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A PETROLOGICAL AND STRUCTURAL STUDY OF THE LEVANG GNEISS-DOME, SOUTHERN NORWAY

A Thesis submitted for the Degree of
Doctor of Philosophy
in the
University of Durham

by

Thomas Gee Elder

Hatfield College
June 1964

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Frontispiece: The Levang Peninsula

Abstract

The Levang granite forms an elliptical body occupying the core of a broad antiformal structure, and covering approximately 50 sq. km. Surrounding this mass of granitoid gneisses is a series of banded gneisses of very variable composition, including amphibolites, quartzites, and nodular sillimanite gneisses. Against these rocks the granitic gneisses make a sharp, though in places 'interfingered' contact. Agmatitic relationships are never seen. Further south, on the Portör sub-peninsula, migmatitic granitoid gneisses are exposed which have mineral assemblages identical to those of rock types from within the main Levang granite.

The composition of the Levang granite gneisses is variable, ranging from quartz monzonitic to tonalitic types lacking potash feldspar, but on the whole corresponds fairly closely with the minimum melting composition of the granite system.

Over much the greater area the Levang granite is strongly foliated, and everywhere shows some degree of preferred planar or linear orientation of minerals. The foliation always parallels the contacts, and it defines a complex fold system within the granite which is in complete structural conformity with that of the surrounding banded gneisses and migmatites. The overall symmetry of the structure is triclinic, the plunge of the linear elements varying from horizontal to vertical. The β axis of the domal structure in the eastern part of the granite mass is completely overturned. Traced eastwards from the core of the dome, β trends initially due east north east, steepens to

vertical, and then plunges due west at angles of 60 to 70°. The very complex tectonic evolution has probably involved disharmonic folding and two phases of deformation.

Within the Levang granite amphibolitic sheets and lenses are invariably conformable to the fold pattern defined by the granite gneiss foliation. In the Helligesvann brachyanticline, a regular sequence of granitoid gneisses of variable composition, interlayered with a thick amphibolitic sheet which forms an unbroken horizon, indicates the presence of a 'ghost' stratigraphy.

Investigation of the potash feldspar obliquities shows that all the potash feldspars, from granitic gneisses, migmatites, and pegmatites, are more or less fully ordered maximum microclines.

The fact that some of the granitic gneisses approximate to the minimum melting composition is not conclusive evidence in favour of an origin through anatexis or fractional crystallization, in view of the spatial distribution of these rocks, their metamorphic textures, and the nature of the basic inclusions. The Levang granite is a metamorphic rock, the result of the transformation in an open system of a pre-existing series of supracrustal rocks by processes of granitization and metasomatism.

Preface

From September 1960 until August 1963 the author held a N.A.T.O. Science Studentship, administered by the Department of Scientific and Industrial Research. The first two years of tenure of this award were spent in Norway. A brief period of field work was carried out in the autumn of 1960. The major part of the field investigations occupied a total of seven months during the summers of 1961 and 1962. All field mapping was carried out on a scale of 1:10,000, on the basis of aerial photographs. Laboratory investigation of hand specimens and structural data was undertaken at the Mineralogisk-Geologisk Museum, Oslo University, during the winters of 1960 and 1961.

Since October 1962 the author has been engaged in further study of the material collected in Norway at the Department of Geology, Durham University. Finance for the academic year 1963 to 1964 came from lecturing duties with the British Association for the Advancement of Science and Sunderland Technical College.

Acknowledgements

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The Department of Scientific and Industrial Research is thanked for providing financial support during the study.

Personal acknowledgement is due to Dr. Scott Smithson for a great deal of helpful advice and discussion, to Dr. Roger Morton for suggesting the Levang peninsula as an area for study, and to Mr. M. Pettersson and Mr. J. Gammon for fruitful discussion.

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CHAPTER 1

INTRODUCTION

The aerial photographs of the Levang Peninsula reveal the presence of a large, sharply defined area of lighter weathering rocks, within which a complex fold structure is clearly visible. This area of felsic gneisses has been termed the Levang granite by B. Hofseth (1942). The granite mass is roughly elliptical in outline, elongated east north east - west south west, and covers an area of approximately 50 square kilometres.

Location and Accessibility

The area studied lies on the south east coast of Norway, on the Skagerrak seaboard. Situated some 145 km. south west of Oslo, the centre of the area lies, very approximately, at a latitude of 58^{o} 48' North, and a longitude of 9^{o} 23' East. Fig. 3 shows the general location of the area studied.

The natural seaward limits of the peninsula form the boundaries of the mapped ground to the north, east, and south east. To the west, mapping was extended as far as Eidsvann, a lake which forms a major topographical feature, running north to south, while to the south west the boundary of the area runs from Storholmen, (227 164), to the farm of Levangsdalen, (193 167), and from there to the north end of Leivann, (183 188). The mapped area totals 45 square kilometres.

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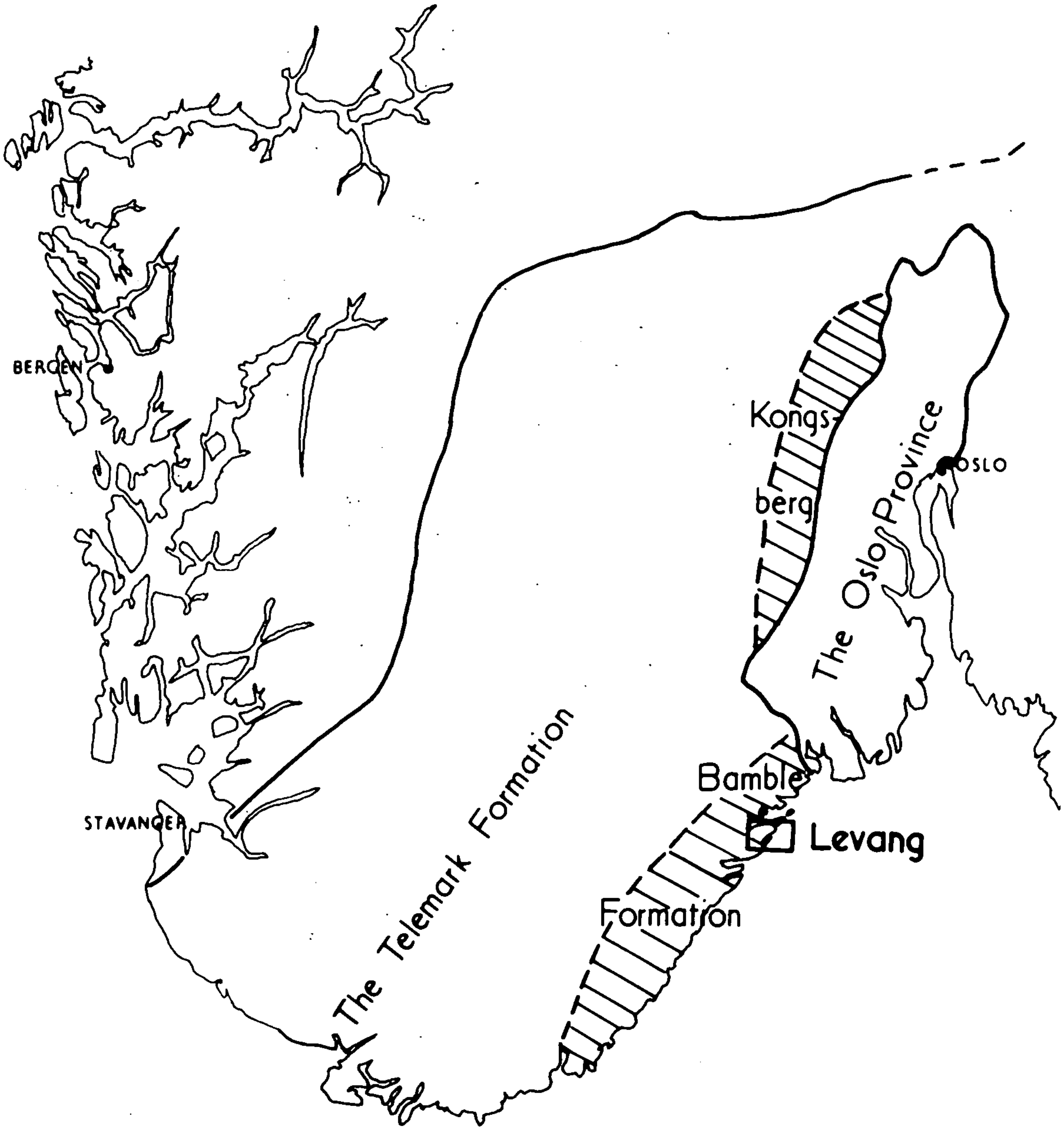
The accessibility by road in this relatively small area is excellent. The main road runs along the north coast of the peninsula from Eidsvann, through Stabbestad, (234 236), to Viborgtjern, (239 232), where it turns south and crosses the peninsula in a general south westerly direction, to Levang, (216 172). A branch of this road runs from Myre Skole, (244 221), south to Bekkeviken, (252 204), and another runs from a point just north of the Skole due east to Lövdalen, (252 223). Work is at present in progress on a further extension to Skjörsvik, (260 227). A new road now runs along the length of the sub-peninsula from Levang to Portör, (250 187). Thus, even the least accessible parts of the area, i.e. west of Mörk Vann, (198 192), and around Rapen, (271 213), are nonetheless only a few kilometres from the nearest road.

Topography and Exposure

The maximum relief of that part of the peninsula which has been studied is about 115m., so that the area is one of subdued relief. Granitic rocks underlie the highest ground which is found close to the northern margins of the main granite gneiss. The limits of the resistant granitic gneiss are generally marked by a steep feature, but within it the topography is that of an undulating plateau, tilted somewhat towards the south, the areas of basic gneiss usually forming lower ground. The two long rectilinear lakes of Eidsvann and Leivann lie in a very deeply incised valley, and almost certainly follow a tectonic line of



THE LOCATION OF THE LEVANG PENINSULA
SOUTHERN NORWAY.

FIG. 3

weakness in the Bamble rocks. Similarly, the configuration of the valley of Finsbudalen suggests that it, too has been eroded along another major line of fracture.

The degree of exposure varies considerably in different parts of the area, but is, over much the greater part, excellent. The Pleistocene ice has swept much of the region clear of surface detritus, and the drift filled depressions and valleys are generally separated by large areas with close to 100% exposure, particularly where the bed-rock is felsic. The only areas of very poor exposure are the steep slopes along the northern side of the peninsula, that part of the Langholmen sub-peninsula which lies immediately to the south east of Hagen (221 196), and a strip of country south of the main Levang granitic gneiss mass, extending from Hovet south westwards through Finsbudalen to Eidsvann. All of these areas are underlain by basic rocks, largely amphibolites and biotite amphibolites, and are thickly forested.

In addition to the excellent natural exposure, several roads which traverse the area afford extremely useful fresh outcrops in a third dimension. Their particular importance in an area of very good exposure is due to the fact that the ice-swept rock surfaces are almost invariably nearly planar and perfectly smooth, so that it is often virtually impossible, firstly, to ascertain the attitudes of minor folds, contacts, etc., in the third dimension, and, secondly, to take hand specimens.

Previous Work

The ultra-basics and quartzites of the Valberg peninsula north of Kragerö, were studied as long ago as the middle of the last century, and in works by Forbes (1857), and Kjerulf and Dahl (1861), mention is made of the granitic and banded gneisses of the Levang peninsula. In the earlier part of this century a great deal of work was done on the rocks of the Bamble Formation in general, chief among these being the writings of Brögger. The major work to date solely concerned with the geology of the Levang peninsula is that of Hofseth (1942). This fairly short paper dealt with the petrology of the various rock types exposed, and included a map on a scale of 1:50,000. More recently, Wegmann and Schaer (1962) carried out a survey of the amphibolitic rocks of the Portör peninsula, paying special attention to the amphibolite - quartz diorite relationships seen on Blåbærsholmen, and were able to distinguish three main phases of intrusion of basic magma.

Regional Geological Setting

The Levang peninsula lies within an area of strongly metamorphosed rocks of variable type, exposed along the Skagerrak coast of Southern Norway, from Langesund in the north east to Kristiansand in the south west. Trending parallel to the coast some 25 km. inland is a narrow zone of intense fracture and mylonitization termed the Great Friction Breccia, (A. Bugge, 1928)

This "Breccia" is used by Norwegian geologists to demarcate the "Bamble Formation" and the "Telemark Formation". Both of these "Formations" are of Pre-Cambrian age. The coastal strip is termed the "Bamble Formation", and the "Telemark Formation" lies to the north west of the Great Friction Breccia. Further north, a roughly north-south trending fault to the west of Kongsberg defines a series of Pre-Cambrian metamorphics termed the "Kongsberg Formation", the eastern boundary of which is the Oslo Province of Cambro-Silurian sediments and Permian eruptives. Because of similarities in petrography and structure, this latter area and the coastal rocks are generally grouped together as the "Kongsberg-Bamble Formation" (A. Bugge, 1928, J.A.W. Bugge, 1943).

J.A.W. Bugge, (1960), has distinguished two major divisions within the "Kongsberg-Bamble Formation", an 'older complex' of infra-crustals and supra-crustals, and a 'younger complex' of migmatites, granites, granite-pegmatites, etc. The former were formed, Bugge believes, before an older orogenic period, and the 'younger complex' during and after a later orogeny, being largely derived from the metamorphism of the pre-existing infra- and supra-crustals. He also suggests that the two periods of deformation can be separated in time by the intrusion of the 'Hyperites', a series of widely distributed gabbroid rocks. The supra-crustals and granite gneisses of the "Telemark Formation" to the north and west of the "Kongsberg-Bamble" area he tentatively correlates with the younger orogeny.

Recent age determinations (Neumann, 1960), most of which were carried out on biotite micas, using the Potassium-Argon method, have indicated ages for a series of "Kongsberg-Bamble" rocks of between 760 and 1040 million years. The intrusive Herefoss granite (Neuman, op. cit.) was, for example, dated at 900 million years. It may well be that the later intense metamorphism and granitization of Bugge's second period of deformation has effectively re-dated the rocks of the 'older complex'.

With regard to the relationship of the "Kongsberg-Bamble" rocks to those of other areas, attempts have been made to correlate them with the "Leptite formation" of southern Sweden. J. Bugge (op. cit.) claims that the metamorphics of the older orogenic period have similarities with a series of red and grey gneisses in south west Sweden, classified as Pre-Gothian, while the younger orogenic period may be correlated with the Gothian rocks in Sweden.

The metamorphic facies of the "Kongsberg-Bamble Formation" is variable. In the Bamble and Kragerö region, the rocks are of Almandine-Amphibolite facies, while further to the south west the grade of regional metamorphism increases to granulite facies. About 25 km. south west of Levang, a series of rocks which range in composition from norites to acid hypersthene granites occurs, which has been shown to have originated through the metasomatic transformation of pre-existing rocks (J.A.W. Bugge, 1940), in pressure/temperature conditions corresponding to Charnockite facies (Granulite facies). Barth states, (1960) that the degree of granitization in the Bamble area increases towards the south west, but that remnants of the Pre-Cambrian sediments can still be recognized, mainly in the form of quartzites, arkoses and marbles, in the Arendal to Kristiansand region.

The part of the "Bamble Formation" which lies between Kragerö and Langesundsfjord has long been famed for the rare minerals which have been discovered there.

CHAPTER 2

THE LEVANG GRANITE GNEISS

INTRODUCTION

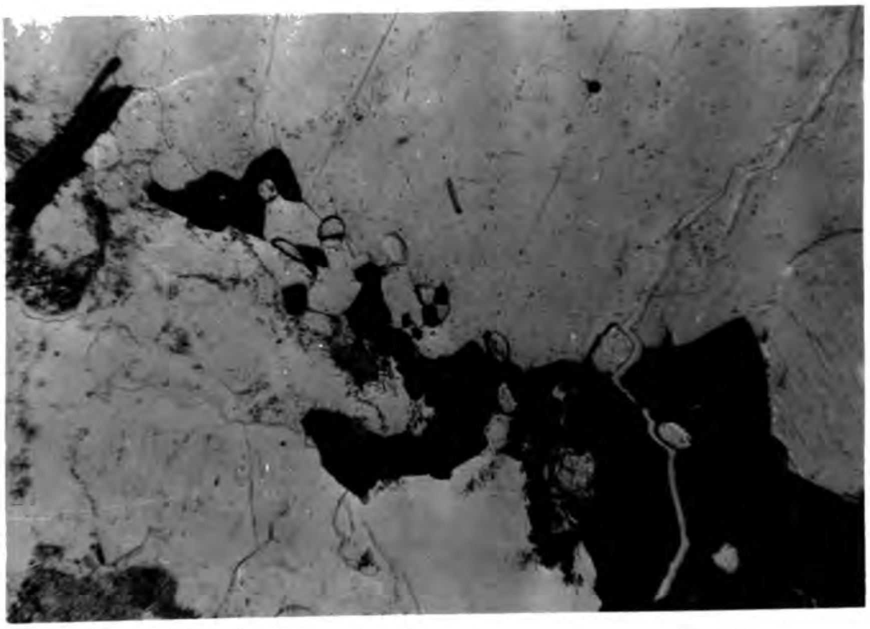
The sharply defined area of felsic gneisses which forms the major part of the core of an antiformal structure trending roughly north east - south west on the Levang Peninsula has been termed the Levang granite (Hofseth, 1942). Bounded on all sides by basic amphibolites, this broadly ellipsoidal mass of granitoid rocks also contains numerous inclusions of basic gneisses and schists, for the most part amphibolitic. Hofseth (op. cit.) described the 'granite' in general terms with regard to the individual mineral groups represented, but did not give any account of the variations in mineralogy occurring in these felsic gneisses, or, even more importantly, the spatial distribution of the different types. In the following section representatives of the most important varieties of the 'granite' are described, and the significance of the observed variations in mineralogy and textures and of the distribution of the several rock types are discussed.

VARIETIES IN THE LEVANG GRANITE GNEISS

Specimen L.141 is a dark grey 'augen' gneiss exposed close to the axial region of the Myre Dome, some 300 m. north of Myre farm (247 213). 'Augen' of pink microcline 1 to 2 cm. long are abundant and the orientation of these and of the amphiboles and platy mica imparts a strong foliation and lineation to the rock. The 'augen' are flattened elongate discs, rather than nematoblastic.

In thin section the rock is chiefly composed of plagioclase, quartz, microcline, and biotite, in decreasing order of abundance. Amphibole, apatite, orthite, magnetite, zircon, and sphene occur in accessory amounts. The texture is granoblastic. Microcline occurs mainly as aggregates of xenomorphic grains up to 5 mm. in diameter in the 'augen'. In the groundmass the potash feldspar occurs as small irregular interstitial grains. All the microcline is fresh and grid-twinned. Inclusions of rounded grains of quartz and plagioclase are very common in the microcline of the 'augen' (see pl. 1). Film perthite, mostly fine but in some cases coarse, is developed in some but not all of the microclines. The plagioclase is oligoclase, ranging in composition from An_{18} to An_{26}, occurring in 1 to 2 mm. anhedral polysynthetically twinned grains which are generally extensively sericitised. Myrmekite is commonly developed where plagioclase is in contact with microcline. Rounded quartz inclusions also occur in the plagioclase. Patches and thin screens of sericitised and corroded plagioclase occur between larger fresh microclines. Quartz is generally granulated and shows strong strain extinction, fracturing, and Böhm lamellae. Biotite, with a pleochroic scheme X: pale yellow, Y and Z: dark brown, occurs in ragged, occasionally bent and broken, plates showing a very strong preferred orientation. Pleochroic haloes around inclusions of zircon are common. The biotite appears in part to be replacing the amphibole, but is itself quite fresh without any signs of chloritization. The anhedral amphibole is

Pl. 1. Photomicrograph of L.141, showing rounded inclusions and quartz in grid-twinned microcline. x 40. Crossed nicols.



Pl. 2. Photomicrograph of L.276, showing a distribution of well rounded apatites and zircons suggestive of palimpsest sedimentary segregation. x 40. Ordinary Light.

biaxial negative, with a very small 2V, pleochroic in X: very pale green, Y: green, Z: dark olive green, and has a maximum extinction $c \wedge Z$ of 17°. It appears to be a hastingsitic hornblende. Zircon, which is occasionally zoned, occurs in well rounded grains, while apatite is rounded to subhedral. Sphene is anhedral and occurs in close association with the biotite. The mode of this rock appears in table 1.

