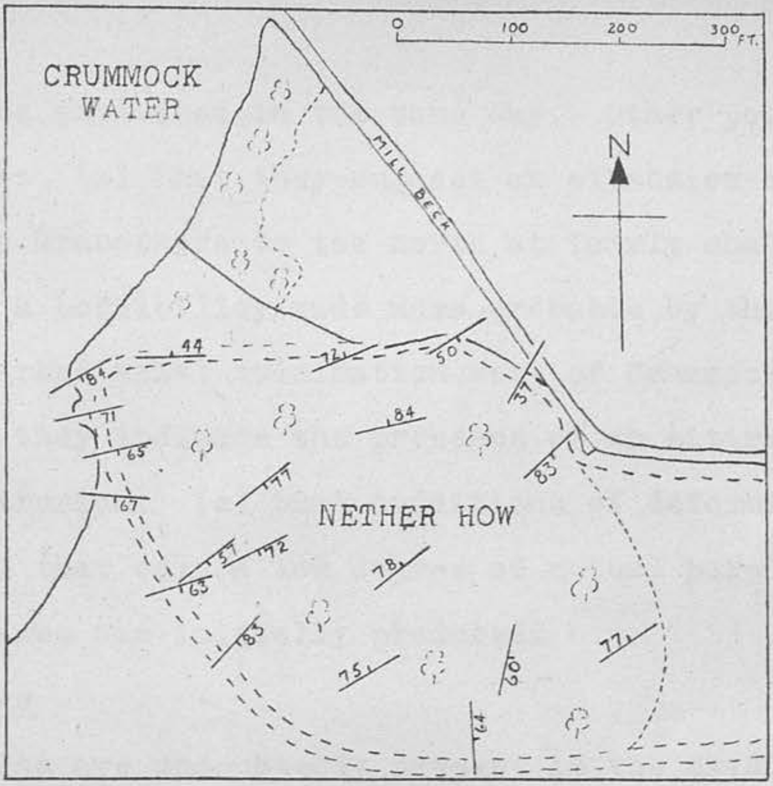
The data shown on Map 4 agree closely with those shown on Map 3. Where the data in the two maps differ markedly, the β-maxima for the sub-areas concerned are of generally less than 15% per one per cent area. The orientations of the small folds yield information not supplied by the more general β-diagram.

d. <u>Plunge of Linear Structures</u>

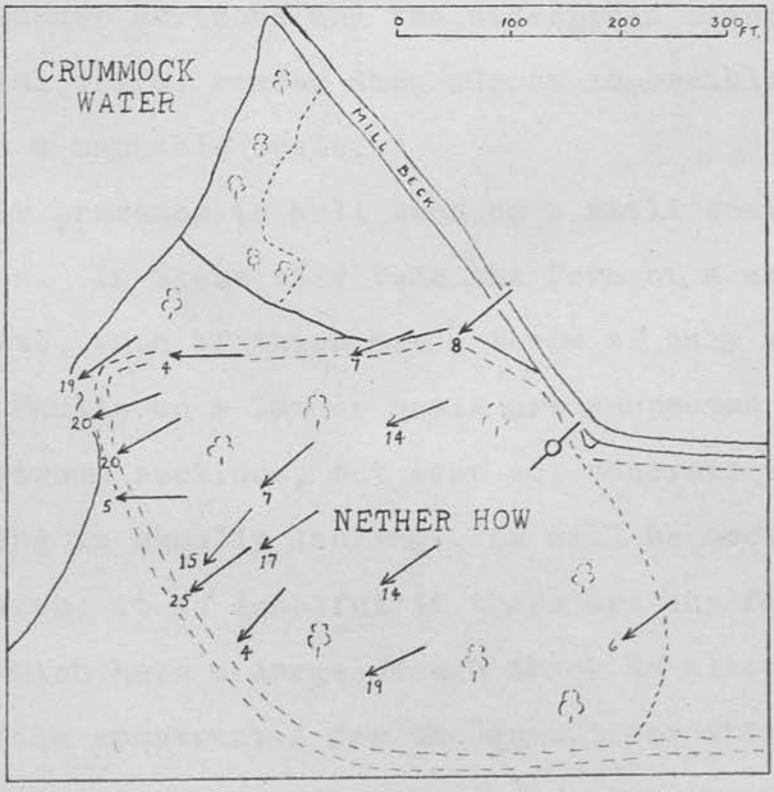
Like those of the small folds, the trends of B-lineations shown on Map 5 correspond with those on Map 3; but they illustrate more clearly the lack of homogeneity of axial plunge on scales larger than that of one exposure. At Nether How (Fig. 5), the orientations of B-lineations are mapped in detail. The variations seen in this small area may be taken as typical of the way in which the trend and plunge vary elsewhere in the shales of the Skiddaw Slates Series.