Specimen L. 194 was collected 800 m. west of Heligesvann (213 212). In hand specimen it is a grey relatively fine-grained gneiss in which the mica is almost wholly segregated into distinct layers, imparting a strong foliation along which the rock splits readily. In thin section the essential minerals are plagioclase, quartz and biotite, and present in accessory amounts are microcline, muscovite, chlorite, zircon, orthite, opaque minerals and apatite. The texture is holocrystalline granoblastic. Anhedral plagioclase is albitic (An_6) with a maximum extinction on sections normal to (010) of 15° and a refractive index less than that of quartz. The degree of alteration is variable, some grains being quite fresh while in others discrete flakes of sericite have developed. Rarely the plagioclase is antiperthitic, the irregular patches of potash feldspar being grid-twinned microcline. The plagioclase frequently contains rounded inclusions of quartz, and discontinuous deformation twins are not uncommon. Most of the quartz grains are strongly crushed and granulated, but some large grains are unstrained. Inclusions of quartz in quartz are common. Biotite occurs in ragged laths and is generally extensively chloritised. It is pleochroic in X: pale yellow, Y and Z: dark

TABLE 1

MODAL ANALYSES OF GRANITIC GNEISSES

Specimen Number	Quartz %	Microcline %	Plagioclase %	Biotite %	Amphibole %	Garnet %	Accessories %	Area counted cm^2. %
L.228	22.8	18.3	38.1	4.1	11.9	3.2	1.6	54
L.276	28.7	23.4	35.3	6.9	3.2	1.7	0.8	54
L.254	29.1	28.8	32.8	4.2	4.4	0.1	0.5	54
L.146	31.0	31.0	32.1	4.9	0.6	-	0.6	54
L.132	44.6	3.3	46.3	5.1	-	-	0.7	36
L.141	28.4	20.8	38.5	8.9	2.5	0.2	0.7	54
L.175	30.5	27.3	34.0	6.1	1.9	-	0.2	36
L.240	30.6	21.3	35.8	9.9	2.0	0.1	0.3	54
L.74	32.8	20.4	36.6	6.7	3.4	-	0.1	36
L.189	25.2	21.7	37.0	6.4	7.8	1.2	0.7	36
L.282	28.8	22.5	39.0	8.0	1.2	-	0.5	54
L.222	27.7	23.9	37.0	7.6	3.7	-	0.2	36
L.69	34.8	9.7	40.3	12.2	1.4	1.3	0.3	36
L.248	35.2	30.2	29.5	4.8	-	-	0.3	36
L.194*	48.0	3.0	44.8	3.0	-	-	1.2	29
L.80	33.6	16.6	39.0	9.6	1.0	-	0.2	36
L.85	34.3	17.2	43.1	5.4	-	-	0.1	36

* 800 counts

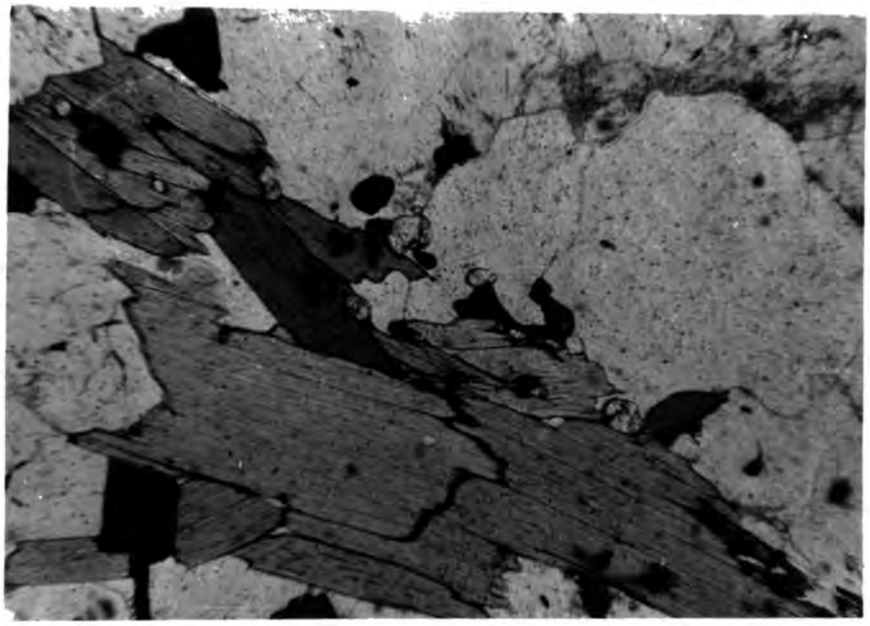
All other specimens 1000 counts

brown. Muscovite is associated with biotite or with heavily altered plagioclase. Fresh, grid-twinned microcline occurs as small anhedral interstitial grains in which perthites were not found. Grains of magnetite occur, often showing a good degree of rounding, and a group of grains is concentrated on a single foliation plane. Rounded apatites and zircons are common. The mode of this rock appears in table 1.

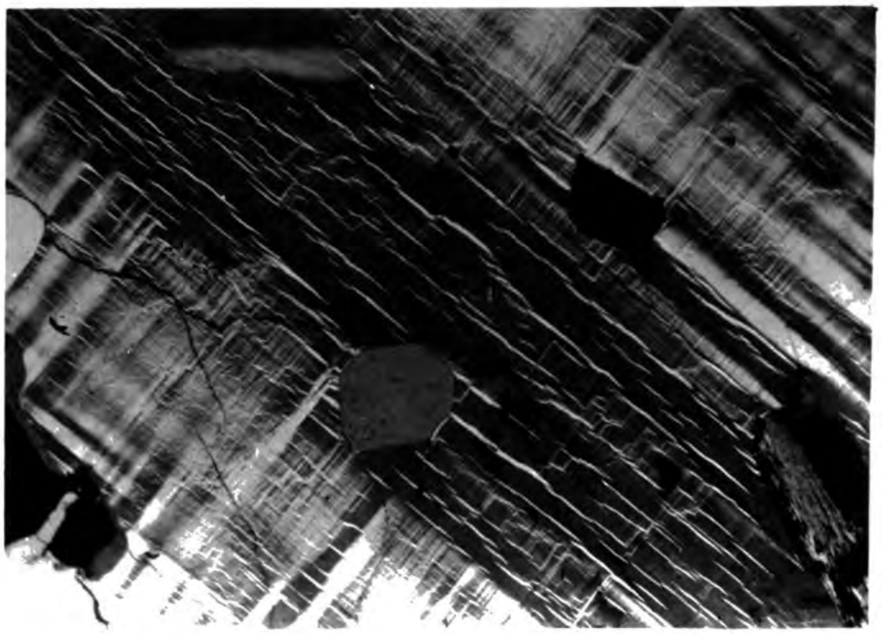
Specimen L.276 was collected 400 m. north of Mörk Vann (198 192). This rock is a coarsely crystalline garnetiferous gneiss with a tendency to development of feldspar 'augen'. In thin section the major minerals are seen to be plagioclase, quartz, microcline and biotite. Accessory minerals are garnet, amphibole, orthite, zircon, apatite, chlorite, and sphene. The texture is holocrystalline, inequigranular, granoblastic. Plagioclase (An_{20}) occurs in anhedral grains up to 2 mm. in diameter. Deformation polysynthetic twinning is common, as are perfectly rounded inclusions of quartz. The degree of alteration of the plagioclase is highly variable, but all the crystals show some sign of sericitisation. Myrmekite is common where plagioclase and microcline are in contact. Fresh microcline occurs in anhedral grains up to 6 mm. across and is grid twinned. Fine to coarse film perthite is variably developed in some grains, and in places there is incipient development of flame perthite, usually in close association with corroded plagioclase grains or with plagioclase inclusions. Quartz takes the form of rounded inclusions and anhedral grains up to 6 mm. in diameter most of which are crushed while others do not show any undulation in their extinction. Biotite tends to occur in clots and aggregates of ragged laths, some of which are slightly chloritised. It is pleochroic according to the scheme X: pale yellow, Y and Z: dark reddish brown. Anhedral amphibole (X: light yellow, Y: brownish yellow, Z: dark brownish green) is much subordinate to biotite with which it is closely associated. Garnet occurs in pinkish seive textured grains up to 1 cm. across. Pl. 2 illustrates the way in which rounded apatites and zircons and anhedral sphenes are concentrated at the sharper junction between layers of femic and felsic minerals. This distribution is strongly reminiscent of the concentration of heavy accessory minerals commonly observed in clastic sedimentary rocks. The mode of this rock appears in table 1.

Specimen L.146 is a rock found within 5 m. of the granite gneiss contact at Bekkeviken (252 204). In hand specimen it is light grey, fairly coarse grained, well foliated gneiss. The colour index is low, and there is no readily discernable lineation. In thin section the essential minerals are plagioclase, quartz and microcline. Present as accessories are biotite, sphene, amphibole, epidote, sericite, zircon, apatite, chlorite, and calcite. The texture is markedly inequigranular and granoblastic. Quartz displays a variations in grain size from tiny rounded and xenomorphic grains to sub-rounded and flattened grains over 10 mm. across. Both interlocking and sutured boundaries between quartzes are seen. Extinction in most of the larger grains is in distinct patches, indicating that the grain has been crushed almost to the point of disintegration. Microcline is present as isolated anhedral interstitial grains, and as aggregates of roughly equidimensional 5 mm. grains. Grid twinning is universally developed and perthites, which include coarse to fine film perthite, patch perthite, and flame perthite, are not uncommon. Pockets and screens of altered plagioclase are frequently seen between potash feldspar grains. The plagioclase is oligoclase ranging in composition from An_{20} to An_{25}. Polysynthetic twinning, in some cases strain induced, is common. Many of the oligoclases are extensively altered to an indefinite aggregate of sericite-epidote group minerals. Rounded quartz inclusions are again a feature of both types of feldspar. Green pleochroic amphibole with the optical properties of hastingsite (see p. 12) predominates over biotite, the two minerals occurring in close association in clots and streaks paralleling the foliation. In part the biotite (X: pale yellow, Y and Z: dark greenish brown) appears to be replacing the amphibole, and is itself slightly chloritised. Apatite and zircon occur in well rounded grains, and these minerals, together with the abundant sphene and epidote, are almost exclusively found in close association with the ferro-magnesian minerals. Pl. 3 shows the way in which rounded accessory minerals are concentrated at the sharper junction between layers of ferro-magnesian and felsic minerals, this arrangement being strongly suggestive of a palimpsest sedimentary segregation. Calcite occurs mainly as infilling of fractures and may have been a late introduction to the rock. The mode of this rock is presented in table 1.

All of the granite gneisses examined display textures which are granoblastic to cataclastic; in no cases have granitic textures been encountered. The rocks are foliated to a greater or lesser extent, the extreme case being represented by augen gneisses, and



Pl. 3. Photomicrograph of L.146, showing rounded accessory apatites and zircons concentrated at the junction between mafic and felsic layers in the granitic gneiss. x 40. Ordinary light.



Pl. 4. Photomicrograph of L.63, showing the inverse relationship between the coarseness of the film perthite and twinning in the microcline host. x 40. Crossed nicols.

many show a well developed lineation caused by preferred mineral orientation. In rare cases, usually in the hinge zones of major folds, a linear structure is dominant over an ill-defined planar structure.

In thin section there is abundant evidence for cataclasis and shearing. Quartz has frequently recrystallised, as indicated by sutured boundaries and trails of quartz granules through larger quartz individuals, and exhibits every variation between crushed granules and large, practically unstrained, grains. Discontinuous polysynthetic twinning in plagioclase and bent and streaked out biotite laths likewise appear to be the result of deformation.

Two kinds of potash feldspar are in evidence in many sections: anhedral interstitial microcline in the ground mass which appears generally to be non-perthitic but may be sub-microscopically perthitic, and relatively coarse-grained interlocking crystals of microcline not infrequently showing one or more types of perthitic intergrowths. Particularly in the augen gneisses, these latter aggregates of microclines appear to have resulted from the granulation of a larger porphyroblast.

Grid-twinning is universal in the potash feldspars and the Carlsbad twins of orthoclase have not been seen in any sections.

Pl. 4 illustrates a textural feature which is widespread in these rocks, namely, the inverse relationship which exists between the development of grid-twinning and coarse film perthite. Fine film perthite is confined to areas in individual microclines where the twinning is complex, while coarse perthites are developed where the twins are very broad or absent. Oriented inclusions of sub-hedral plagioclase in microcline which may be indicative of porphyroblastesis (Smithson, 1963) have not been found.

Antiperthitic plagioclases are rare, and zoned plagioclase have not been observed. Also, a variation in the anorthite content of the different plagioclases of a single specimen is common.

Accessory minerals, particularly apatite and zircon, are almost always well rounded, and pl. 1 shows the typical occurrence of rounded quartz and plagioclase grains as inclusions. These textural features, together with the considerable variation in grain size in a rock of a single mineral species, and the frequent distribution of heavy accessory minerals in thin continuous bands in association with ferro-magnesian minerals, (pl. 2), are strongly suggestive of palimpsest sedimentary textures and structures.

THE COMPOSITION OF THE LEVANG GRANITE GNEISS

None of the felsic gneisses constituting the Levang granite is a 'granite' sensu stricto. In fig. 4, 17 modal analyses have been plotted on a quartz-plagioclase-microcline diagram incorporating a compositional classification for granitic rocks which is slightly modified after Bateman (1961). On Bateman's original diagram the upper limit for quartz content was put at 50%. Chayes (1952) states that in granites sensu stricto a quartz content of more than 45% is almost never recorded, and values in

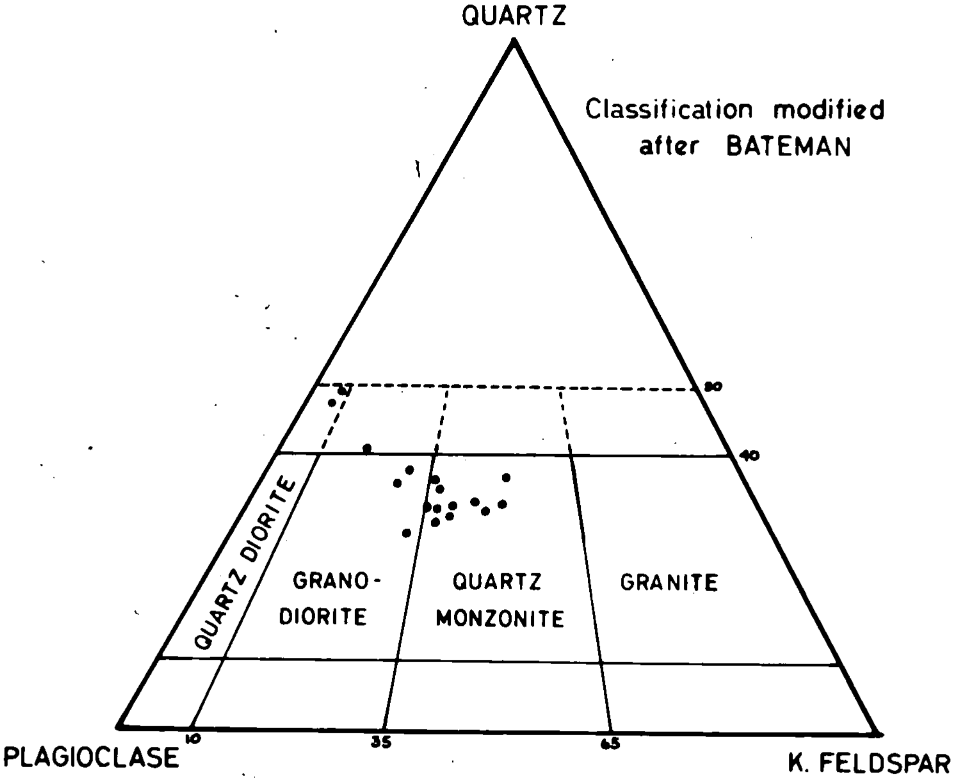
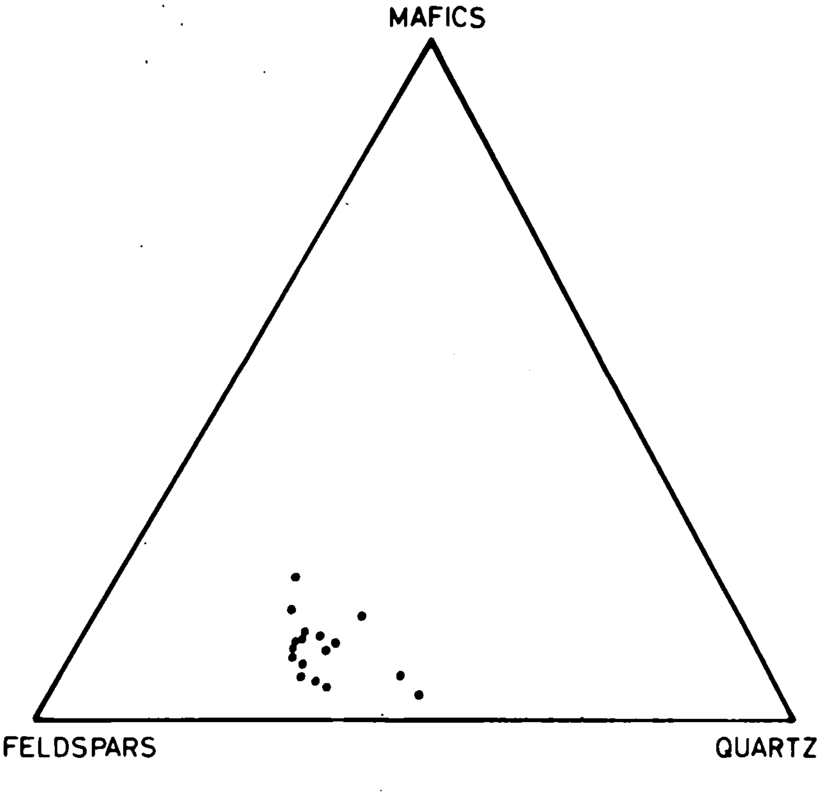


FIG. 4 - LEVANG GRANITE MODAL ANALYSES



excess of only 40% are rare. In general Chayes believes that where values greater than 40% are observed an igneous origin is to be viewed with great scepticism. In fig. 4 the upper limit for quartz is at 40%.

The mineralogy of the Levang rocks varies, in the main, between fairly narrow limits, and on the basis of their quartz and feldspar content most of the gneisses could be classified as quartz-monzonites. The overall range is from quartz-monzonitic, through granodioritic, to a rock approaching a quartz-diorite.

The analyses which plot close to the upper limit of Bateman's field for quartz diorite (though outside that of Chayes) are for specimens L.194 (described above) and L.132. These rocks are from the central part of the doubly plunging structure, in the north western part of the area, termed the Heligesvann antiform. They are representative of a large and very well defined area of gneisses, of quite uniform composition, in which the quartz content is abnormally high, mafics very low, and microcline present in only accessory amounts. Surrounding these gneisses is an unbroken sheet of foliated amphibolite averaging some 70 m. in thickness. The foliation in this sheet parallels that of the felsic gneisses. Immediately overlying the amphibolite is a broad zone of relatively coarse grained, garnetiferous, 'granite' gneiss, 300 m. thick. Specimen L.276 (p.14) was collected in this zone. Compared to the central gneisses, the plagioclase and especially the quartz contents are substantially lower, and microcline accounts for about 25% by volume of these rocks. Between the limits of this garnetiferous gneiss and the contact to the north, a lighter grey, non-garnetiferous, gneiss, 400 to 450 m. thick, is exposed. The central Heligesvann rocks excepted, the general tendency in the Levang granite is for the sub-central gneisses to be more mafic, poorer in potash feldspar, and much more frequently garnetiferous than the felsic gneisses exposed in a zone closer to the contact. Specimen L.146 (p. 15) is illustrative of the typical border 'facies' of these granitic gneisses.

The distribution of rock types in the Levang granite is believed to be primarily the result of the inheritance of a 'ghost' stratigraphy from a pre-existing supracrustal sequence of variable rock types, this 'ghost' stratigraphy being particularly clearly exemplified by the gneisses in the Heligesvann area.

The majority of the felsic gneisses which have been modally analysed are found to correspond closely with the minimum melting composition for the granite system. (Bowen, 1950).

THE PEGMATITES

Pegmatites occur extensively throughout the area, and range in size from small pods a few centimetres in diameter to very large masses, the largest, on Langholmen, measuring 600 m. long by 100 m. wide. With the exception of allanite bearing pegmatites which are not uncommon, rare earth pegmatites of the type found in the Kragerö to Langesund region to the north have not been observed.

The pegmatites may be broadly divided into two main types:

(1) Irregular or tabular shaped bodies, generally of approximately granitic composition, emplaced in all the exposed rock types from orthoquartzites to amphibolites.