The change in trend of the axes around the north-eastern margin of the granophyre is shown by both lineations and small folds; on the western margin of the granophyre, neither folds nor lineations were observed.

In the north of the area, the lineations conform to an arcuate pattern which is crudely parallel to the northern margin of the granophyre. The agreement in this area between the trend and plunge of lineations, small folds (Map 4) and β-axes (Map 3) is close. The reason for this arcuate pattern is not understood, but it is possible that it is an expression of the complex forces brought into play, in an already folded region, when the Ennerdale Granophyre was emplaced. The north-west -- south-east axial trends on Maps 3, 4 and 5 could



Dips and strikes in shales at Nether How.



B lineations in shales at Nether How.

Fig. 5.

perhaps be explained in the same way. Other possibilities are: (a) that they suggest an extension of the Ennerdale Granophyre to the north at fairly shallow depth -- a possibility made more probable by the presence of the marked axial culmination west of Crummock Water; (b) that they indicate the presence of an entirely separate intrusion; (c) that conditions of deformation were such that only a low degree of mutual parallelism of fold-axes was initially produced.

e. Faults

Faults are undoubtedly present in the Skiddaw Slates, but the complex nature of the folding, coupled with the lack of marker horizons and the widespread cover of peat and glacial drift, render them almost impossible to detect on a mappable scale.

Their presence is well seen on a small scale in the siltstones. In these they take the form of a series of step faults, each of which has a throw of only one or two inches. Faults on a larger scale are suspected to occur in many stream sections, but even so, concrete evidence of faulting is usually lacking. As will be shown in the next section, it is doubtful if there are any faults present which have a large enough throw to alter seriously any profile constructed for the area. For this reason, the presence of faults has been ignored, and the faults have been omitted from the maps.

f. Profile

If the trend and plunge of a fold-axis is constant over a considerable area, then the projection of the strike of the surface outcrops parallel to the axis on a plane normal to the axis, gives a profile of the structure. (Fig. 2). This method has been used by Wegmann (1929) and McIntyre (1951).

If a profile is to be constructed from the strikes shown on Map 2, it must take one of two forms. It must either be constructed in one plane on the basis of a generalised axial trend and plunge, or it must be constructed in parts on different planes for individual sub-areas which are combined to give a complete profile. If the former, then the profile will have significance only on a large scale; the axial trend and plunge of individual sub-areas will only rarely agree with the mean axial trend and plunge used in the construction, and the greater the disagreement, the greater the error. The false impression so given by the profile is especially apparent for those sub-areas in which the axes trend north-west -- south-east. If the latter, then it will be impossible to represent the profile so prepared on a plane surface, because of the great variation in axial trends and plunges used in the construction.

It is doubtful whether a profile can be constructed for each sub-area. A profile is constructed by projection of strike lines parallel to the fold-axis. The orientation of the axes of small folds and B-lineations show that within each sub-area, there is a considerable lack of mutual parallelism of these structures. Also, it is dangerous to connect either strike lines, or the resulting lines on a profile since there is no marker horizon to act as a guide. The exposures from which the strikes are mapped are very small compared with the spaces between and the thickness of the strata. Individual bedding planes cannot be properly equated from outcrop to outcrop in this region of complex folding. For the above reasons, no true profile can be constructed for the whole area.

However, from Map 1, it can be seen that the beds on the north-west side of the belt of shales generally dip to the north-west, whereas on the south-east side of the area, they dip to the south-east or south-west. Map 3 shows that to the west and north-west of the Ennerdale Granophyre, the trend and plunge of the axes is more constant than anywhere else. The π-poles of the