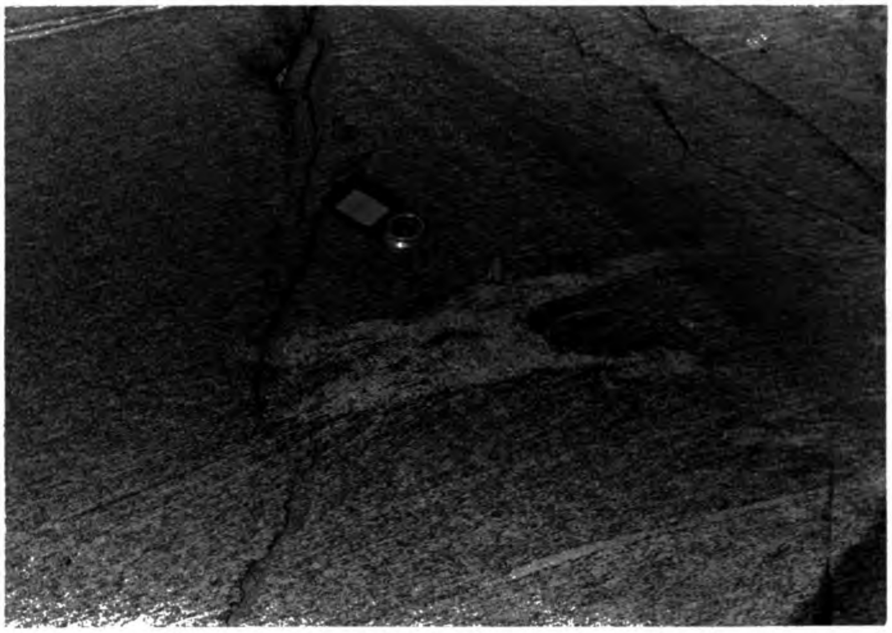
(2) Small lens or pod shaped bodies, termed secretion pegmatites, which are closely related mineralogically to the host rock, usually comprising to a large extent the felsic components of the latter.

A further sub-division of the type (1) pegmatites is possible. Early, more or less conformable stringers and lenses of granitic pegmatite have been intruded into the migmatites, and have undergone deformation and folding. These are synkinematic pegmatites. Later, frequently discordant and dilatational pegmatites, are massive and commonly show only slight signs of deformation. These are the late to post-kinematic pegmatites. Lastly, at a very late stage in the geological evolution of the area, infilling of fractures by quartz-calcite material has taken place, these being rated as pegmatites by virtue of their grain size.

Pl. 5 shows early synkinematic pegmatites being cut by a tabular undeformed granite pegmatite in the migmatites at the eastern end of the Portör peninsula.

Also exposed near Portör is the pod shaped secretion pegmatite in granodioritic gneiss shown in pl. 6. The foliation in the gneiss in the region of the pegmatite displays "surreitic structure" (Holmquist, 1920) which Hofseth (1942) states "indicates that a 'lateral secretion' has taken place from the adjacent rocks. By molecular interchange the pegmatitic material was removed from the rocks and the dark minerals were arranged in directions resembling power lines around a magnetic field". Sec-

Pl. 5. Early synkinematic pegmatites cut by a tabular undeformed pegmatite in the migmatites at Portör.



Pl. 6. A pod shaped secretion pegmatite formed in granodioritic gneiss exposed near Portor, displaying 'surreitic texture'.

retion pegmatites comprising calcic plagioclase and quartz are particularly common in some of the amphibolites.

The late kinematic pegmatites sometimes show a degree of structural control in their emplacement, and are to be found on faults, fractures, and associated with boudinaged amphibolite layers. Certain definite directions of emplacement predominate for the structurally controlled pegmatites of the Flå area, (Smithson, 1963) but no clearly defined preferred orientation has been noted on Levang. The usual paragenesis for this type of pegmatite is microcline, plagioclase (An_{10} to An_{20}), quartz and biotite. Tourmaline, allanite, and magnetite have been found in accessory amounts. In some graphic granite pegmatites, for example at Stölestranden (288 197), the plagioclase content is very low or nil. That some of the post kinematic pegmatites were emplaced passively is shown by the fact that enclosed blocks of gneiss show no sign of rotation. On the other hand the disturbed strike and dip of the foliation of the gneisses into which the large Langholmen pegmatite is emplaced clearly demonstrates forceful intrusion.

Concordant bodies of anthophyllite gneiss in which individual crystals attain pegmatitic proportions are discussed under a separate heading (see p. 114).

Hofseth (1942) was of the opinion that "the quantity of pegmatite is evenly distributed over a great area and does not increase noticeably near the granite." The present mapping would seem to indicate that there is a tendency towards a concentration of major pegmatites in the granitic and basic gneisses in the immediate vicinity of the contact. Another marked concentration of pegmatitic material occurs at the level of the 'marker horizon' amphibolite in the Heligesvann antiform (see p. 62). In both cases it is suggested that the basic amphibolites formed a physical and chemical barrier to ascending pegmatitic fluids, which were thus concentrated at these levels.

FELDSPAR STUDIES

The Temperature of Formation of the Granite Gneiss

Barth, (1960), has developed a geothermometer based upon the distribution coefficient of albite between co-existing plagioclase and potash feldspars, crystallising under equilibrium conditions. This distribution constant, k, is given by:

$$k(T,P) = \frac{\text{Mol fraction of albite in alkali feldspar}}{\text{Mol fraction of albite in plagioclase}}$$

A temperature graph has been determined by correlating the k values with empirically determined temperatures (Barth, op. cit., p. 15). In order that the graph should be applicable, the two feldspar phases must have crystallised under equilibrium conditions at constant temperature, pressure, and chemical composition.

The compositions of the plagioclases in the Levang rocks were determined in two ways: by measurement of the extinction angle of albite polysynthetic twins on (010) in sections perpendicular to (010) on a five axis universal stage, and by measurement of the α refractive index on (001) cleavage fragments using the immersion method.

The compositions of the potash feldspars were determined by a method developed by Orville (1960). The position of the $\bar{2}01$ reflection is variable according to the plagioclase content of the perthitic potash phase. It is also, however, dependent upon the degree of ordering of the Al and Si atoms in the lattice, and for this reason the obliquity (triclinicity) of the potash feldspar must also be known. The compositional range through which the degree of ordering deflects the determinative curve (Orville, 1960) is about five parts plagioclase, between the limits of maximum and minimum triclinicity. The presence of perthite may give rise to anomalous results for the ($\bar{2}01$) spacing (Laves, 1950). This problem is solved by keeping all the samples at a temperature of 1025°C. for 48 hours, thus homogenizing the perthites.

Smithson, (1963), in determinations of the bulk compositions of potash feldspars from the Flå area, checked by chemical analyses the results obtained from X-ray patterns. The twenty perthite samples involved ranged in composition from Ab_{10} to Ab_{30}. The mean difference between the X-ray determination and the chemical analysis was found to be +1.0 part plagioclase, and the standard deviation 1.14. The negative bias of the chemical analyses is explained by the fact that this method determines the Na_2O and K_2O contents, while the X-ray determination is for total plagioclase.

The results obtained for 23 Levang gneisses and pegmatites are presented in table 2. The range in composition of the potash

TABLE 2

COMPOSITION OF FELDSPARS FROM GRANITIC GNEISSES AND PEGMATITES

Specimen number	Alkali Feldspar Parts Plagioclase	Plagioclase Parts Albite	K
L.75a	13	77	.17
L.83	11	75	.15
L.212	17	72	.24
L.260	17	78	.22
L.175	16	73	.22
L.87	14	76	.18
L.240	15	76	.20
L.146	12	78	.15
L.141	15	80	.19
L.130	18	75	.24
L.137	16	78	.21
L.63	13	84	.15
L.201	15	80	.19
L.36	19	74	.26
L.222	12	79	.15
L.69	13	80	.16
L.101*	19	76	.25
L.126*	12	70	.17
L.219*	13	68	.19
L.3*	16	80	.20
L.93*	17	70	.24
L.117'	15	-	-
L.118'	14	-	-

* Specimen from the Portör Peninsula

' Pegmatites

feldspar is from 11 to 19% plagioclase, while the albite content of the co-existing plagioclases varies between Ab_{84} and Ab_{68}.

Barth's geothermometer has recently been criticized on a number of grounds; in particular the fact that no account is taken of the possible influence on the distribution coefficient of the total soda content of the rock, its geological history, and the grain size of the minerals involved (Dietrich, 1960). Recent work has shown (Smithson, 1963) that grain size does not appear to have any direct bearing on the amount of plagioclase taken up by the potash feldspar. However, Smithson (op. cit.), demonstrated clearly that in the rocks of the Flå area considerable variation in the plagioclase content of the microcline could occur in different grains in a single hand specimen, irrespective of their grain size. The markedly variable perthite content of the potash feldspars of many of the Levang gneisses has already been noted.

Fig. 5 indicates the possible range of k values which could be produced by the feldspars in the Levang granite gneisses, and illustrates the impracticability of applying the geothermometer to the rocks of this area. Variability in the composition of both the plagioclase and microcline in a single hand specimen results in a purely arbitrary figure for the k value. Furthermore, from petrographical evidence it seems probable that some of the perthite has originated by replacement, and this would also preclude the use of the geothermometer on these rocks.

On the evidence of the feldspars, it appears that the Levang granite, far from crystallising at constant temperature and pressure, has been subjected to variable pressure-temperature conditions

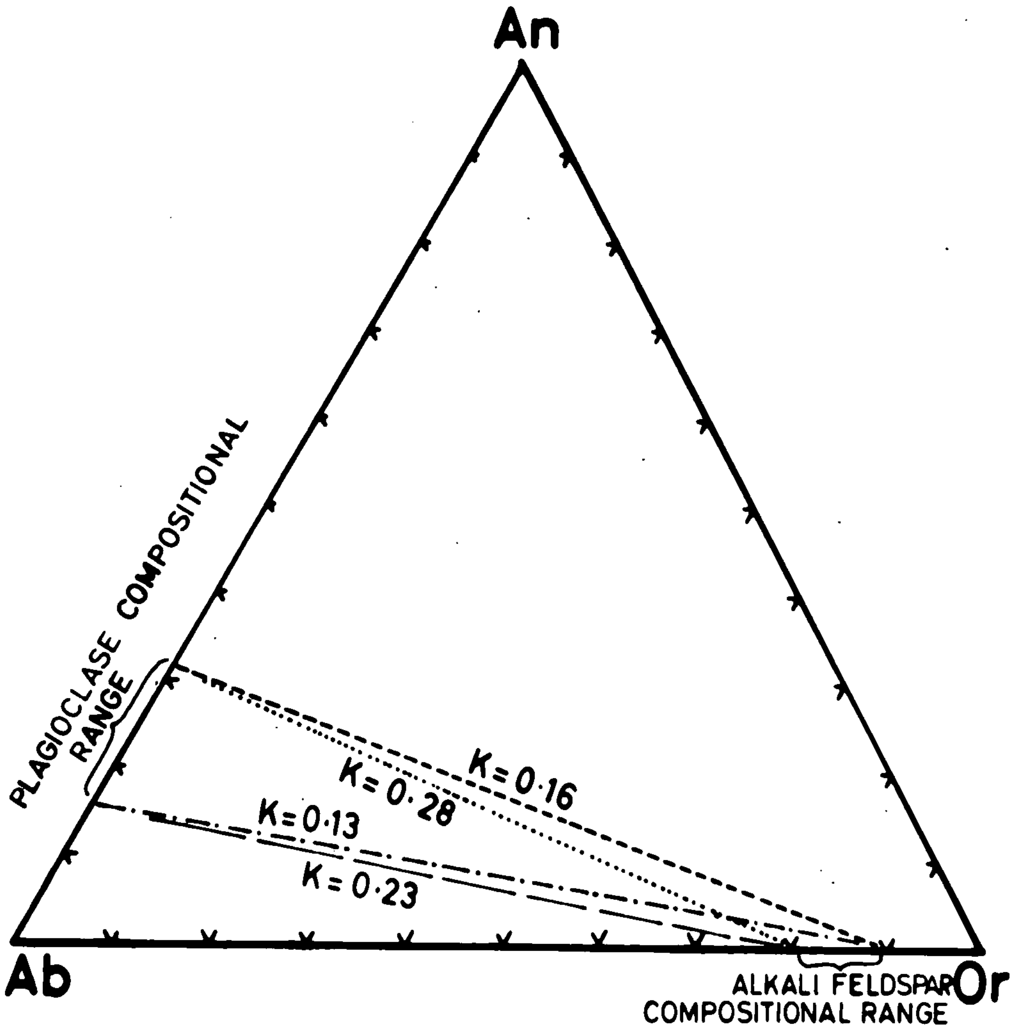


FIG. 5 APPROXIMATE COMPOSITIONS OF FELDSPARS FROM THE SAME ROCK. TIE-LINES REPRESENT SOME OF THE POSSIBLE K VALUES WHICH COULD RESULT.

and also, possibly, bulk composition.

The Symmetry Relations of the Potash Feldspars

A number of studies have recently been carried out on the symmetry relations, or degree of ordering, of potash feldspars, in relation to, for example, regional metamorphic gradients, thermal metamorphism and igneous intrusion, (Heier, 1957, 1960; Rao, 1960; Emerson, 1960; Smithson, 1963; Parsons, 1963).

Two techniques were employed during the investigation of the Levang potash feldspars. A number of samples were run using the powder method on a Guinier-Nonius quadruple camera, the powder films which this machine produced being measured after enlargement onto a screen using a 35 mm. projector. The precision of this method is 0.03 units. The remainder of the feldspar samples were run on a Philips wide angle diffractometer, and in addition a number of the samples originally run on the Guinier powder camera were run again on the diffractometer in order to cross check the results. Smear mounts were used on the diffractometer, and the traces were run using $CuK\alpha$ radiation. The traces from the diffractometer were measured using a vernier to an accuracy of $\pm 0.005^\circ$ 2θ. The oscillator mechanism on the diffractometer was used with every trace, so that all of the data quoted represent the means of not less than two measurements. The mid point approximately two thirds of the way up the limbs of symmetrical peaks was recorded as the 2θ value for that peak, while with asymmetrical peaks the top of the peak was used.

The specimens collected during field work supplied the samples of potash feldspar which were X-rayed. The feldspars from 36 rocks were investigated; 26 samples were run on the Guinier powder camera, of these 21 were run a second time on the Diffractometer, together with the remaining 10 samples. The potash feldspars were hand picked, so that most of the samples are from porphyroblasts and megacrysts.

On the basis of the degree of ordering in the distribution of aluminium and silicon in the lattice, the potash feldspars are divided into three varieties, viz., sanidine (completely disordered, monoclinic), orthoclase (partly ordered, monoclinic), and microcline (fully ordered, triclinic), (Barth, 1959). All transitions exist between these three phases. Completely ordered sanidine is stable at elevated temperatures, and on cooling the symmetry requirements make it pass into a partly ordered orthoclase. Ordered triclinic microcline is stable at low temperatures (Barth, op. cit.). X-ray studies have shown that several single reflections in monoclinic potash feldspars are represented by a double reflection in triclinic types. The degree of separation of these 'doublets' gives an indication of the triclinicity or obliquity of the potash phase. Doublets which can be employed are $111/1\bar{1}1$, $130/1\bar{3}0$, and $131/1\bar{3}1$, but it is the separation of the $131/1\bar{3}1$ doublet which Goldsmith and Laves (1954) have defined as a measure of the triclinicity. The spacing of $131/1\bar{3}1$ is termed Δ, where $\Delta = 0.0$ in monoclinic feldspar, and $\Delta = 1.0$ in triclinic feldspar. As a measure of Al/Si order-disorder, Δ may assume any value between 0.0 and 1.0.

The triclinicity determinations are presented in table 3. All of the potash feldspars from the granite gneiss, and from several of the granitic gneisses and migmatites exposed south of the main granite mass, have been found to be more or less maximum microcline. Fig 6A shows the locations of the specimens for which Δ has been determined. Fig 6B illustrates the lack of any correlation between the degree of ordering of the microclines and their positions within the granite mass. Nilssen (1961) has likewise recorded potash feldspars which are predominantly maximum microcline from the Herefoss granite in the Telemark-Bamble area south west of Levang. These observations are in contrast to those of Smithson (1963) on the feldspars of the Flå granite, where the majority of the potash feldspars are near maximum microcline, but rocks from the contact zone are occasionally found to contain feldspars displaying medium or low obliquity. The lack of ordering of the potash feldspars from the contact zone Smithson (op. cit.) believes to be connected with a potash metasomatism at the granite contact.

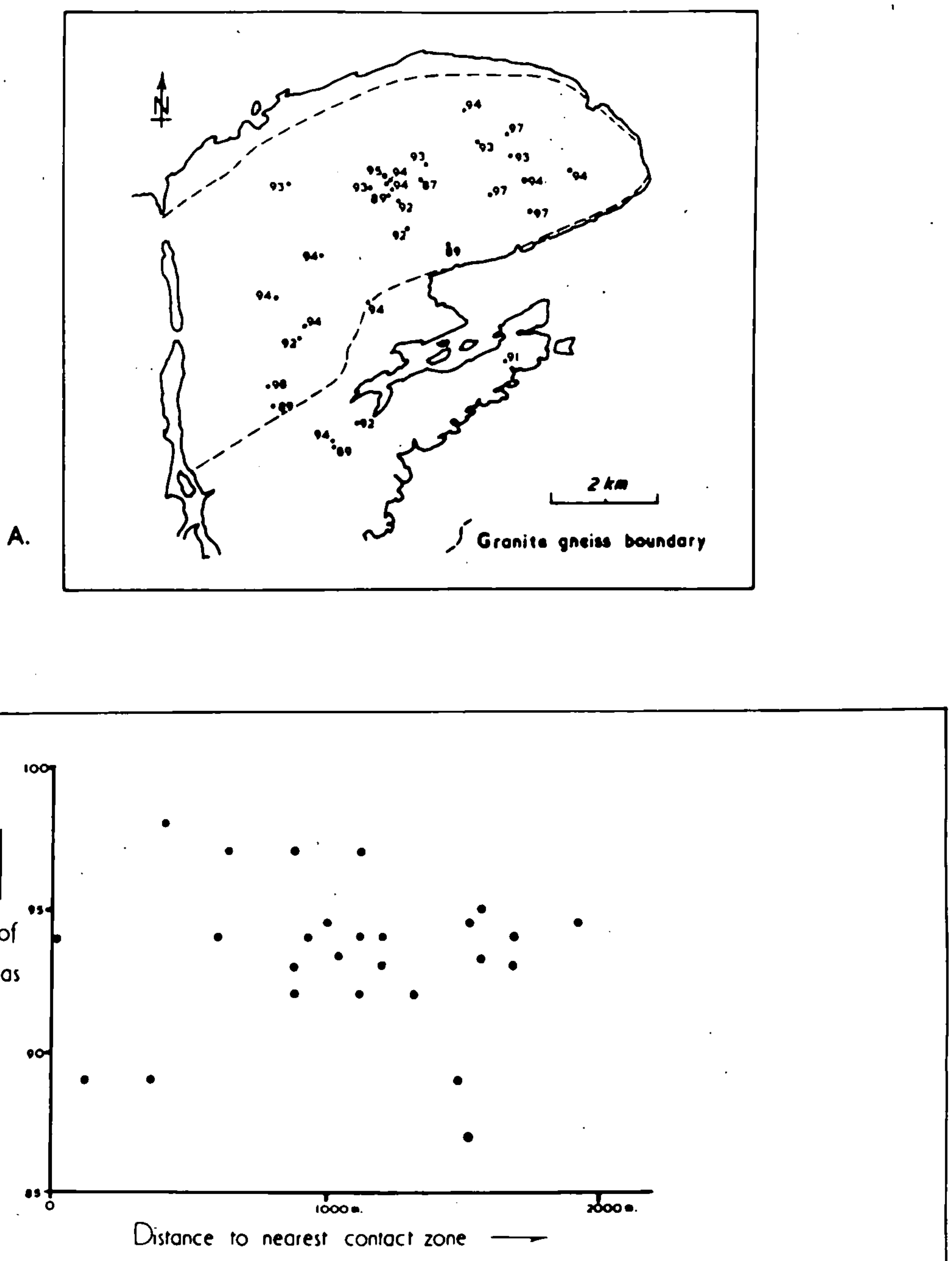
The temperature of formation of the granite gneisses cannot be determined from the compositions of the feldspars, but the relatively low plagioclase content of the alkali feldspars is, nevertheless, suggestive of formation at fairly low temperatures. (Smithson, op. cit). Since no varieties displaying medium or low obliquities have been found, the potash feldspars have not provided positive evidence for the existence of an earlier high temperature form. This, together with the fact that alkali feldspars may form metastably anyway, (Goldsmith and Laves, 1954),

TABLE 3

POTASH FELDSPARS - TRICLINICITY DETERMINATIONS

Specimen number	Δ Guinier	Δ Diffractometer	Mean value
L.3*	0.92	0.93	0.925
L.36	0.94		-
L.74	0.92	0.92	0.92
L.211	0.94	0.95	0.945
L.238	0.94	0.93	0.935
L.257	0.94	0.95	0.945
L.262	0.92	0.93	0.925
L.198	0.94	0.95	0.945
L.222	0.94	0.94	0.94
L.246	0.92	-	-
L.280	0.97	0.97	0.97
L.200	0.94	-	-
L.215*	0.89	0.90	0.895
L.225	0.92	0.93	0.925
L.183	0.94	0.99	0.965
L.212	0.89	-	-
L.255	0.94	0.95	0.945
L.266	0.87	0.85	0.86
L.189	0.89	0.89	0.89
L.214*	0.94	-	-
L.240	0.94	0.93	0.935
L.249	0.92	0.96	0.94
L.173	0.97	0.99	0.98
L.177	0.94	0.98	0.96
L.252	0.94	0.96	0.95
L.175	-	0.89	-
L.141	-	0.94	-
L.201	-	0.95	-
L.94*	-	0.90	-
L.67	-	0.97	-
L.137	-	0.97	-
L.69	-	0.93	-
L.356	-	0.93	-
L.23.9.2	-	0.96	-
L.357	-	0.95	-
L.226	0.92	0.93	0.925

* Specimen from the Portör Peninsula



ILLUSTRATING THE RELATIONSHIP BETWEEN THE DEGREE OF ORDERING IN THE MICROCLINES AND THE POSITION WITHIN THE LEVANG GRANITE-GNEISS

FIG.6

precludes the possibility, on the basis of these feldspar studies, of definite conclusions as to the origin of the granite through either magmatic or non-magmatic processes.