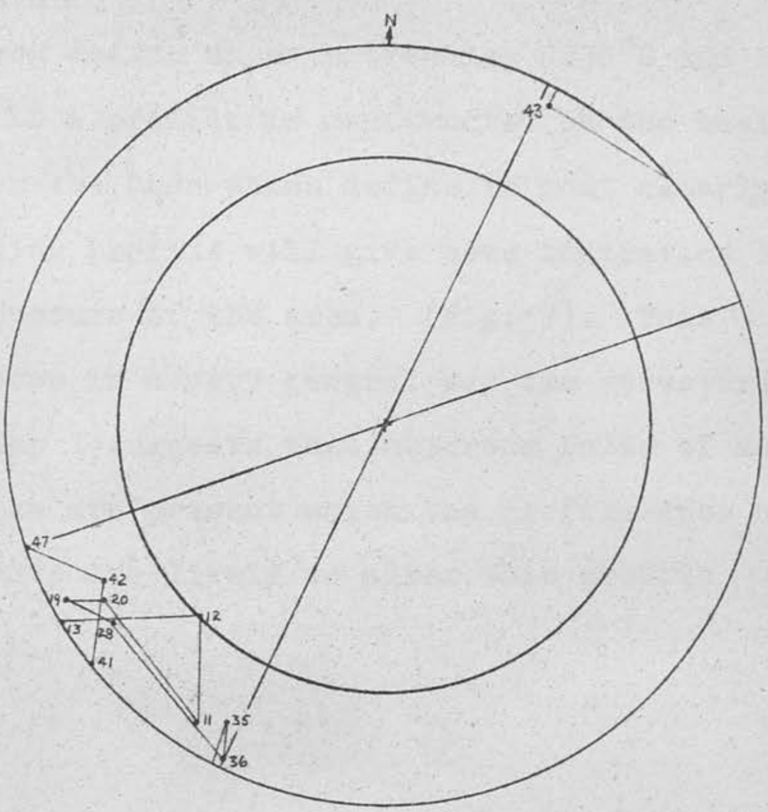


Fig. 6. Diagram showing the variation in the statistical trend and plunge of the axes along line A-A on Map 3. Sub-areas having β-maxima of 7·5% are ignored.