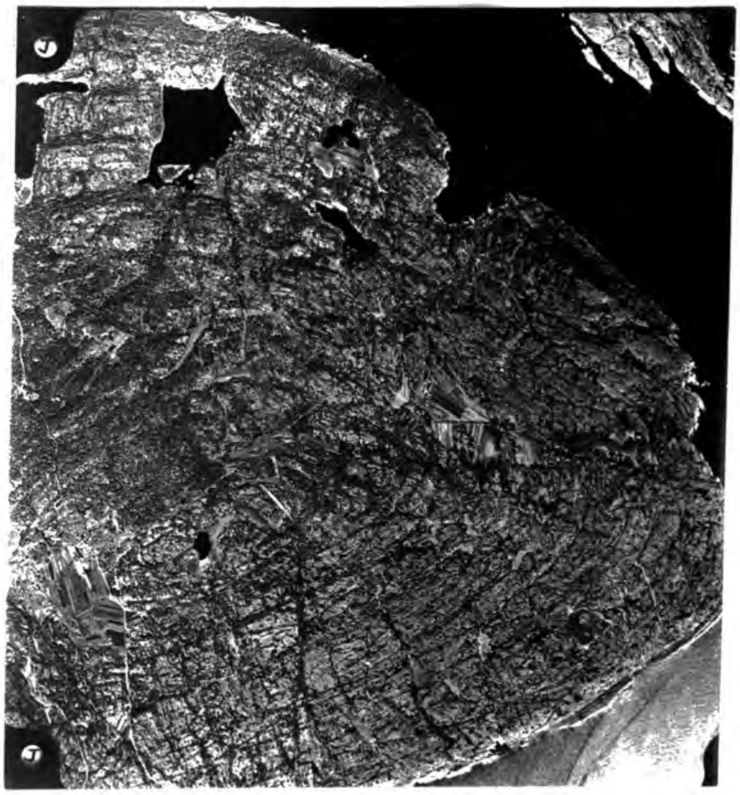
THE FAULT AND JOINT PATTERN

Introduction

The aerial photographs of the Levang Peninsula show a complex pattern of linear features, some of which are extremely prominent, e.g. the long line of the two lakes Eidsvann and Leivann in the west. A number of possible causes are suggested for these topographic features. They could be caused by foliation, faults, joints, or dykes. In the area studied, the vast majority can be accounted for by the first three, and where a dyke is seen to give rise to a pronounced feature it has, in the cases examined, been intruded along a prominent fracture or fault direction. Glacial erosion has undoubtedly accentuated many of these features, but none which could be attributed solely to the action of ice were seen on the scale of the aerial photographs. Plate 7 is an aerial view of the eastern part of the peninsula, and shows very well the strong features formed by the foliation as it is bent around the nose of the dome, and cross-cutting, generally rectilinear, fractures and faults are also very much in evidence.

The Fault Pattern

It proved frequently to be the case that features on the



Pl. 7. Aerial photograph of the eastern part of the Levang peninsula, showing the gneissic foliation and the fault and joint pattern clearly expressed in the topographic features.

Pl. 8. Late stage minor faulting in the banded gneisses on the coast between Bekkeviken and Lyrstrand.

photographs which were strong enough to suggest major lines of faulting and displacement could not, in the field, be identified with any such phenomena. The very prominent feature which defines the southern side of Finsbudalen is almost certainly a major fault, (and it has been marked as such on a structural map compiled by Elders (1961)), but since it has a bearing of 070°, exactly parallel to the strike of the steeply dipping gneisses of that region, no displacement could be seen. It may be significant that pegmatites are exceptionally abundant along this line.

Of the many possible lines of displacement traversing the area, few have been recognized as actual faults. 500m. north west of Stölestranden a sub-vertical dislocation which is marked by a narrow zone of brecciation can be traced for 350m., trending 013°. The deformation of the strongly foliated granitic gneiss adjacent to the fault indicates a sinistral displacement, at least in the final stages of movement, but the amount could not be determined. A similar zone of brecciation was mapped in a short section of a second fault which forms a feature over 600m. in length, trending 015°, just west of Kapelen, (217 204). A fault throwing sinistrally some 20m.+ is responsible for the displacement to the south of the granite gneiss - amphibolite contact on the west side of Myrstranden. All these are presumed high angle faults, but at Strömtangen Fyr, (268 222), a fault breccia which dips at a shallow angle, ca. 30°, is exposed at the base of a cliff of granitic gneiss very close to the main contact.

In addition, a large number of small scale displacements have been mapped throughout the area, none of which result in features visible on the aerial photographs. These are of two types, viz. those of probably pre-Cambrian age which show horizontal displacements of the order of 5 to 10 m., and have generally been pegmatized, and secondly very small scale fracturing and displacement representing a late-stage shattering without cementation, in which movements of only a few centimetres have occurred. Many of these late fractures have been filled by a calcite-quartz-limonite deposit of hydrothermal type. Since the fracturing is seen to affect the diabase dykes of ?Permian age, it could have taken place at any time during the Mesozoic or Tertiary, possibly in response to the removal of the Cambro-Silurian cover. Pl. 8 shows two such fractures in the banded gneisses of the coast at Myrstrand, the larger displaces the gneisses 40 cm. sinistrally, the other 8 cm. dextrally. Calcite which formerly filled the larger open fracture has been leached out to a depth of several centimetres below the surface.

The Joint Pattern

Joints are well developed throughout the mapped area. Hofseth, (1942) noted the presence of prominent north - south trending and sub-horizontal "cleavages" (i.e. joints) in the granite gneiss, and adds, "Balk, (1937), mentions that if an eruptive body has a flat roof, the pressure of the overlying rock, different from the pressure farther down, may cause this to split up horizontally, and that differences in temperature during the consolidation may also give such results."

The present study of the joint pattern is not a detailed one. It involved the selection of a total of 15 small areas in which the jointing appeared to be particularly well developed and exposed, the attitude of every joint then being recorded. The readings are presented in fig. 7.

In the contoured stereogram fig. 7A, all the measurements from the nine widely separated stations within the granite gneiss are combined, and in fig. 7B, the readings from joints in the banded gneisses are presented. Fig. 7C shows the locations of the 15 stations.

It will be seen that within the granite gneiss as a whole there are four dominant joint directions making up the pattern. Best developed is a roughly north - south trending set of vertical joints. Sub-horizontal joints with a general tendency towards a shallow easterly dip make up the next strongest maximum, followed by joints which trend close to 140° and dip 80° towards the north east. Lastly, a group of joints trends from 070 to 090°, dipping vertically or at steep angles towards the south.

The joint pattern from the area of banded gneisses produces only two strong maxima. These are for joints trending north - south, with a dip close to vertical, and for a second set trending from 120 to 140°, dipping vertically or at steep angles north eastwards. Sub-horizontal joints are developed, but they tend to be rather more variable in attitude than those from the granite gneiss, and do not form a strong maximum. It is probable that the flatter joints are more common than is indicated in the stereogram, but that they were not seen because exposures in the

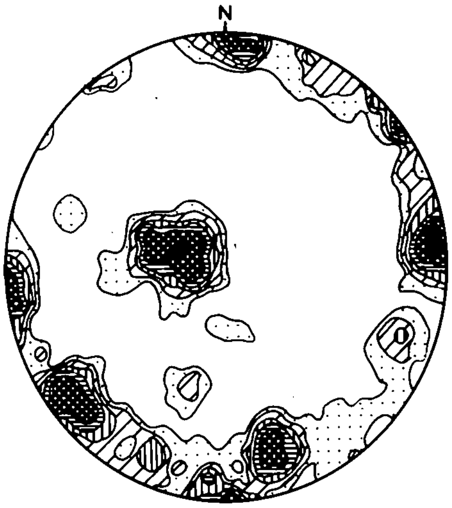
Fig. 7 The Joint Pattern

A. Contoured diagram for 185 readings on joints measured at nine stations within the granite gneiss.

B. Contoured diagram for 163 readings on joints measured at six stations in the banded gneisses.

C. Showing the locations of the stations.

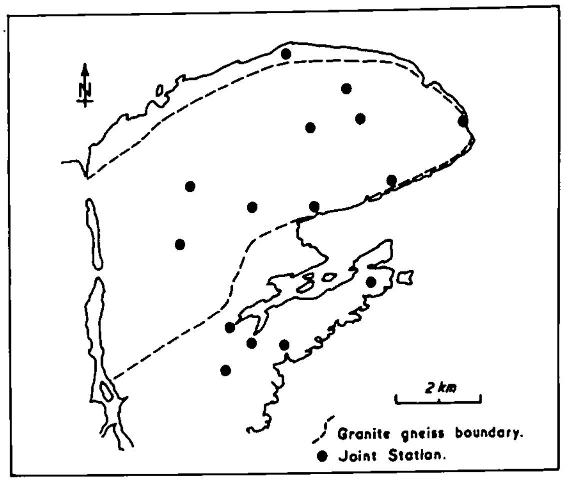
Contour intervals at 10-5-4-3-2 per cent per 1 per cent area. Schmidt equal area net, lower hemisphere.



A.

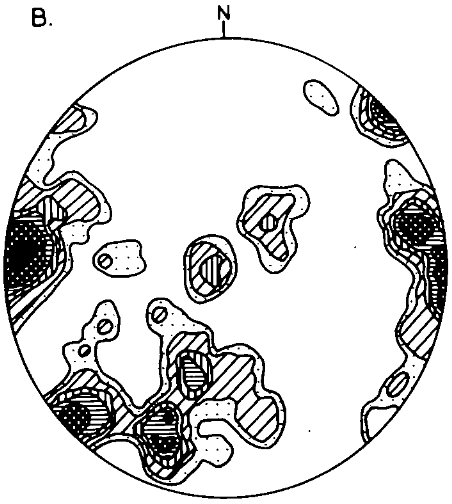
185 Readings

JOINT PATTERN - LEVANG.



C.

B.



163 Readings

Levang - Portör region are invariably of only very short vertical extent.

The essential differences between the joint patterns are the absence, in the banded gneisses, of a set of joints trending 070 to 090°, and the relatively poor development of sub-horizontal joints.

Throughout the area from which readings on joints were taken in the banded gneisses, the foliation strikes 070 to 080°, and dips vertically or steeply towards the north, and it is evident that it is the joint set most nearly parallel to this direction which is not developed. Smithson, (1963), mentions that in the Flå area the joint pattern developed in the granite persists into the surrounding gneisses, except that the joint most closely paralleling the foliation is poorly developed or missing in many places. The Levang granite gneiss is also strongly foliated, and examination of the joint measurements from individual stations reveals that here also the joint set which trends closest to the local foliation is rarely well developed.

With regard to the flatter lying joints, Berthelsen (1960) finds that sheet joints are most highly developed in the migmatitic rocks, where granitization has a tendency to homogenization. In the Tovqussaq area, sheet joints are strongly developed in the comparatively homogeneous gneiss granites although absent from the surrounding amphibolites. Berthelsen accepts the theory that sheet joints have been formed by expansion after the removal of the overlying rocks, but believes that the original set up may, however, have originated from tensions following cooling after granitization.

Neglecting the sub-horizontal joints as probably being essentially late-stage phenomena having no direct connection with the Pre-Cambrian tectonic evolution of the region, the joint pattern for the area as a whole may be summarised as follows:

(1) A set of vertical joints trending 175°.

(2) A set of joints trending 135 to 140°, which are vertical or dip steeply north eastwards.

(3) A set of joints trending 070 to 090°, dipping vertically or steeply towards the north.

Balk, (1937), recognizes four systems of primary fractures in an intrusive mass, all of which will have a definite orientation relative to the primary flow structure, where such is developed. Balk points out that in older granite bodies much of the very complex pattern of joints now observed was induced by mechanisms other than that of the original emplacement. Late differentiates of the granite, in particular pegmatites and aplites, filling fractures formed in the late stages of consolidation, aid in the identification of the latter, while those joints which have a coating of hydrothermal minerals may also be genetically related to the intrusion. In the Levang granite gneiss mass, however, classification of the joints is difficult since several phases of pegmatization and mineralization are in evidence.

The joint pattern from the granite gneiss mass does not display any characteristics which might be attributable to an origin for the joints through processes of intrusion and consolidation (in which case the observed foliation would be presumed to be primary flow structure). Also, a joint pattern developing within the granite gneiss in response to magmatic processes would not persist into the surrounding country rocks beyond the immediate margins of the body, nor would it bear any resemblance to that developed in the country rocks. It is, however, evident from the stereograms of the two joint patterns that there are no essential differences between them (bearing in mind the reason for the poor development of the set (3) joints in the banded gneisses). In all the major folds investigated within the granite gneiss, the axial planes are vertical or dip steeply towards the north. The set (3) joints are likewise vertical or dip steeply northwards, and they are interpreted as tensional fractures forming more-or-less parallel to the axial planes of the folds.

It is thus concluded that the conjugate set of joints is part of a regional pattern, developed in direct response to the deformation which gave rise to the major folds with roughly east north east - west south west trending axes.

THE FIELD RELATIONS OF THE LEVANG GRANITE GNEISS

Introduction

Brit Hofseth, (1942), in her paper on the geology of the Levang Peninsula, states with reference to the Levang granite gneiss that, "the boundary is sharp and runs straightly and evenly around the lens-shaped body," and also that, "the granite does not send out apophyses into the neighbouring rock, and in a few places only is the clear boundary disturbed by greater pegmatitic dykes." While these statements are broadly true, detailed examination of the 'contacts' has shown that they require qualification.

In the following account the terms 'contact' and 'contact zone' are not used with any genetic connotation, i.e. with regard to an eruptive origin for either or both of the rock types concerned, but are synonymous with 'limit' or 'boundary' for the Levang granite gneiss.

The aerial photographs of the area studied during the present investigation reveal the presence of a large area of light-weathering rocks, the boundary of which is sharply marked by an abrupt change in the amount of vegetative cover. The quartzose granite gneiss supports a relatively scanty vegetation, with large areas of bare rock, particularly in the north east, while the amphibolites and mica-schists immediately surrounding it have a relatively dense cover of conifers. Stereoscopic examination of the photographs reveals further that there is an abrupt change in relief at the granite gneiss boundary, the resistant granite gneiss forming a plateau-like block with steeply sloping margins. This feature is particularly well marked in the north and north west, since the granite gneiss forms, topographically, a tilted block inclined somewhat towards the south east. Thus, at Ørvik, (198 225), the granite gneiss plateau maintains a height of about 100 m. for a distance of over 1 km. south of the contact, while north of it the more easily eroded amphibolites, etc., fall to sea-level within 300m.

The regional trend of the foliation in the banded gneisses of the Bamble Formation is approximately 040°. This is also the trend of the long axis of the Levang granite gneiss, but at the north eastern extremity of the gneiss complex, folding terminates the granite gneiss in an antiformal culmination with a steeply plunging to 'overturned' axis, the foliation describing a closed arc around the Myre 'dome'.

With the exception of the region between Stölestranden, (228 197), and Hovet, (215 188), the attitude of the contact is everywhere steep, as shown in fig. 2. At no point could a difference in angle of dip be detected between the foliated margins of the 'granite' and the foliation in the surrounding gneisses. The plane of contact is sensibly parallel to these foliations and there is no transgression of the layering of amphibolites and banded gneisses by the granitic gneiss.

Detailed Descriptions

a. The Rapen to Stolestranden Region.- It is along this coastal section, on the south eastern side of the granite gneiss, that the contact relations can best be studied, in the many wave-washed exposures. With the exception of some short breaks, as, for example, at Bekkeviken (252 224), and the stretch from just west of Grönsvik (236 200) to Myrstranden (246 203), when the granite gneiss contact runs out to sea, the boundary is continuously exposed. The granite gneiss forms a steep cliff, sloping at times precipitously to sea-level from a height of up to 25m.

At the extreme north eastern end of this section, at Rapen (271 213), the contact runs out to sea. It is from here that pl. 9 is taken, illustrating perfectly Hofseth's statement, (1942, p.23), that "one can put one's finger on the spot where the granite begins". The contact here strikes 040°, and dips 65° towards the north west, under the granite gneiss.

The 'granite' is here a grey, medium grained, quartz-rich, variety, rather low in mafics, but with nevertheless a well developed foliation. The general grain size is slightly less than that of the major part of the mass, but this rock could not be said to constitute a 'fine grained border facies' of the granite gneiss. The microcline occurs as granular aggregates, pinkish in colour. The contact rocks are of typical banded gneiss, (see pl. 9), and immediately adjacent to the contact is a quartzose mica-amphibolite.

A thin section of the contact shows it to be perfectly sharp. Exactly at the contact, and also running parallel to it within the mica-amphibolite, are a series of closely spaced, rectilinear, shear-zones, each some 0.1 mm. wide. Along the shears the biotite has been comminuted and the quartz assumes the very finely grained aggregate texture typical of a mylonite. The biotite has been only slightly chloritized. The oligoclase in the granite gneiss has been heavily sericitized, and the biotite more extensively altered to chlorite.

At this locality there are no sheets or schlieren of basic rocks within the granite gneiss, as will be described for other areas along this coastal section. Some 200 m. west of Rapen, a large body of granitic pegmatite transgresses the contact, and is intruded in a more or less '<u>lit-par-lit</u>' fashion into the banded-gneisses.

As the contact is traced westwards, its strike swings round to 060 to 070°, and the dip steepens to vertical 1 km. east of Bekkeviken. Fig. 8 shows the contact relations in this area.

Pl. 9. The contact of the granite gneiss with banded amphibolites at Rapen. The foliation in both rock types and the plane of contact strikes 040° and dips 65° towards the north west.

Pl. 10 Showing the inhomogeneity of the granite gneiss, with a well marked compositional banding. Bekkeviken coast.

THE CONTACT ZONE 1KM. SOUTH WEST OF RAPEN

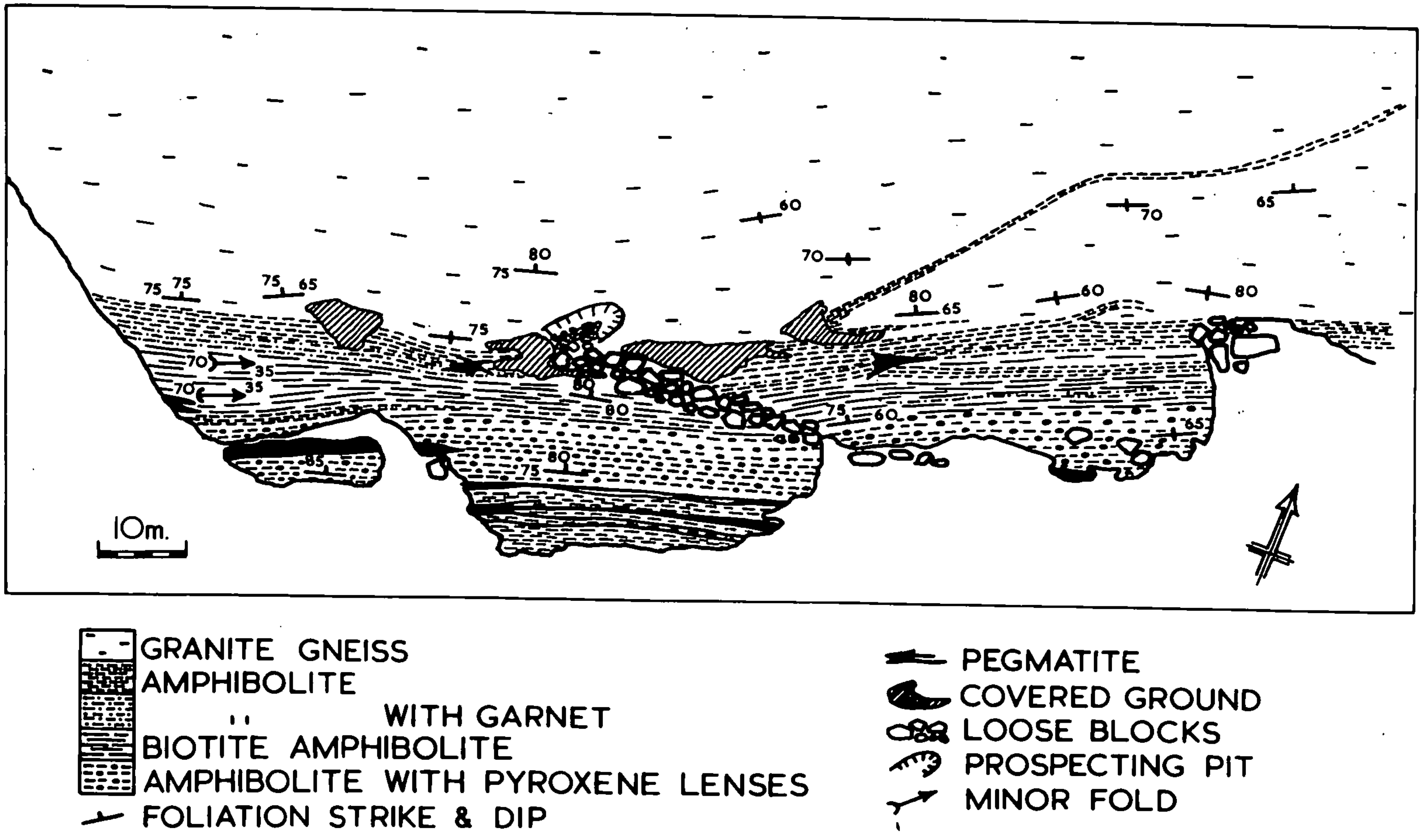


FIG.8

A vertical sheet of amphibolite penetrates the granite gneiss for a distance of 100 m. It is well foliated, medium-grained, equigranular, there being no evidence of a finer grain at the margins which are perfectly sharp. Common hornblende makes up some 60% of the rock, plagioclase (An_{30}), and opaque ore being the other essential minerals. Accessories are quartz, tiny euhedra of apatite and biotite, (as alteration product after hornblende). The granitic gneiss is a grey strongly foliated quartz-rich type, with quartz, microcline, oligoclase, and biotite. Exactly adjacent to the contact it shows extensive alteration of the oligoclase to epidote, muscovite and calcite, while the mica is chloritized.

The maximum width of the sheet is 2 m. close to the contact, narrowing to ca. 1 m. as it is traced north eastwards. It terminates in a drift covered area. It is distinctly discordant for the first 25 m. inside the 'granite', bearing 040°, then it turns sub-parallel to the foliation of the latter to bear 060° for 20 m., before swinging back to 040°. Unfortunately, the junction between the sheet and the banded-gneisses at the main contact is not exposed.

Two possible interpretations of this feature are to be proposed: that it represents a metamorphosed basic dyke, or, that it may be a section of the gneiss envelope which could have been 'torn' from the walls by the intruding 'granite'. No extension of the sheet could be seen cutting the banded gneisses, as might be expected if this were an intrusive dyke, but if the 'dyke' changed direction at the contact to strike parallel to the foliation it would be indistinguishable from the other amphibolitic bands in the gneiss. It seems highly improbable that the granite gneiss, assuming some degree of mobility at one stage, could detach such a long sheet from the wall to its present strongly discordant position about a 'hinge' where the sheet still maintains contact with the wall rocks. This amphibolitic sheet is therefore interpreted as an orthogneiss, a metamorphosed basic intrusive, probably of similar age to the 'L' dykes of Portör, (see p.100).

Some 20 m. further east a much smaller sheet of basic gneiss, 3 m. long and 0.5 m. thick, penetrates the granite gneiss as shown in fig. 8. Again an intrusive origin seems probable, although the possibility is greater that in this case a mobile or plastic phase of the granite gneiss could have penetrated the banded gneisses to produce this feature.

Fig. 9 shows the contact relations in the small bay 50 m. west of the last described locality. Here, wave-washed exposures reveal the distinct banding into light and dark layers in the granite gneiss, (see pl. 10), a feature normally obscured in lichen covered outcrops. The greyish granite gneiss is seen to be inter-fingered on a fairly large scale with the predominantly amphibolitic gneisses and schists. A sheet of granite gneiss, initially 10 m. wide, penetrates for a distance of 120 m. into the amphibolites, roughly parallel with the latter's foliation, and tapering evenly out westwards. The sheet of gneiss enclosed between it and the main granite gneiss mass terminates in a more complex inter-leaving. The general strike here is 070°, and dips are from 70 to 80° towards north. There has been a sinistral movement of approximately 2 m. along the line of a coarse grained granite pegmatite, which transgresses at an oblique angle the contact and the western extremity of the granite gneiss sheet.

THE CONTACT ZONE I KM. EAST OF BEKKEVIKEN.

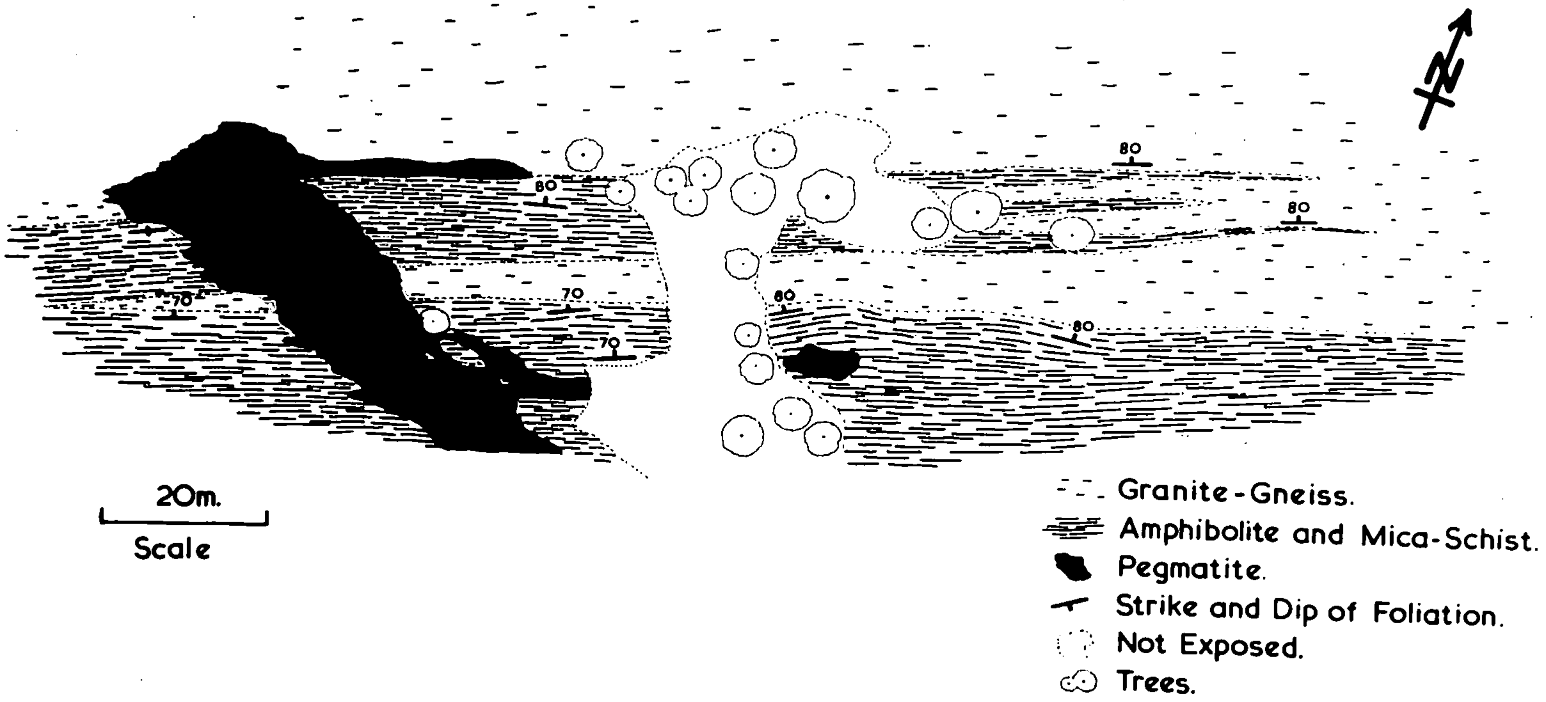


FIG.9

The interpenetration here of acid and basic rocks may be the result of very tight isoclinal folding about steeply plunging axes, with axial planes parallel to the present foliation. Indisputable isoclinal folding in the amphibolites has been observed along this coastline, so that this seems the most probable mechanism.

The contact maintains an attitude close to vertical as it is traced further west, and no major disturbances can be seen before it runs out to sea on the east side of Myrstranden bay, (246 203). A late, unmetamorphosed, presumed ?Permian, dolerite dyke runs north-south across the contact 200 m. east of Bekkevika, (251 204), but there is no lateral displacement along its line. The long narrow inlet of Myrstranden has been carved out along a zone of weakness, which was probably a fault throwing sinistrally a matter of several tens of metres. It is not possible to estimate how far out at sea the contact is on the west side of the bay, and there are no distinctive horizons in the homogeneous granite gneiss inland from which the amount of displacement could be measured.

Just west of Grönsvik, (236 200), the contact reappears, where it is striking 080°, and dipping 70° south, off the granite gneiss. It maintains the same strike, but shallows slightly to 60° as it is traced westwards to Stölestranden, (228 198), where the detailed map which is shown in fig.10 was made.

A profile from north to south, across the contact zone 100 m. west of the area covered by the detailed map shows, firstly, the marginal grey granite gneiss, then 12 m. of micaceous amphibolite, followed by 18 m. of granite gneiss. Next comes an 8 m. thick band of amphibolite, again micaceous, and lastly a 6 m. thick

THE CONTACT ZONE AT STØLESTRANDEN.

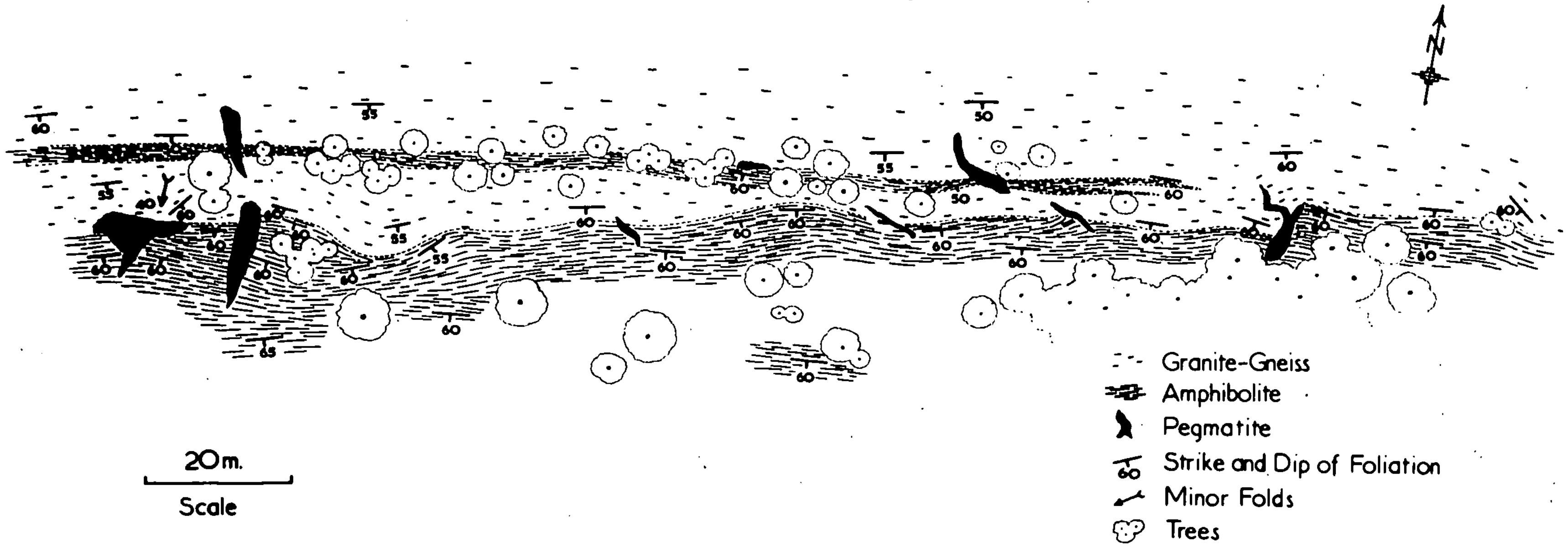


FIG.10

sheet of granitic gneiss, before the contact 'proper' against amphibolite which is garnetiferous in part. All the boundaries between these sheets strike 080° and dip 50 to 55° towards the south, and are perfectly sharp. The more northerly of these sheets is the one which terminates at the eastern end of fig. 10. The other thinner basic sheet merges with the wall rocks to the west of the area covered by fig. 10.

It can be seen that the 'boundary' of the granite gneiss has been thrown into a broad open fold, with a vertical axial plane and an axis which plunges sub-parallel to the general true dip at 50 to 60°, bearing 170°. The sheet of basic gneiss varies in width, rather irregularly, from 3 m. to 6 m. and a few metres before its eastern termination it bifurcates, the northern tongue being the thicker and extending further east. In one exposure the granite gneiss appears to be somewhat discordant to the basic metamorphics transgressing the 'bedding' in the latter at an oblique angle for a distance of about one metre, (see pl. 11).

At the eastern end of fig. 10, the basic gneisses have been faulted, with a horizontal sinistral displacement of 5 m. The fracture has been pegmatized. Remarkable is the fact that the fracture does not affect the foliation in the granite gneiss, since where the amphibolite is abruptly sheared out, the acid gneiss foliation bends around the northern end of the fracture, as shown in pl. 12. Evidently, the fracture has taken place in the more brittle basic gneisses at a time when the acid gneiss was able to accommodate the stress through plastic flow, analogous to that which occurs during 'boudinage' of amphibolites.

Pl. 11. Showing the apparent slight transgression of the foliation in the amphibolites by the lighter weathering granitic gneiss. Stölestranden.

Pl. 12. The amphibolites have been faulted and displaced, but the fault does not penetrate the granite gneiss, the latter appearing to have accommodated the displacement by more plastic deformation.

b. The Stölestranden to Hovet Region.- The trend of the contact zone swings round from 080° at Stölestranden to 020° where it crosses the main Levang to Stabbestad road, then veers again to 050° behind Hovet farm (215 188). Simultaneously, the dip shallows to 50° in the central section, steepening again to 65 to 70° towards the south west near Hovet, where the granite gneisses form a line of steep cliffs.

The contact rocks are again predominantly amphibolitic, and are in parts extremely garnetiferous.

The marginal granite gneiss is a pinkish-grey, medium grained rock, with a strong foliation, resulting in a tendency for it to split along slightly uneven planes composed entirely of ferromagnesian minerals, mostly biotite. Modal analyses indicate that it approaches granodiorite in composition, since plagioclase (An_{20}) exceeds potash feldspar in the ratio 4:3. Mafics, in this case biotite, partly chloritized, are low at 6%. Present as accessory minerals are orthite, zircon, apatite, and opaque ores.

In the part of the granite gneiss boundary close to Hagen, (221 196), a series of faults is seen. Four of them have been mapped along a 200 m. stretch of the contact. All of them are followed by granite pegmatites. They trend at right angles to the strike of the contact, and are probably sub-vertical. All four show a dextral displacement of a few metres. The total length of the lens-shaped pegmatites is never more than 30 to 40 m., and the disturbances could not be traced beyond the limits of these pegmatites in either the granitic gneiss or the banded gneisses.

These faults may be analogous to the marginal fissures which Balk (1937) describes in his treatise. Their attitude is different, however, in that the system of aplites, pegmatites and barren fissures which accompany the steep borders of large intrusives generally dip into the igneous mass at angles between 20 and 45°. Balk states that as far as the consolidation of many igneous masses is concerned, the zones of marginal fissures are of the utmost importance, and that even where the rock is structureless, marginal dykes and upthrusts must be regarded as evidence of a strong upward motion in the plutonic mass. He maintains that marginal upthrusts should be regarded as an expression of especially intense lengthening of rising igneous masses. The fact that marginal thrusts are found only in certain sections of a single mass he thinks is because these probably represent regions where the upward lengthening, during the breaking phase, was more intense than elsewhere. Where lengthening is less intense, inward dipping joints and dykes without displacements suffice for the adjustments. It is only along this section of the contact of the Levang granite gneiss that a system of marginal dyke faults and fissures has been seen.

The 'included' sheet of amphibolite the eastern end of which is shown in fig. 10, can be readily traced for a distance of 1200 m. sub-parallel to the contact. It attains a maximum width of 20 m., and thins evenly westwards, where its termination is 100 m. inside the main contact.

The western end of an even more remarkable and persistent basic sheet can be seen 200 m. inside the granite gneiss boundary north of Hovet, (215 188). This body can be followed for 2500 m., roughly parallel to the contact, to a point midway between Grönsvik and Myrstrand. Like the smaller sheet, it too apparently gradually approaches the contact, and at the point where the latter runs out to sea just west of Grönsvik, it is about 100 m. inside the granite gneiss. At three localities this sheet was seen to be cut by pegmatites of granitic composition, which may have occupied tensional zones in the brittle amphibolite, formed as a result of stretching within the probably more plastic leucocratic gneisses. There is no sign of displacement along these dykes.

c. The Hovet to Kvihagen Region.- The first part of this section, from Hovet to a point north west of Finsbudalen farm, (214 178), is one of considerable complexity, due to the occurrence of a series of large granite pegmatite bodies.

Ignoring relatively minor irregularities, the trend of the contact changes from 045° at Hovet, to north-south 500 m. south west of Hovet. As it is traced further, the trend again swings towards north east-south west, and at Finsbudalen it has a bearing of 060°. This trend is maintained with remarkable constancy for the remaining 6 km. of the boundary exposed on the east side of Leivann.

The attitude of the contact zone varies considerably between Hovet and Eidsvann. From the 65 to 70° dip towards the south east at Hovet, the dip rapidly steepens to vertical where the trend changes to north-south, and then the plane of contact overturns to dip at 70° under the granite gneiss. The dip towards the north west is maintained, but becomes shallower at 50 to 55° at Kvihagen, (201 174).

Just south west of the road from Hovet to Mörkvann a sheet of amphibolite 250 m. long and with a maximum thickness of 5 m. is exposed, trending parallel to the main boundary of the granite gneiss, and some 50 m. inside it. South of this 'inclusion', running across the stream from Mörk Vann, the granitic and basic rocks appear to be interleaved after the fashion of the Stölestrand section, but the exact relationships are difficult to determine, owing to the difficulty of correlating the exposures at the top and bottom of the vertical cliff on the south side of the Mörkvann stream.

The major granite pegmatite mass in the complex north of Finsbudalen, (214 178), can be traced for 300 m., and attains a maximum exposed thickness of 40 to 50 m. Two other masses are almost as large and there are numerous scattered exposures of smaller pegmatites. The larger bodies are discernable on aerial photographs. They are all lens-shaped or tabular, and intruded more-or-less '<u>lit-par-lit</u>', roughly following the foliation. The pegmatites are not replacive, since isolated rotated blocks of basic gneiss can be seen within them. South of the largest pegmatite, which transgresses the main boundary of the granite gneiss very slightly, a tongue of amphibolitic gneiss extends some 250 m. into the granitic gneiss, parallel to the foliation and attenuating evenly south westwards.

d. <u>The Strömtangen to Skjörsvik Section</u>.- Along this 2 km. section, from Strömtangen (268 222) to Skjörsvik (260 227), on the north east side of the peninsula, the boundary of the granite gneiss is nearly rectilinear, trending 120^{o}, with a dip of from

70 to 75° towards the south east, under the acid gneiss. A small dilatational pegmatite pushes aside the foliation in both the contact rocks at a point midway along this section, as it transgresses the contact, the lens-formed body trending 070°.

The granite gneiss, which is low in mafics, well foliated, and lacks any distinct 'augen' structure, is bounded abruptly by dark amphibolite, low in felsic minerals, and there is no interleaving of the two rock types.

e. <u>The Skjörsvik to Ørvik Region</u>.- Along this northern boundary the granite gneiss forms the scarp of a steep, thickly forested slope, facing Kragerö and Kilsfjord. The contact is not as well exposed as it is in the south, particularly west of Viborgtjern, (239 232).

On the north west side of Skjörsvik, the plane of contact dips 75° towards the south west, and trends 135°. As it is followed northwards the dip steepens as the strike swings towards east-west and at Bjelkeviken, (251 234), it is vertical, trending 110°. From Bjelkeviken to a point south of Rosvik the trend of the contact changes from 110° to 070°, while the dip is constantly close to vertical. West of Rosvik, (216 234), the dip is somewhat shallower at around 65 to 70° towards the north west, with a general strike of 050°.

Only one basic inclusion close to the contact has been mapped along this 10 km. section. This was a biotite amphibolite 15 m. thick and 0.5 km. long, situated 70 m. inside the main boundary south of Espehalsen, (206 230).