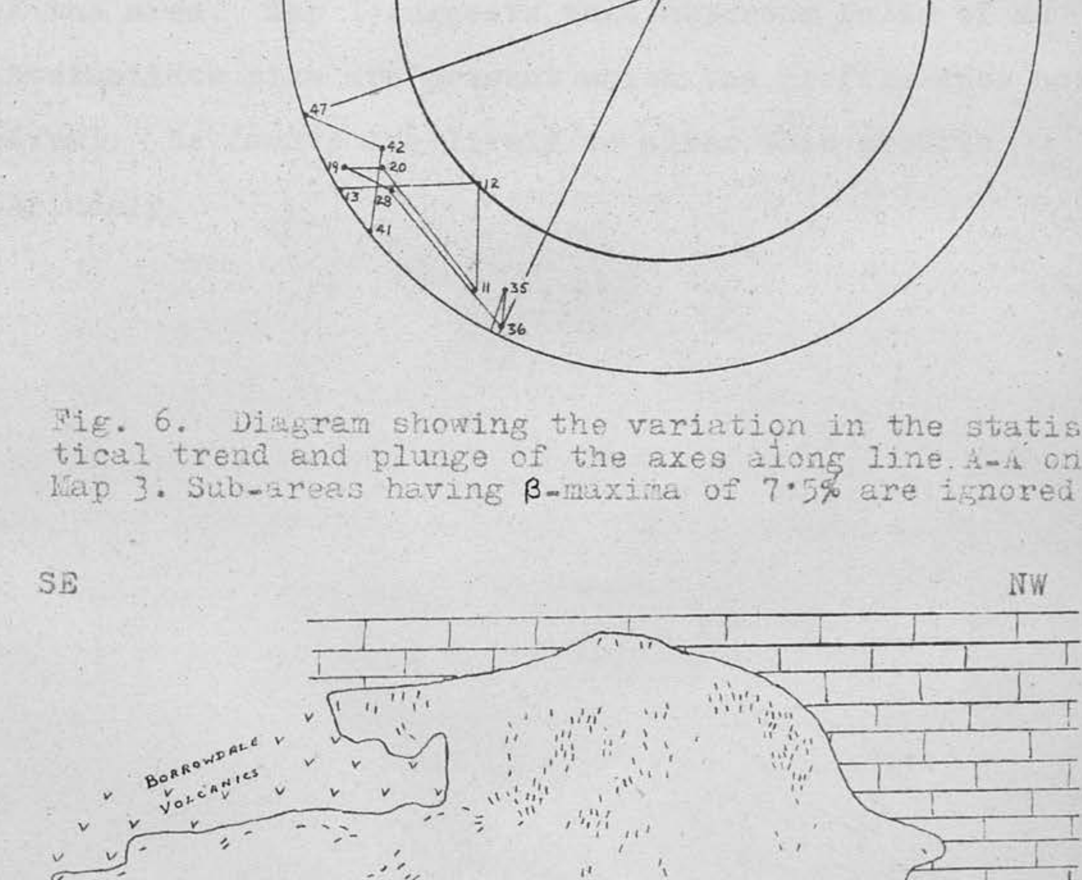


Fig. 7. Profile of the Skiddaw Slates south-west of a line passing through Ennerdale Water. Construction is based on a statistical axial trend of N235°E and plunge 15°. Only those bedding attitudes which agree closely with the statistical axis were used.

beds in this area define an axis trending N235°E and plunging 20°. If a profile is constructed on the basis of this axis for the beds which define it most clearly, then the resulting profile will give some indication of the general structure of the area. (Fig. 7). This profile only shows in a very general way the structure of the area. Map 1 suggests that numerous folds of an intermediate size are present which the profile does not reveal. No faults are likely to alter this profile seriously.

VI ENNERDALE GRANOPHYRE

It has been mentioned above that, contrary to the results of previous workers, the Ennerdale Granophyre appears to have displaced the Skiddaw Slates very strongly. Not enough evidence was collected from the area of the remnants of the roof, around Starling Dodd, to show whether there had been any "arching up of the beds", but the axial culmination in the shales to the north suggests that arching may have occurred. Along the northern margin of the granophyre, the shales dip generally towards the contact at fairly low angles. Nowhere is there a marked dip away from the contact. The inward dip of the shales may possibly be the result of crumpling during the emplacement of the granophyre.

The sediments do not show strong metamorphism. Hornfels is known, but more commonly, almost unaltered shales are found right up to the contact with the granophyre. Quartz veining is common in the region of the contact.

VII CARBONIFEROUS AND PERMO-TRIAS

The shales are overlain to the west and north-west by Carboniferous and Permo-Triassic strata. The former includes limestones, grits and Coal Measures; and the latter, breccias, limestones and sandstones. The general dip of all these rocks is between 0^{o} and 20^{o} to the west and south-west.

Returning the Carboniferous and Permo-Triassic strata to the horizontal does not simplify the structure of the Skiddaw Slates in any way. This was to be expected, since they lie roughly on fold-axes of similar trend.

VIII POSSIBLE ERRORS

It is suspected that on some of the steeper slopes, soil creep affects the attitude of the bedding. A test for the presence of soil creep was made on Redhow Crag, just south-east of Thackthwaite. Here, the River Cocker flows at the foot of a steep scarp slope. The shales dip roughly westwards at about 30° away from the river. The crag is capped with boulder clay, which, together with soil, have slipped down the scarp slope over the outcrops of shale. The attitude of the bedding was recorded in beds of three different types:-

(a). Beds unlikely to be affected by soil creep.

(b). Beds possibly affected by soil creep.

(c). Partly unsupported beds which appeared to be bending under their own weight.

All points recorded under (a) -- crosses -- fall along the dotted great circle in figure 8b. Those recorded under (b) -- black circles -- fall along a girdle giving a plunge of approximately 20° to N270°E; whilst those noted under (c) -- hollow circles -- consist of the three innermost points. These data could be explained in terms of a change in axial plunge, but such a coincidence is unlikely. It is concluded that soil creep does occur, and that its affect on the shales can be measured.