THE BASIC INCLUSIONS IN THE LEVANG GRANITE GNEISS

Introduction

In this account the term 'inclusion' is used for any body or fragment of rock enclosed by another rock, and there is no implication concerning the origin of the matrix or how the inclusion came to be in it.

The basic inclusions can be classified broadly into three main groups: (a) conformable sheets of amphibolitic and biotite-amphibolite schists and gneisses, (b) amphibolitic dyke-like bodies generally of small size frequently discordant to the foliation of the granite gneisses, and (c) basic masses recognized as 'hyperites', very variable in size and form and often showing some degree of discordance to the foliation of the surrounding acid gneisses.

Inclusions are found throughout the granite mass and there is no tendency for them to be concentrated near the margins of the body. On the contrary, particularly in the east, the inclusions are most common near the centre of the granite, and are rare in a broad belt around the margins of the mass. It is noteworthy that nowhere have the type of small angular rotated blocks characteristic of agmatitic 'intrusion breccia' type relationships been found.

The Amphibolites and Biotite Amphibolites

a. <u>Conformable Sheets</u>.- These are idential mineralogically and texturally with their counterparts in the banded gneisses surrounding the granite gneiss. They show considerable variation in dimensions and degree of alteration. Hofseth, (1942, p.43), makes a distinction between the basic inclusions found close to the margins of the granite gneiss mass and the sub-central inclusions. She states, "Near the boundary schlieren of amphibolite are frequently encountered.......they represent part of the neighbouring rock which they often closely resemble. Farther towards the centre inclusions of another type occur. These are pieces of amphibolite and amphibolitic mica-schists that can be 2 - 3 km. long and several hundred metres wide, but most of them are smaller, ca. 0.5 km. long and 50 - 100 m. wide. The schistosity is parallel to the foliation of the granite. The inclusions usually lie in the direction north east - south west, but exceptions exist, for example at Eidsvann." This differentiation is difficult to justify since the 'schlieren' and the sub-central inclusions are identical petrologically, and the largest mapped marginal inclusion is fully 2.5 km. long. (see p. 57). Hofseth (op. cit.) believed the larger inclusions to be downfallen fragments of a batholith roof, which had later taken part in movements of the granite. The present mapping has shown that the relationship of these inclusions to the fold structures within the granite and to each other is such that the 'downfallen fragments' hypothesis is not tenable.

The most remarkable single sheet is one which forms part of the Heligesvann Antiform. This is a unit mappable as a complete amphibolite 'shell' in the doubly plunging antiform west of

Heligesvann. It averages 80 m. in thickness and its total exposed length is 7.2 km. This rock and the granite gneisses with which it is associated are discussed in more detail on p.21.

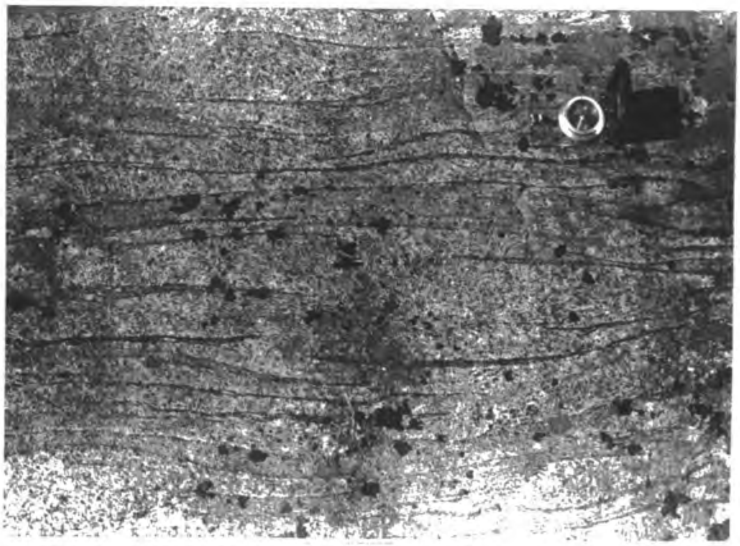
Another conformable amphibolite horizon has been traced from near Tonstøl (227 215) 3.3 km. south westwards into the hinge zone of the Kapelen Synform at Mörk Vann, and for a further 1.5 km. striking roughly east-west in the southern limb of the fold.

Examination of fig. 1 will reveal the location and extent of the remainder of these conformable basic sheets.

Inclusions show all stages of transformation to granite, the granitization taking place in two main ways:- by migmatization through interpenetrating acid and basic layers parallel to the gneissic foliation, and by growth of potash feldspar porphyroblasts within the basic units. The ultimate end product is a rock with the appearance of a 'normal' granite gneiss, and in some cases only the presence of a relatively high concentration of biotite mica indicates origin through transformation of an inclusion.

The contact between the sides of the amphibolite sheets and the surrounding granite gneisses is usually quite sharp. At the ends of the sheets there is complex interfingering and migmatization between felsic and basic rock types. Pl. 13 illustrates such a relationship exposed at the northern termination of the large sheet in the northern limb of the Heligesvann antiform, 600 m. east of Heibö (210 222). At a more advanced stage only thin septa of biotite indicate the former position of an inclusion

Pl. 13. Complex interpenetration and migmatization between basic and felsic gneisses at the northern extremity of a large amphibolite sheet which forms part of the Heligesvann antiform, near Heibö.



Pl. 14. An advanced stage in the granitization of a basic inclusion, this exposure being near Bekkeviken, about 300 m. from the granite contact.

pl. 14 shows such a rock from near Bekkevika (252 204). The larger inclusions frequently have a core of amphibolite and are markedly biotite rich along their margins.

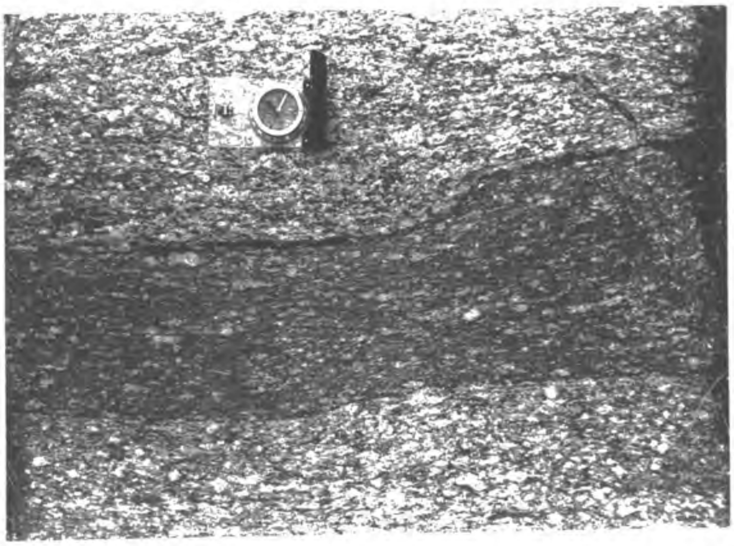
The transformation of amphibolites can take place through an intermediate spotted gneiss stage, where the mafic minerals become segregated into clots, the amphibole breaking down more or less completely to biotite. Potash feldspar comes in as patchy interstitial grains in the ground mass and later begins to form porphyroblasts. The end product is a granitoid rock rich in biotite, but if the ferro-magnesian components are removed a rock indistinguishable from the main mass of granitic gneiss results.

Pl. 15 and pl. 16 show a 10 cm. thick amphibolitic horizon at an intermediate stage in the conversion to granitic gneiss. The microcline porphyroblasts are clearly visible. In these cases of transformation through growth of new potash feldspars no change in volume of the rock is apparent. Thus, the reactive solution and reactive precipitation proposed by Bowen (1928) which involves an increase in volume is not strictly followed.

These extensive conformable basic horizons are interpreted layers in the original sedimentary sequence which were least susceptible to conversion to granitoid gneisses. Prior to their metamorphism to amphibolites they may have been basic extrusives, either lavas or tuffs, concordant intrusives, or even limestones of a particular composition.

b. <u>Discordant amphibolites</u>.- Those minor intrusives which have been emplaced parallel to the granite gneiss foliation are not

Plates 15 and 16. A conformable basic sheet at an intermediate stage in its conversion to a rock of granitic composition. The large microcline porphyroblasts are clearly visible in the close up below. Exposed north west of Myre skole.



readily distinguishable from conformable layers dealt with in section (a). Only those tabular bodies which can be demonstrated to be definitely discordant are included here.

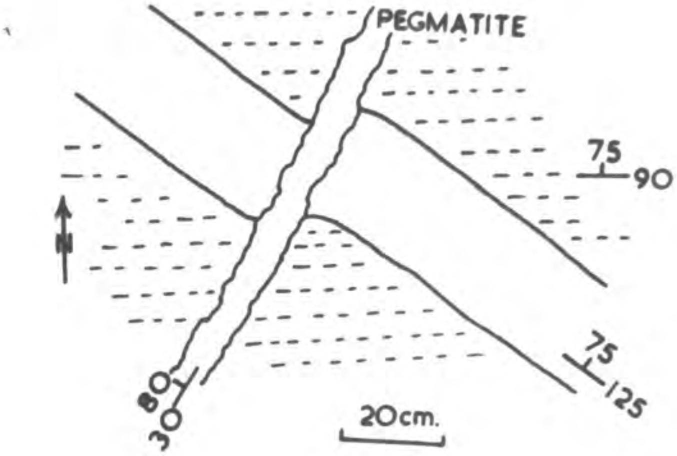
At Kapelen (217 204) three vertical sheets of micaceous amphibolite with thicknesses of ca. 15, 20, and 40 cm. respectively have parallel trends at 080°. Their contacts with the granite gneiss are sharp. At this locality the granite gneiss, which is garnetiferous, strikes 170°, with a shallow dip to the west of 15°. The sheets are in the hinge zone of the Grönsvik antiform, parallel to the axial plane. All the sheets show a preferred mineral orientation which is parallel to their walls and hence to the lineation in the granite gneisses.

Pl. 17 illustrates the relationship of another sheet to the granite gneiss foliation, this exposure being 300 m. south of Viborgtjern (239 232). The 20 cm. thick sheet strikes 125° with a dip of 75° towards the north east. The granite gneiss strikes 090°, dipping north also at 75°. Contacts are again sharp, but here no preferred mineral orientation was discerned. A pegmatized minor fault striking 030° has later displaced the sheet 8 cm. sinistrally.

Examples of these phenomena are widespread and fairly numerous, and they are not confined to any particular section of the granite gneiss mass. There is a tendency towards a preferred trend for these features at about 060 to 080°, but many exceptions exist.

The cross-cutting relationships of these basic sheets indicates that they are post foliation intrusives, probably

Pl. 17. A discordant amphibolite dyke which has been displaced a few centimetres by a pegmatized fault. The sketch below shows the attitudes of the dyke, the granite gneiss foliation, and the fault. Exposed 300 m. south of Viborgtjern.



contemporaneous with the L_1 and L_2 dykes described by Wegmann (1962) from Blåbærsholmen.

The Hyperites

Several of the larger inclusions exposed within the main mass of the Levang granite gneiss have been recognized as a rock type, common in the Bamble Formation, termed by Scandinavian geologists 'hyperite'.

The term was first introduced by Erdmann, early in the nineteenth century, in descriptions of the gabbroic rocks from southern Sweden, and is a general one taken to include rocks of gabbroic, olivine gabbroic, and noritic composition, of manifestly igneous origin. According to Heinrich (1956, p.74) hyperites are rocks intermediate between gabbros and norites which contain both essential clino- and orthopyroxene.

The distribution of hyperites within the Kongsberg Bamble Formation is wide, and they can form intrusions of considerable size, e.g. at Valberg near Kragerö, on Langöy and on Gumöy. The hyperites generally occur as concordant intrusions, tabular or lens-shaped masses, parallel to the strike of the surrounding gneisses.

Eight hyperites have been mapped and with one exception they occur as essentially concordant tabular bodies. The exception is the largest mass lying 1 km. east of Heibö (210 222). Its outcrop is roughly trapezoidal, measuring 900 m. by 400 m., the long diameter trending north east - south west. The northern and southern boundaries are approximately parallel to the foliation in the adjacent granite gneiss, but the western and, to a lesser extent, eastern contacts are discordant. Bugge, (1943), notes that even in fairly small bodies the hyperites are found to be highly differentiated, and in the Heibö mass rock types ranging from pyroxenites through gabbros and norites to plagioclase dykes have been found.

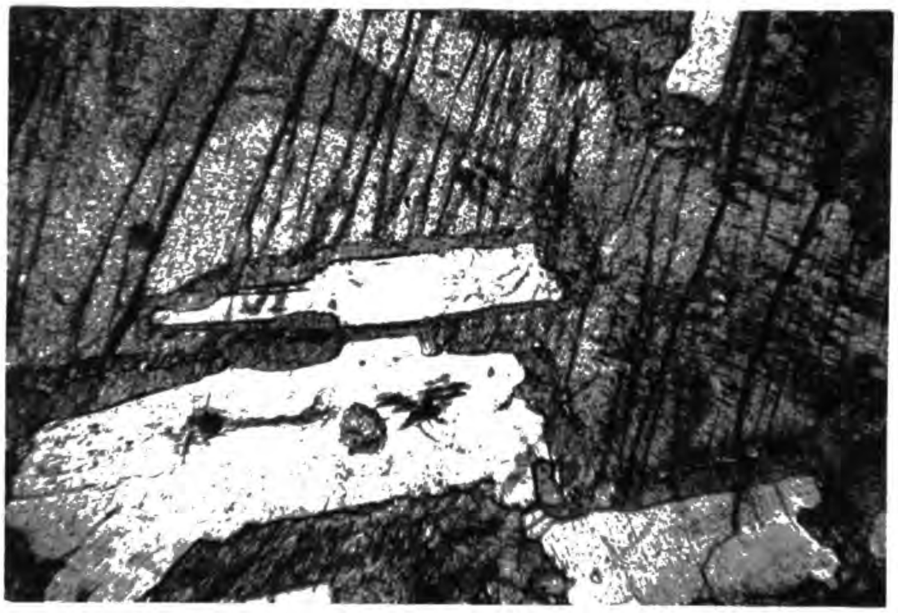
All the hyperites have suffered some degree of deformation and retrograde metamorphism. As relatively rigid blocks they typically show an unfoliated core in which primary igneous minerals and textures are still discernable, grading outwards with increasing amphibolitization of the ferro-magnesian minerals to a marginal foliated amphibolite. Generally, the larger the body the better preserved is the core, although the time of intrusion is also an important factor. The good state of preservation of the small gabbroic mass mapped in the hinge zone of the Grönsvik antiform indicates that it must have been a late stage intrusive.

The following series of rocks is illustrative of the reactions and textural reorganizations leading to amphibolite formation.

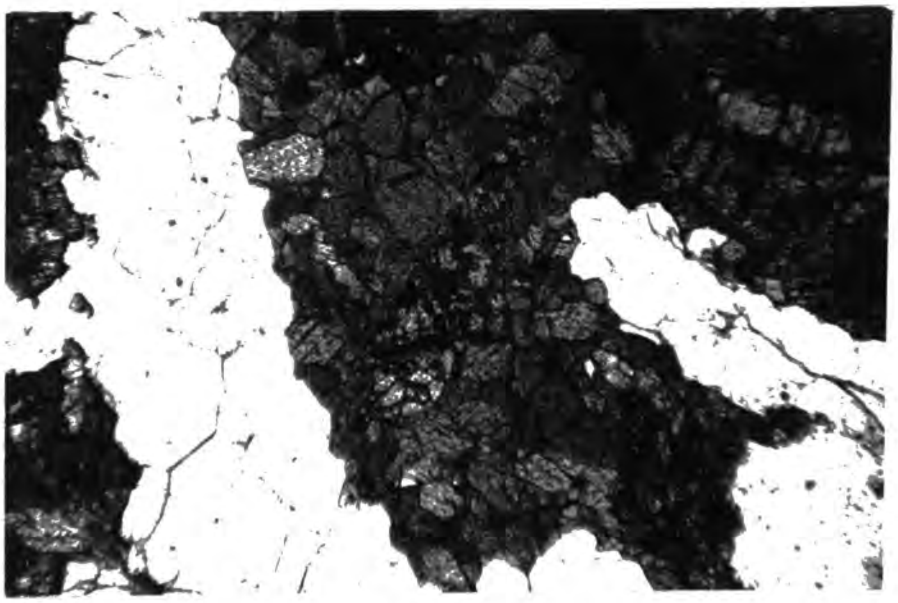
Specimen L.23.8.2.c. This rock is found in the central part of the hyperite intruded into the marginal region of the main granite gneiss mass 100 m. west of Myrstranden (246 203). In hand specimen it is an unfoliated brownish melanocratic rock of igneous aspect. In thin section the major minerals are diopsidic augite, hornblende, and plagioclase. The texture is holocrystalline, inequigranular, and sub-ophitic. Poikilitic clinopyroxene ($2V{:}60^{\circ}$, $c\hat{}Z{:}45^{\circ}$, $\beta=1.693$) frequently shows oriented plates of exsolved iron ore, and encloses plagioclase laths (see pl. 18). Alteration to uralitic amphibole is taking place around the margins of the grains and along cleavages. The secondary amphibole may be deuteric as well as metamorphic. Where it is found in association with magnetite it is pleochroic in brown, elsewhere in the rock the pleochroism is X:pale green, Y: green, Z: dark green. Refractive indices are $\beta = 1.666$, $\gamma = 1.674$. Plagioclase occurs in laths up to 3 mm. long and frequently displays a combination of albite, Carlsbad, and pericline twinning. It is andesine (An_{44}), with a maximum extinction on (010) of 24°. Present in accessory amounts are magnetite, which may in part be primary but is also a product of the alteration of pyroxene, garnet, biotite, and apatite.

L.360. This rock represents an intermediate stage in the metamorphism. The most important change is in the plagioclase which is completely recrystallized to an equigranular aggregate of interlocking grains showing 'stable' polyhedral crystal boundaries. At this stage the deformation has not been sufficient to completely destroy the ophitic texture, so the new aggregates of grains pseudomorph the original plagioclase laths. (see pl. 19). The plagioclase is quite fresh and commonly untwinned. The clinopyroxene is much more extensively altered to hornblende and the latter mineral is also partially recrystallised in polygonal grains. Small amounts of quartz are also present.

L.23.8.2.d. This rock occurs very close to the margin of the Myrstrand hyperite. It is black foliated amphibolite. In thin section no vestiges of pyroxene remain and the amphibole has completely recrystallized to polygonal grains, pleochroic in



Pl. 18. Photomicrograph of L.23.8.2.C. from the centre of a small hyperite 100 m. west of Myrstranden. Poikilitic pyroxene encloses euhedral laths of plagioclase and is being altered to amphibole around the margins of the grains and along cleavages. x 40. Ordinary light.

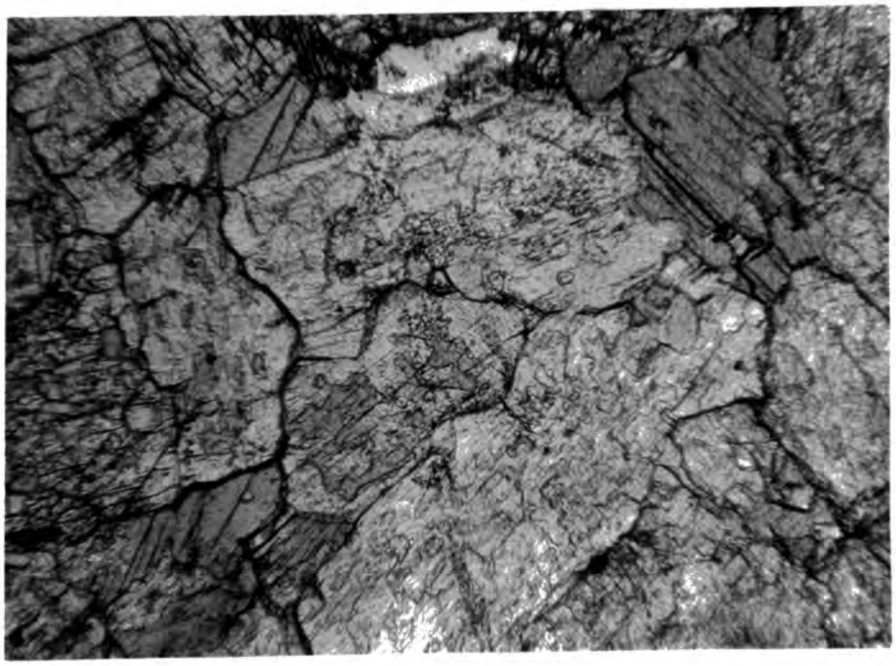


Pl. 19. Photomicrograph of L.360. Plagioclase has recrystallised to an interlocking aggregate of anhedral grains which are pseudomorphing the original euhedra. Pyroxene now extensively altered to amphibole. x 40. Ordinary light.

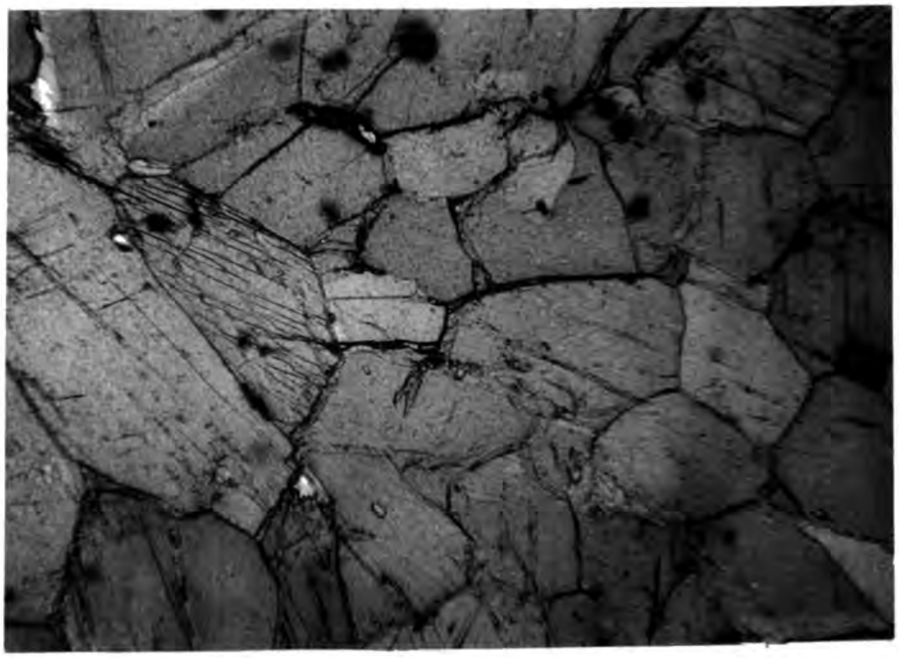
brownish greens, 1 to 2 mm. in diameter. All trace of the ophitic texture has been destroyed and many of the plagioclase grains show partial saussuritization. Biotite is now common as an alteration product of the hornblende. Other accessory minerals are quartz, magnetite, and apatite.

The metamorphic trend followed by the ultrabasic differentiate found in the Heibö mass is essentially similar to that seen in the gabbros. In specimen L.7.9.2.a. collected close to the centre of the body some 140 m. from the nearest contact, the metamorphism is already fairly well advanced. The rock is a pyroxenite in which no felsic minerals are present. Two pyroxenes have been identified, hypersthene, pleochroism X:pale red, Y: yellowish red, Z: pale green, occurs in accessory amounts, and augite (c:Z 43°, 2V 60°). Uralitization of the pyroxenes has taken place around their boundaries and in extensive irregular patches through the grains. The uralite is in optical continuity in individual grains. Pl.20 shows the patchy uralite and the interstitial amphibole. Much of the latter has begun to recrystallise, developing well defined crystal boundaries and cleavages. Secondary amphibole, which is pleochroic in light and dark greens, accounts for an estimated 40% by volume of the rock. The not uncommon twinning in the clinopyroxene is probably strain induced since many of the twin planes are irregular and discontinuous. Magnetite is the only other accessory mineral present and brown hæmatite staining is common.

L.281. This rock, which is found within 2 m. of the contact of the Heibö mass in the extreme north east, represents the end product of the metamorphism of the ultrabasic differentiates.



Pl. 20. Photomicrograph of L.7.9.2.A. Pyroxenite exposed near the centre of the Heibö hyperite, showing extensive uralitisation around grain boundaries and in irregular patches through the grains. x 40. Ordinary light.

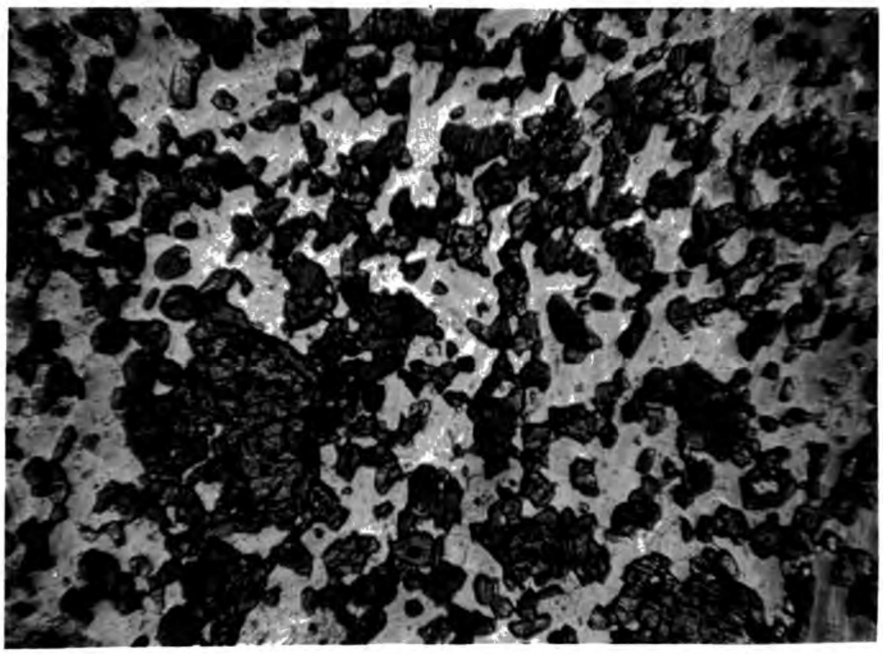


Pl. 21. Photomicrograph of L.281. An amphibolite from the north eastern contact of the Heibö hyperite. This rock may represent the end product in the metamorphism of a rock like L.7.9.2.A. x 40. Ordinary light.

In hand specimen it is a dark green, melanocratic, medium-grained, foliated amphibolite. In thin section the texture is holocrystalline, inequigranular, granoblastic, with interlocking anhedral grains of amphibole (pl. 21). With a maximum grain size of 5 mm., hornblende ($c\hat{}Z = 28^{\circ}$, pleochroic scheme X: pale yellow, Y: yellowish green, Z: green) makes up 98% by volume of the rock. Accessory minerals are magnetite, zircon, and quartz, the latter occurring as inclusions in hornblende.

The larger hyperite intrusions in the Bamble Formation are commonly intersected by medium and fine-grained dykes having more or less the same petrographical character as the hyperites themselves (Brögger, 1934). Such minor intrusives are also represented in the Heibö mass. Specimen L.297 was collected from a fine grained dyke rock exposed in the centre of the body. In thin section its texture is holocrystalline, porphyritic, and sub-ophitic (see pl. 22). The major minerals present are plagioclase, ortho- and clino-pyroxene, and amphibole. The orthopyroxene hypersthene occurs in anhedral phenocrysts up to 1 mm. across and is also a constituent of the ground mass. Maximum grain size of the ground mass minerals is less than 0.5 mm. The plagioclase laths are fresh, unzoned, labradorite, An_{54}, (extinction on (010) = 30°) in which both albite and Carlsbad twinning is well developed. Augite occurs in small anhedral grains exhibiting schiller structure with regularly oriented exsolved plates of a brownish to opaque mineral which was not identified. The pyroxenes are fairly extensively altered to greenish brown pleochroic hornblende.

The rocks which have been mapped (see fig. 1) under the



Pl.22. Photomicrograph of L.297, fine grained norite dyke from the centre of the Heibö hyperite, showing phenocrysts of orthopyroxene and the sub-ophitic texture.

x 80 Ordinary light.

general classification of 'hyperites' are representatives of a suite of basic and ultrabasic igneous rocks, for the most part intruded as semi-concordant sills and plugs. On petrographical evidence it would seem that the several intrusions may have been separated by considerable periods of time, but since all have undergone retrograde metamorphism to the extent that a marginal zone of foliated amphibolites has in every case been developed, even the youngest (at Grönsvik?) must have been intruded synkinematically. It is probable that the K and L basic dykes of the Portör peninsula and elsewhere (see p. 100) are genetically connected to these larger gabbroic intrusions.

CHAPTER 3

THE BANDED GNEISSES

INTRODUCTION

Surrounding the mass of predominantly granitic gneisses which form the core of the elongate domal structure of the Levang peninsula is a series of strongly folded, regionally metamorphosed rocks of very variable character. The major units of this series are amphibolites, quartzites, sillimanite gneisses, and granitic to quartz-dioritic gneisses. These types are merely the 'end members' in the series, and they frequently grade into one another through the increase of particular constituents at the expense of others. Other minor rock units include pegmatitic masses, generally of granitic composition, much more rarely gedrite-anthophyllite, nodular pyroxene-garnet amphibolite, and late, transgressive, diabase dykes.

The considerable variation in thickness and lateral extent of the different units makes the compilation of a stratigraphical sequence difficult. The thick vegetation and relatively poor exposure of the northern slopes hinder detailed comparisons with other areas, and only about 400 m. of banded gneisses are exposed, compared to over 2 km. south of the granite. Hofseth, (1942), has described a series of three profiles, one in the south at Finsbudalen, and two in the north at Langvarp (197 223) and Stabbestad (234 237). Hofseth found that although there is a broad similarity in the successions of rock types, the detailed sequences in the three localities are, as would be expected, dissimilar. In each of the profiles poorly foliated amphibolite is in contact with the granite gneiss. On the north side, the 30 to 40 m. thick basic gneisses are overlain by a more leucocratic gneiss rich in quartz, plagioclase, and some biotite. At Stabbestad this rock is succeeded by a more hornblende rich amphibolite, and about 100 m. from the contact sillimanite gneiss is exposed. The total thickness of the sillimanite quartzites is 140 m., and within them the sillimanite displays every gradation from a more-or-less uniform distribution to concentration wholly within discrete nodules. Hofseth (op. cit.) noted a small occurrence of crystalline limestone with a rim of skarn within the quartzites. Exposed at the junction of the Stabbestad ferry road with the main road is a body of garnetiferous anthophyllite, within a sheet of amphibolitic biotite schist. The schist itself forms a conformable basic horizon within the quartzites, 40 m. inside the southern limit of the latter. The quartzites are overlain by biotite amphibolites which are extremely garnetiferous in the region of Stabbestad. The total thickness of this section is 450 m.

In the Langvarp area, 4 km. to the west, the main sillimanite quartzite horizon was mapped 100 to 150 m. from the granite gneiss contact, and it is hear 80 to 120 m. thick, thinning westwards as the basic gneisses between it and the granite gneiss thicken. A biotite amphibolite layer is again seen within the quartzite, and is here garnetiferous. The remaining 250 m. of gneisses which overlie the sillimanite quartzites are predominantly biotite amphibolites, interbedded with biotite sillimanite quartz gneisses.

South of the granite gneiss, at Finsbudalen, (214 128), a 400 m. thick series of amphibolites and biotite amphibolites is exposed. Close to the contact these gneisses are cut by a complex of major granitic pegmatites. Overlying these rocks is an 80 m. thick sillimanite quartzite, interbedded with thin amphibolites. At Varpesund bridge (215 177), biotite amphibolites exhibit complex isoclinal folding and are in part richly garnetiferous. The next 300 m. of the profile are made up of predominantly biotitic amphibolites. South of these a 220 m. wide zone of granitoid gneisses carrying large potash feldspar porphyroblasts extends almost to Levang (216 172). The remaining 1400 m. of the profile are made up of banded gneisses, i.e. alternating felsic quartz-dioritic gneisses and basic amphibolites, the latter much subordinate in volume.

The general similarities between the different profiles are evident. The variations must be due to sedimentological facies changes, lateral variation in the thicknesses of the sedimentary units, an intrusive origin for some at least of the amphibolites, and lastly, metamorphic deformation and differentiation. Further reference will be made to the spatial distribution of the individual rock types in the sections which follow.

The Quartzites

Specimen L.17 was taken 100 m. north west of Fiane (220 183) at a point 70 m. from the northern limit of the major quartzite unit. In hand specimen it is a very dark grey glassy rock in which the micas impart a vague foliation. No lineation is visible.

In thin section the rock is seen to be made up largely of quartz, while biotite, muscovite, plagioclase, tourmaline, chlorite, zircon, apatite, and opaque ore occur in accessory amounts. The rock mode appears in Table 4. The texture is xenomorphic and homeoblastic. Some of the quartz grains are flattened parallel to the foliation. The larger quartz grains (up to 8 mm.) are crushed almost to the point of disintegration to a large number of smaller individuals, shown by the extinction in distinct patches. The small quartz grains generally do not show strained extinction. Sutured grain boundaries are common. All the accessory minerals occur at times as inclusions in quartz grains. Biotite occurs in small (0.5 mm.) ragged laths, occasionally bent or broken. Their pleochroic scheme is X: pale yellow, almost colourless, Y,Z: dark greenish brown. Biotite is altered in places to muscovite, less commonly to chlorite. Parallel orientation of the micas is poorly developed. Tourmaline, probably schorlite, occurs in tiny (0.05 mm.) sub-hedral to euhedral grains. It is strongly pleochroic, E: colourless, O: dark green. The tourmaline may be largely responsible for the very dark colour of this rock in hand specimen. Muscovite occurs in small ragged flakes, mostly quite fresh and is much subordinate to biotite which it partly replaces. Plagioclase (An_4) is in the form of small twinned interstitial grains, for the most part very heavily sericitised. Zircon and apatite only occur as tiny very well rounded grains.

The quartzite shows evidence of strong shearing and recrystallization. No original sedimentary structures have been observed,

TABLE 4

MODAL ANALYSES - BANDED GNEISSES

Specimen Number.	Quartz	Microcline	Plagioclase	Biotite	Amphibole	Sillimanite	Pyroxene	Accessories	Number of counts
L.61	38.1	28.9	30.4	0.3	-	-	-	2.6	3290
L.42	76.1	1.3	-	4.2	-	17.1	-	1.2	1000
L.95	16.6	1.4	37.0	28.7	11.8	-	-	4.5	1100
L.47	3.6	-	30.8	-	64.8	-	-	0.8	1050
L.25	23.3	-	63.2	7.2	5.2	-	-	1.4	1179
L.269	-	-	32.0	2.6	60.0	-	-	1.3	1126
L.297	-	-	43.0	-	16.9	-	39.2	1.0	1185
L.17	88.0	-	4.0	6.0	-	-	-	2.0	1065
L.71	-	-	24.5	11.4	62.6	-	-	1.5	1225
L.233	12.3	-	17.3	-	60.5	-	4.9	5.1	1098
L.235	-	-	29.1	-	67.0	-	-	3.9	960
L.18	81.0	-	-	-	-	16.6	-	2.4	1800
L.292	2.5	-	54.6	1.5	40.2	-	-	1.2	1140
L.267	0.4	-	32.1	-	64.1	-	-	3.4	1094
L.232	-	-	52.1	1.9	23.3	-	21.2	1.5	1145

although cyclic sedimentation of sandstones and shales may be responsible for the thin conformable mica rich horizons which are interlayered with the quartzites. The orthoquartzites often have a coarser grain size than the mica-rich types. While this may have been an original sedimentary feature, it is more likely that deformation is responsible. In the mica-rich quartzites movement took place by inter-granular gliding, while in the ortho-quartzites the deformation was accommodated by repeated solution and recrystallization, leading to an increase in grain size.

Traced north eastwards the quartzites thicken from under 100 m. at Finsbudalen to 300 m. in the region of Haslum (222 186). This may in part be due to lateral variation in thickness on sedimentation, but it can also be shown that repetition through folding occurs.

Quartzites are widely, and comparatively evenly, distributed in the Kongsberg-Bamble Formation (J.A.W. Bugge, 1943). No rocks resembling conglomerates were found on Levang, though these have been described from several localities elsewhere in the Bamble Formation (J. Bugge, op. cit.). The quartzites present the clearest case for a supra-crustal sedimentary origin of any of the gneisses on the basis of their composition, distribution, volume, field relations and textures.

The Sillimanite Gneisses

Specimen L.18 was collected 100 m. north of L.17 (see p.80), from a locality within 5 m. of the garnetiferous amphibolite with which the quartzites are in contact. In hand specimen it is a medium grained, white, glassy rock, with a well marked foliation and lineation produced by the preferred orientation of sillimanite and muscovite and the flattening of the quartzes.

In thin section quartz is seen to be by far the major constituent, while sillimanite makes up 16% of the volume. Occurring in accessory amounts are muscovite, apatite, zircon, magnetite, haematite, and tourmaline. The rock mode appears in Table 4.

The maximum grain size of the quartz is 3 mm. The quartzes are markedly flattened into the plane of the foliation and show strain extinction. In several cases the sillimanite streaks appear to be defining the original rounded outline of a quartz grain which has subsequently been crushed and now comprises several smaller grains all with sutured boundaries. In one case a very well rounded quartz grain with a rim of sillimanite is preserved intact. The sillimanite habit is acicular, and it occurs in felted aggregates mainly interstitial to the quartz although many quartzes contain a few sillimanite needles as inclusions. The distribution of the felted sillimanite is fairly even through the rock and this mineral shows no tendency towards concentrating in discrete nodules. Maximum grain size of the sillimanite is 0.5 mm. Muscovite, apparently replacing sillimanite, occurs in scattered irregular flakes. A few fractures and mineral boundaries have a thin coating of translucent red hæmatite staining. Grains of apatite and tourmaline are frequently euhedral, while zircon occurs only in sub-rounded to well rounded grains.

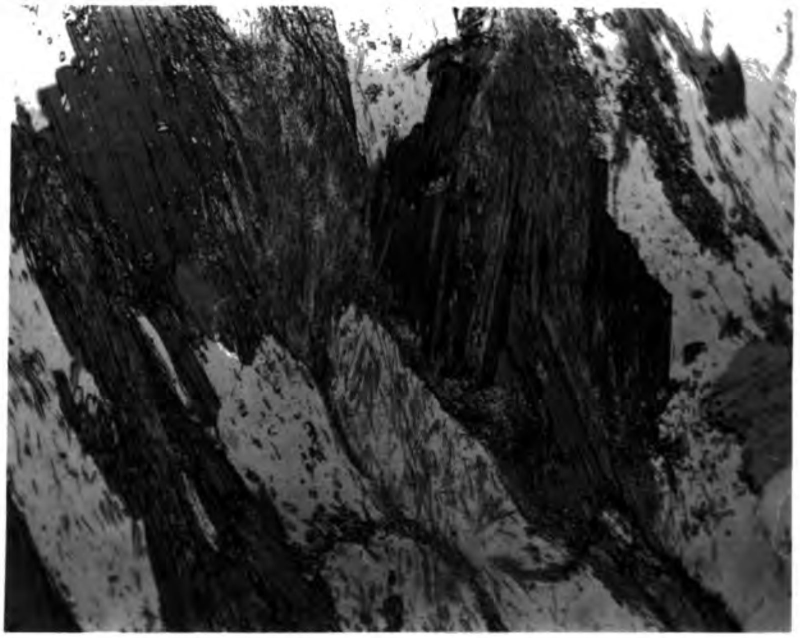
Specimen L.42, was collected from the sillimanite quartz gneisses occurring north of the granite gneiss at a point 240 m. east of Stabbestad (234 237). In hand specimen it is a grey, medium grained, fissile rock which splits readily along the well developed foliation formed by the micas and sillimanite segregations. Tiny specks of reddish iron staining are common throughout the rock. Preferred orientation of the sillimanite produces a strong lineation. In thin section quartz is the main constituent with sillimanite and biotite also important. Accessories are muscovite, chlorite, apatite, zircon, and magnetite. Restricted to one part of the slide is potash feldspar, where it constitutes a major mineral in a band 1 cm. thick. The modal analysis for the quartzose section of the rock, excluding the feldspathic layer, appears in Table 4. Quartz is distinctly flattened parallel to the foliation and the texture is lepidoblastic. Sillimanite is nematoblastic. Strain extinction is slight, even in the larger grains of up to 5 mm. Boundaries between quartz grains are commonly sutured. An unusual feature is the development of numerous very narrow fractures normal to the foliation, which appear to affect only the quartzes. The fractures are now filled by a transparent, anisotropic, highly birefringent mineral which was not identified. These fractures correspond to high angle joints, and must be due to a very late stage deformation to which the quartz responded by fracturing rather than recrystallization. Sillimanite occurs in acicular felted aggregates, most of which are noticably more continuous than those in specimen L.18 (p. 83). Thin, very well defined, layers 1 to 2 mm. thick comprising only sillimanite and quartz, intergrown, are traceable right through the slide. In a few places sillimanite is overgrown, and evidently replaced, by muscovite. Biotite, in ragged laths, shows strong preferred orientation. Its pleochroic scheme is X:pale yellow, Y and Z: dark brown. Biotite frequently alters to either muscovite or chlorite. There is no sign of any reaction between biotite and sillimanite grains. Anhedral grains of magnetite occur, generally in association with biotite where they are probably connected with the breakdown of the latter mineral to muscovite. Zircon occurs in very small, well rounded, unzoned, grains.