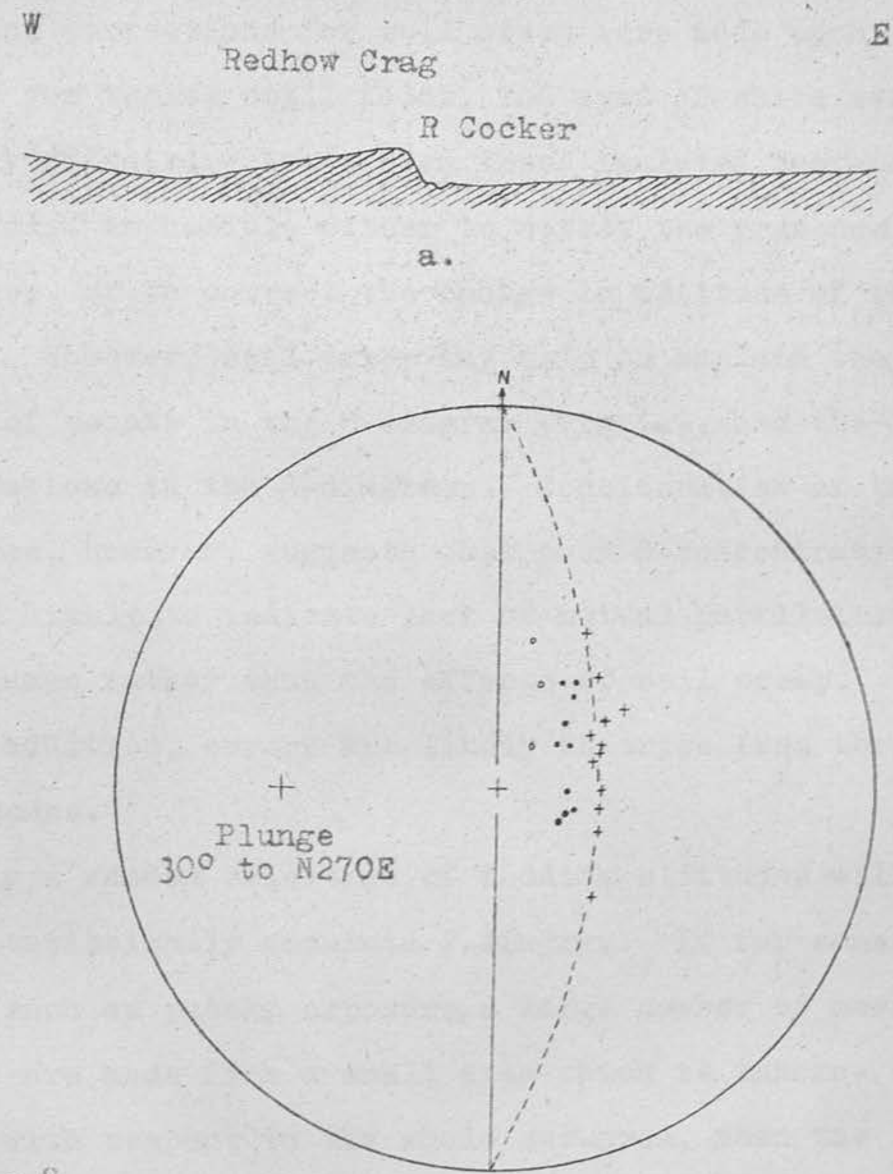


Fig.8.

b.

a. Sketch of Redhow Crag. Shading represents the general dip of the shales to the west. The cap of boulder clay is not shown.

b. π-diagram for Redhow Crag. Symbols represent the attitudes of the bedding on the crag (see text). Correct plunge for the structure is shown by dotted line. Dots and circles inside the dotted girdle represent the effect of soil creep causing a shallowing of the bedding.

Minor corrections for soil creep were made upon readings for twelve small folds, the axes of which were obviously affected. Apart from these isolated instances, it was found impossible either to detect the presence of soil creep, or to correct the change in attitude of the bedding. However, soil creep may help to explain the scatter of points in the π-diagram (Fig 4A), and the low concentrations in the β-diagrams. Consideration of the whole area, however, suggests that poor β-concentrations are more likely to indicate lack of mutual parallelism of fold-axes rather than the effects of soil creep.

In addition, errors are likely to arise from three other causes.

1. Only a random selection of bedding attitudes will give a statistically accurate β-diagram. If for some reason, such as patchy exposure, a large number of measurements are made from a small area which is inhomogeneous with respect to the whole sub-area, then the inclusion of the resulting data into the diagram for the whole area will greatly influence the pattern.

2. β-diagrams may be inaccurate if too few points are used, or too much emphasis is laid upon the absolute maximum of a poor β-concentration.

3. Sedimentary structures such as slump-folds may be

mistaken for folds of tectonic origin (see photograph 4). Possible slump-folds are made more difficult to recognise because their axes are invariably sub-parallel to the fold-axes of small folds of tectonic origin.

Errors which could be introduced by the above causes have been guarded against as far as possible.

IX CONCLUSIONS

1. All the axial structures (β-axes, fold-axes and B-lineations) suggest that there is a weakly developed axis of large scale folding trending N240°E and plunging 15°. This trend agrees with previous views. This axis is statistically accurate only for the area as a whole, and it is thought that it is locally affected by the emplacement of the Ennerdale Granophyre.

2. The low degree of parallelism shown by the fold-axes may indicate the effects of repeated deformation, but it is more likely to be caused by limited deformation of incompetent rocks at shallow depth. Had there been stronger forces acting at greater depth on more competent rocks, then the type of homoaxial structure found in the metamorphic rocks of the Highlands of Scotland might have been produced.

3. π-diagrams have only a limited use for analysing the structure of such an area. Division of a large inhomogeneous area into essentially homogeneous sub-areas, with the construction of a β-diagram for each sub-area, appears to be the best way of analysing complex structures. The most difficult step in this procedure is the selection of areas of homogeneity, which can only be made by trial and error.

4. Small folds and B-lineations occur only sporadically, but in general they agree with the axes deduced from β-diagrams.

It is hoped that the principal results of this work will be accepted for publication shortly.

X ACKNOWLEDGEMENTS

The writer wishes to record his debt to Dr. Donald B. McIntyre for introducing him to the problems of Structural Geology, and for suggesting numerous methods of handling the data collected from the Skiddaw Slates. Dr. L.E. Weiss offered advice, and made constructive criticism of the final work. The study was accomplished with the aid of a research grant from The Shell Petroleum Company, the award of which is gratefully acknowledged.

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PLATE I

1. Small fold NW side of Buttermere Hause.

2. Small fold NW side of Buttermere Hause.

3. Small fold SE of Fangs, near Mockerkin.

4. Small fold possibly of sedimentary origin, Holme Wood, Loweswater. Fold-axis plunges 20° to N247°E.

PLATE I

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PLATE II

5. Cleaved shales between bands of siltstone.
South of Fangs, Mockerkin.

6. Lineation on shale from quarry NE of Buttermere.

7. Folding and cleavage on west slopes of Whiteside.

PLATE II

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PLATE III

8. Panorama; Bowness Knott, Ennerdale Water, Anglers' Crag and Crag Fell. Granophyre, left background.

9. Panorama; Mellbreak and Ling Crags. Crummock Water in foreground. Granophyre at far left.

PLATE III

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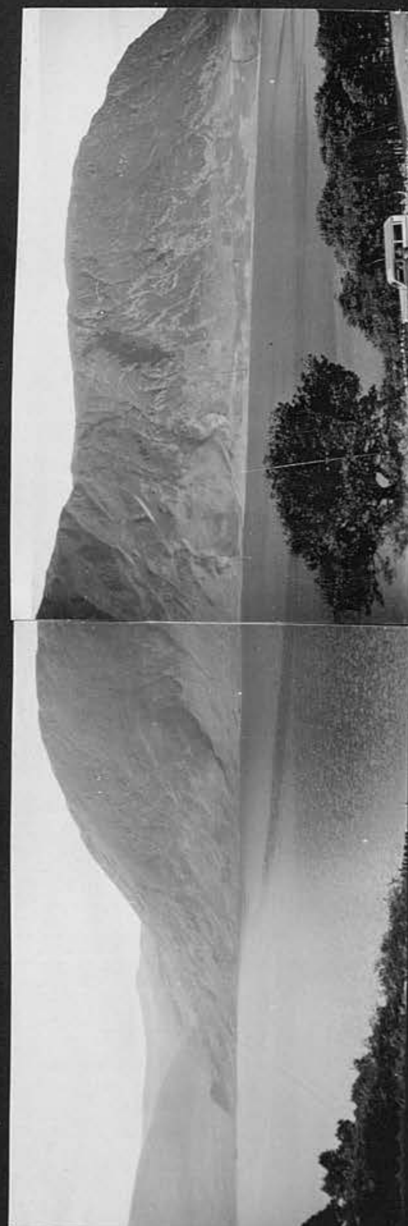

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PLATE IV

10. Mellbreak, Crummock Water and Grasmoor from High Stile.

11. Grasmoor from Scale Hill. Possible fault features can be clearly seen near the top of Grasmoor.

12. Buttermere; High Stile and Red Pike in middle distance; Buttermere Hause on right foreground. Sca Fell behind High Stile.

PLATE IV

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PLATE V

13. Screes causing soil creep on south side of Whiteside.

14. Whiteside and Grasmoor across the valley of the River Cocker from Low Fell.

15. Looking east up the Whinlatter Pass to Skiddaw on the skyline, from Low Fell. Tree covered Redhow Crag in right foreground.

PLATE V

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