The potash feldspar, which constitutes an estimated 15 to 20% of the layer in which it occurs, is grid twinned microcline. The microcline is xenomorphic and interstitial. Many of the grains are altered to sericite along definite planes parallel to twin directions, and in the feldspathic layer the biotite is much more extensively altered to muscovite and/or chlorite as compared with the rest of the slide. Symplectitic intergrowths occur between muscovite and microcline. Sillimanite is as common in this layer as in the remainder of the rock.

Specimen L.120 was collected 400 m. south of Stölestranden (288 197), on the north east shore of Langholmen. In hand specimen the rock is a grey, well foliated, mica-rich schist, in which white, discoidal, patches, 1 to 2 cm. across, rich in sillimanite occur.

In thin section the major constituents are seen to be quartz, microcline, plagioclase, biotite, muscovite, and sillimanite. Chlorite, zircon, apatite, opaque ore, and tourmaline occur in accessory amounts. Quartz shows some degree of flattening in the sillimanite segregations, elsewhere they are more equidimensional. Strain extinction in quartz is slight. Quartz is symplectitically intergrown with muscovite. Maximum grain size only 1 mm. Biotite occurs in ragged laths up to 2 mm. long. Its pleochroic scheme is X: pale yellow, Y and Z: reddish brown. Some grains are completely altered to chlorite and a little magnetite. Acicular sillimanite occurs in felted masses throughout the rock, but also shows a marked concentration into lens shaped areas where it is associated with quartz and a little biotite. In these major sillimanite segregations the biotite is clearly being replaced by the alumino-silicate (see pl. 23). Muscovite appears to be a late crystallising mineral, replacing sillimanite and biotite. It occurs in large poikiloblastic grains up to 9 mm. in length in which the (0001) cleavage shows no regular relation to the foliation of the rock, though the grains are elongated in the plane of the foliation. Where muscovite is enclosing and/or replacing biotite the latter mineral shows a narrow discontinuous rim of opaque ore, probably magnetite. Both grid twinned microcline and plagioclase are xenomorphic, with a maximum grain size for the potash feldspar of 4 mm. and the plagioclase (An_5) 1 mm. Microcline is fresh, but plagioclase is generally extensively saussuritised. Zircon is common, apatite less so. Both minerals occur in small very well rounded grains. One sub-hedral grain of green pleochroic tourmaline was observed.

Specimen L.15 occurs interlayered with the ortho-quartzites south of the main granite gneiss, the exact locality being 250 m. south west of Fiane (220 183), on the main road. In hand specimen it is a grey medium grained well foliated schist in which there are numerous 'nodules' flattened in the plane of the foliation and with their longest axes parallel to the well developed



Pl. 23 Photomicrograph of L.120. showing acicular sillimanite replacing biotite. x 40. Ordinary light.

lineation. The 'nodules' are of fairly uniform size, approximately 5 cm. by 2 cm. by 1 cm., and generally show an irregular distribution within the rock. In places, however, they are definitely seen to be associated in particular horizons, as in fig. 13a. which illustrates a fold in nodular sillimanite schist. The long axes of the nodules are rotated into the axial plane of the fold but the concentration of groups of nodules into individual horizons parelleling the (relict sedimentary?) mineralogical layering of the rock is clearly seen.

In thin section the nodules are seen to comprise an intergrowth of quartz and dense fibrous sillimanite. The sillimanite is generally interstitial, but also commonly occurs as inclusions in the quartz. The sillimanite aggregates show only a slight tendency towards a parallelism with the long axes of the nodules. The interlocking sub-equigranular quartz grains show a moderate strain extinction and slight flattening in the plane of the foliation. Small amounts of muscovite in non-oriented irregular laths occur within the nodules, together with scattered grains of epidote magnetite and tourmaline, the latter frequently sub-hedral to euhedral. The nodules also contain a few grains of very well rounded zircon and apatite, and haematite staining is common. The limits of the nodules are sharply defined, and no sillimanite was observed in the ground mass of the rock. Towards the margins of the nodules non-oriented poikiloblastic grains of muscovite occur, enclosing quartz and containing remnants of trains of sillimanite. Biotite is found up to a few millimetres within the boundaries of the nodules. Only rarely was an apparent genetic connection between the sillimanite and biotite, similar to that in specimen L.120, observed.

The major minerals of the ground mass are quartz, muscovite, biotite and microcline. The accessory minerals are the same as those noted in the nodules, with the addition of plagioclase feldspar. Granoblastic quartz occurs in interlocking, anhedral, generally equidimensional grains with a maximum grain size of 2 mm. In parts of the rock the quartz contains abundant evenly distributed dusty inclusions (of magnetite?) while elsewhere these inclusions are confined to the central parts of the grains. Muscovite predominates over biotite, both micas showing a strong preferred orientation of their (0001) cleavages parallel to the plane of the foliation. The muscovite laths, up to 2 mm. long, are coarser grained than the biotite which has a pleochroic scheme: X pale green, Y and Z olive green. Examples are numerous of white mica replacing biotite, and abundant iron ore associated with the micas may be a product of this conversion. Perfectly fresh, grid-twinned, perthitic microcline occurs in anhedral interstitial grains less than 1 mm. across. The potash feldspar is much more abundant than plagioclase, which is found in smaller, heavily saussuritised, grains, the composition of which was not determined. Staining of a polished slab of this rock showed that the microcline is more or less evenly distributed through the ground mass, while the plagioclase distribution is sporadic.

All the sillimanite bearing rocks of Levang occur as non-transgressive conformable horizons in the banded gneiss series, sometimes showing gradational, but never intrusive, contacts with surrounding gneisses. According to J. Bugge (1943, p. 113), these remarks are true for the sillimanite gneisses of the Kongsberg-Bamble Formation as a whole.

The four specimens described above illustrate the different modes of occurrence of the sillimanite. Although those described were taken from widely separate localities, it should be emphasised that the different rock types are frequently closely associated and grade into one another, as for instance at Fiane (220 183), where there is complete gradation between the extremes of nodular sillimanite gneiss and non-sillimanitic orthoquartzites.

In specimen L.120 the association of sillimanite and fresh microcline points to a formation from the breakdown of pre-existing muscovite according to the well known reaction (Turner and Verhoogen, 1951, p. 457):

$$\underset{\text{Muscovite}}{KAl_3Si_3O_{10}(OH)_2} + \underset{\text{Quartz}}{SiO_2} = \underset{\text{Orthoclase}}{KAlSi_3O_8} + \underset{\text{Sill}}{Al_2SiO_5} + \underset{\text{Water}}{H_2O}$$

Barker, (1962, p. 913), believes that the sillimanite in some gneisses in Massachusetts and Connecticut has formed as a result of this reaction. While it is not unlikely that the Levang rocks were of such initial composition with regard to Al_2O_3 and K_2O content that muscovite would have formed at lower metamorphic grade, and that, with advancing metamorphism, this muscovite subsequently dissociated on the attainment of upper amphibolite facies conditions, positive textural evidence for this transformation has not been found. In the Levang rocks muscovite appears to be commonly involved only in retrogressive reactions, since it replaces sillimanite or biotite.

Staurolite and kyanite have not been found in any of the sillimanite bearing rocks. Sillimanite may arise from the reaction

(Deer, et al, 1962, (1)):

3 Staurolite + 2 Quartz = Almandine + Sillimanite + 3 Water

or, with rising temperature, by inversion from kyanite. None of the Levang sillimanite gneisses are garnetiferous. Kyanite may have been present before the P-T conditions reached amphibolite facies grade, but if so the inversion to the stable high temperature aluminosilicate has been complete.

The formation of sillimanite through the degeneration of biotite has definitely occurred in the Levang rocks. If kyanite was present in these rocks at lower grade, it may have taken part in the conversion of biotite according to the reaction expressed by Francis (1956) as follows:

$$\underset{\text{Fe Biotite}}{KFe_3AlSi_3O_{10}(OH)_2} + \underset{\text{Kyanite}}{Al_2O_3 + SiO_2} = \underset{\text{Orthoclase}}{KAlSi_3O_8} + \underset{\text{Sill}}{Al_2SiO_5} + 3FeO + H_2O$$

Tozer, (1955), has examined the mode of occurrence of sillimanite in rocks subjected to high grade thermal metamorphism in the aureole of the Donegal granite. He finds that the sillimanite has resulted from the degeneration of russet coloured biotite (cf. the biotite in specimen L.120, p. 86 , which is markedly reddish brown, indicating either that it is rich in TiO_2 or poor in Fe_2O_3, (Hayama, 1959) with the expulsion of K, Mg, and some Fe, part of the iron remaining as magnetite dust. Magnetite is a common accessory in the sillimanitic rocks of

Levang. Tozer (op. cit.) makes the observation that while sillimanite has formed from the biotite it is not strictly correct to say that it replaces biotite since, as is also seen in the Levang rocks, the sillimanite needles project out from the biotite flakes into the surrounding groundmass, implying a certain amount of diffusion of the elements making up the sillimanite.

The large, poikiloblastic, grains of muscovite are a late stage phenomena which appear to have crystallised under static conditions. For the most part they replace sillimanite, to a lesser extent biotite. Examination of the sparsely distributed needles of sillimanite which run through the muscovites, in relation to the dense matted trains elsewhere in the rocks, indicates that a large amount of sillimanite has been consumed in the growth of the white mica. The microclines are generally fresh, so that an introduction of potash is proposed to explain the muscovite formation. The source of the potash may have been the numerous ptygmatic veins and minor pegmatites of granitic composition which cut the sillimanitic rocks.

The origin of the sillimanite nodules is problematic. Sanders, (1955) in a study of the Basement rocks of Kenya, describes a sequence of metamorphosed pelitic and semi-pelitic rocks which have been converted by alkali metasomatism to microcline bearing nodular sillimanite granulites and gneisses. Throughout the series of rocks the sillimanite occurs as fine fibrous needles enclosed in granoblastic quartz, the other minerals in the granulites being microcline, and albite-oligoclase, with subsidiary biotite and titanomagnetite. This is essentially similar to the

Levang parageneses, but with the addition of muscovite.

The sequence described involves the progressive feldspathization of sillimanite-garnet-biotite gneisses, where initially the biotite folia are replaced by microcline and oligoclase, while quartzose bands together with their sillimanite are preserved and remain enclosed in an otherwise granitised host. After the initiation of feldspathization in the quartz-sillimanite layers these break up into irregular, sub-rounded, bodies of varying size. The next stage, Sanders claims, involves the further reduction in size of the quartz-sillimanite fragments which simultaneously become more rounded. Finally, at the maximum extent of the granitization, the spheroidal bodies are drawn out into ovoids or in extreme cases into sillimanite streaks arranged in plastic flow streams in a granitoid groundmass, producing 'faserkiesel' gneisses.

The conclusion which Sanders (op. cit.) draws is that the nodular sillimanite rocks are the result of the response to elevated temperatures and pressures of a series of aluminous sediments, kyanite having given way to sillimanite under extreme regional metamorphism. Sanders believes that this ability of the sillimanite quartz combination to survive in an area of syntectonic granitization makes it unnecessary to seek the source of the sillimanite outside the alumina rich orthogneisses of the Basement System.

On Levang rocks in which sillimanite is wholly restricted to nodules are intimately interlayered with and gradational to rocks which have evenly distributed sillimanite. The nodular sillimanite rocks have a groundmass of roughly granitic composition, which may indicate that these are layers which have suffered selective granitization on the lines of the Kenya gneisses.

Starkey, (1960), concludes that the 'faserkiesel' in the Maum Turk area seem to have resulted from the removal of potash, possibly into the intervening orthoclase rich rock. The shape of the sillimanite knots he believes would depend upon the ease with which the migration of material and the growth of the minerals occurred within the fabric of the host rock.

An alternative hypothesis to explain the origin of the Levang nodular sillimanite gneisses is that these nodules may simply represent highly metamorphosed clay galls, which Pettijohn (1957, p. 193) states are small, somewhat flattened, pellets of clay, generally rounded to sub-angular in outline, which are most frequently embedded in a sandy matrix. Clay galls are both similar and related to clay flakes and shavings, and are a relatively common sedimentary phenomenon. They are especially abundant (Pettijohn, op. cit.) at the base of heavy sand beds, and record contemporaneous chanelling and erosion of the intercalated shales. In some cases they may arise from the dessication and breaking up of a thin mud parting.

The sillimanite bearing rocks found on the Levang peninsula have resulted from the metamorphism under pressure-temperature conditions corresponding to upper amphibolite facies, of a series of alumina rich sedimentary rocks of variable composition. The sillimanite rich nodules may simply represent original clay galls, but are more probably formed through the deformation and metamorphic differentiation of clay rich horizons.

The Amphibolites

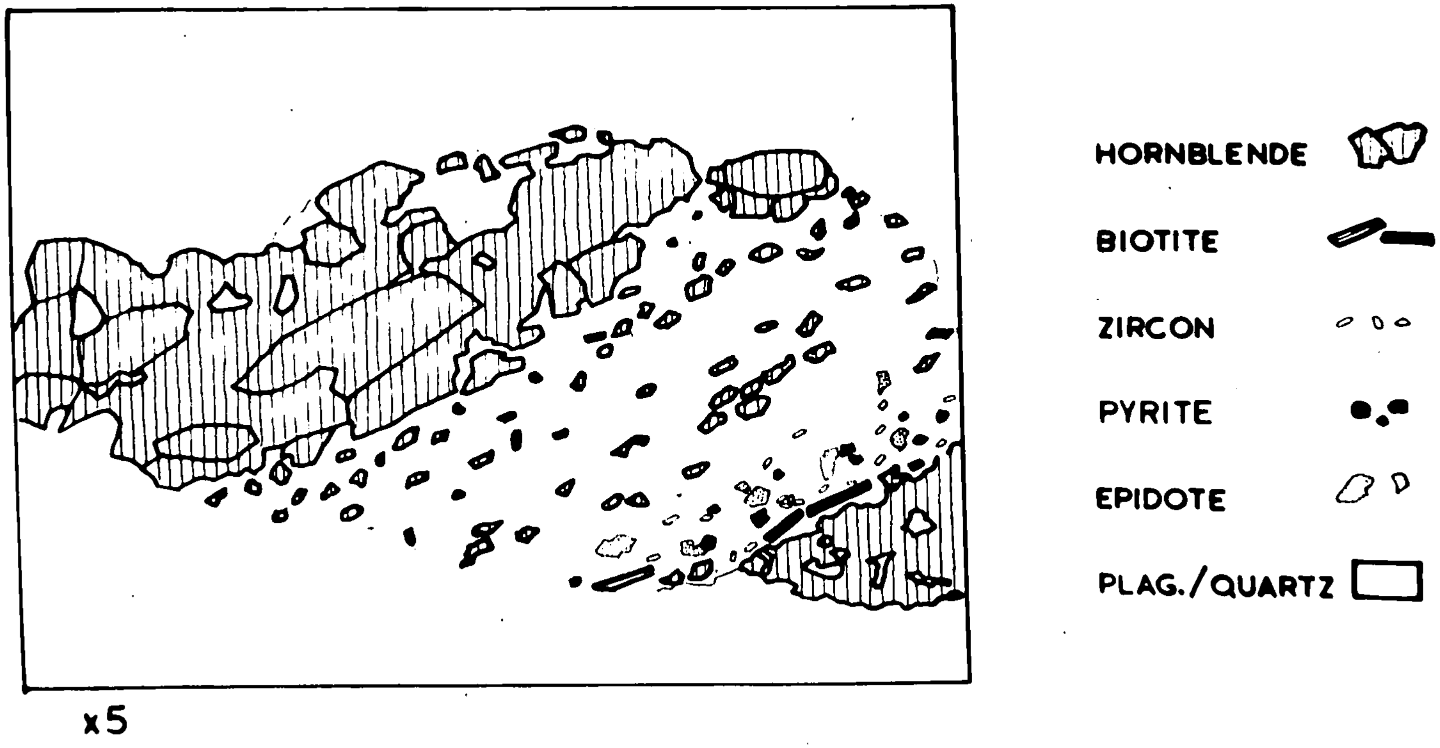
Amphibolites form an important part of the series of banded gneisses surrounding the granite mass. For the most part, they occur as conformable sheets interlayered with the quartzites, sillimanite gneisses, etc., though on the basis of their field relations and degree of deformation, several generations of definitely intrusive amphibolite dykes may be distinguished.

Specimen L.51 is an amphibolite collected near Ekerne farm (220 168) on the Portör peninsula. In hand specimen it is a mafic gneissic rock, showing considerable variation in grain size between mafic and felsic bands, which are from 1 to 2 cm. thick. In thin section the mafic layers are seen to be composed of interlocking anhedral grains of amphibole, up to 7 mm. in length, while quartz and plagioclase occur as inclusions and interstitial grains. The felsic layer is a finer grained equigranular aggregate of plagioclase, amphibole and quartz. The grain size of these minerals is up to 1 mm. Occurring as accessory minerals in this felsic layer are biotite, epidote, pyrite, zircon, apatite, and chlorite. The amphibole throughout the section is pleochroic with X: pale yellowish green, Y: grass green, and Z: dark green. The extinction angle $c \wedge Z$ is 28°, and $\beta = 1.654$, $\gamma = 1.668$. The dispersion is $r > v$. The plagioclase has a refractive index greater than that of balsam, and the extinction on the (010) albite twins indicates a composition of An_{50}, andesine-labradorite. Fig. 11 shows the way in which the accessory minerals in the felsic layer are restricted to a narrow zone on one side of the

FIG. 11

DIAGRAMMATIC SKETCH OF THIN-SECTION

L.51. - AMPHIBOLITE - LEVANG.



layer. This arrangement is very reminiscent of primary sedimentological concentration of accessory grains in a thinly bedded 'varve' type sediment.

Specimen L.143a. was collected a kilometer east of Bekkevika, at a distance of 25 m. from the granite gneiss contact. The appearance of this unusual rock in the field is shown by pl. 24. In hand specimen it is a fairly fine grained, equigranular, foliated amphibolite, through which are scattered small pods or lenses. The pods are ellipsoidal, flattened in the plane of the foliation, or occasionally less regular in shape and streaked out. In thin section the pods are seen to comprise for the most part, colourless pyroxene and calcite. The pyroxene occurs in anhedral poikilitic grains, up to 3 mm. across, enclosing calcite. Extensive retrogressive alteration to green pleochroic amphibole is common in the pyroxene. The pyroxene is also found in the 'groundmass', where it forms a subordinate constituent in an aggregate of amphibole and plagioclase. The amphibole is strongly pleochroic, the scheme being X: very pale yellowish green, Y: dark green, Z: dark green. Its extinction $c^\wedge Z$ is 27°, and $\beta = 1.671$, $\gamma = 1.675$. The amphibole grains are strongly nematoblastically oriented, since in the thin section, which is cut perpendicular to the foliation, euhedral or subhedral (001) sections of the amphibole very much predominate. The plagioclase is largely untwinned and fresh, its extinction on (010) twins indicating a composition of approximately An_{55}, labradorite. Present in accessory amounts are magnetite, apatite, epidote, and quartz. The pyroxene is non-pleochroic, biaxial positive $c^\wedge Z = 42^\circ$, and the β refractive index is 1.695. X-ray diffracto-

Pl.24. Amphibolite exposed on the coast east of Bekkeviken, showing the nodules and lenses into which the calcic pyroxene and calcite are concentrated.

meter data indicates a composition of Ca_{46}, Fe_{22}, Mg_{32}, while the optical data gives Ca_{45}, $Fe_{18.5}$, $Mg_{36.5}$. The pyroxene appears to be salite, a mineral of common occurrence in regionally metamorphosed calcareous sediments of upper amphibolite grade. In such rocks the formation of salite can be represented (Deer, Howie, and Zussman, 1962) by the reaction:

$$\underset{\text{Tschermakite}}{\mathrm{Ca_2(Mg,Fe^{+2})_3Al_4Si_6O_{22}(OH)_2}} + \mathrm{3CaCO_3} + \mathrm{4SiO_2} =$$

$$\underset{\text{Salite}}{\mathrm{3Ca(Mg,Fe)Si_2O_6}} + \underset{\text{Anorthite}}{\mathrm{2CaAl_2Si_2O_8}} + \mathrm{3CO_2} + \mathrm{H_2O}$$

This rock almost certainly represents a metamorphosed calcareous marl or shale, in which the pyroxene-calcite pods may be relics of pre-existing calcareous concretions.

While many of the Levang amphibolites are probably paragneisses, recent work by Wegmann and Schaer (1962) on the rocks of the Portör peninsula has shown that ortho-amphibolites are also very well represented. Largely on the basis of field relations and degree of metamorphism, they have distinguished three main episodes of basic dyke intrusions. The three groups of dykes Wegmann and Schaer (*op. cit.*) term 'K', 'L', and 'M' dykes. The K and L dykes they further subdivide into K_1, K_2, and L_1, L_2. Fig. 12 illustrates the various K and L dykes, all of which are Pre-Cambrian in age. The youngest group, the M dykes, which are not represented in the diagram, are the unmetamorphosed diabase dykes presumed to be of Permian age (p. 122).

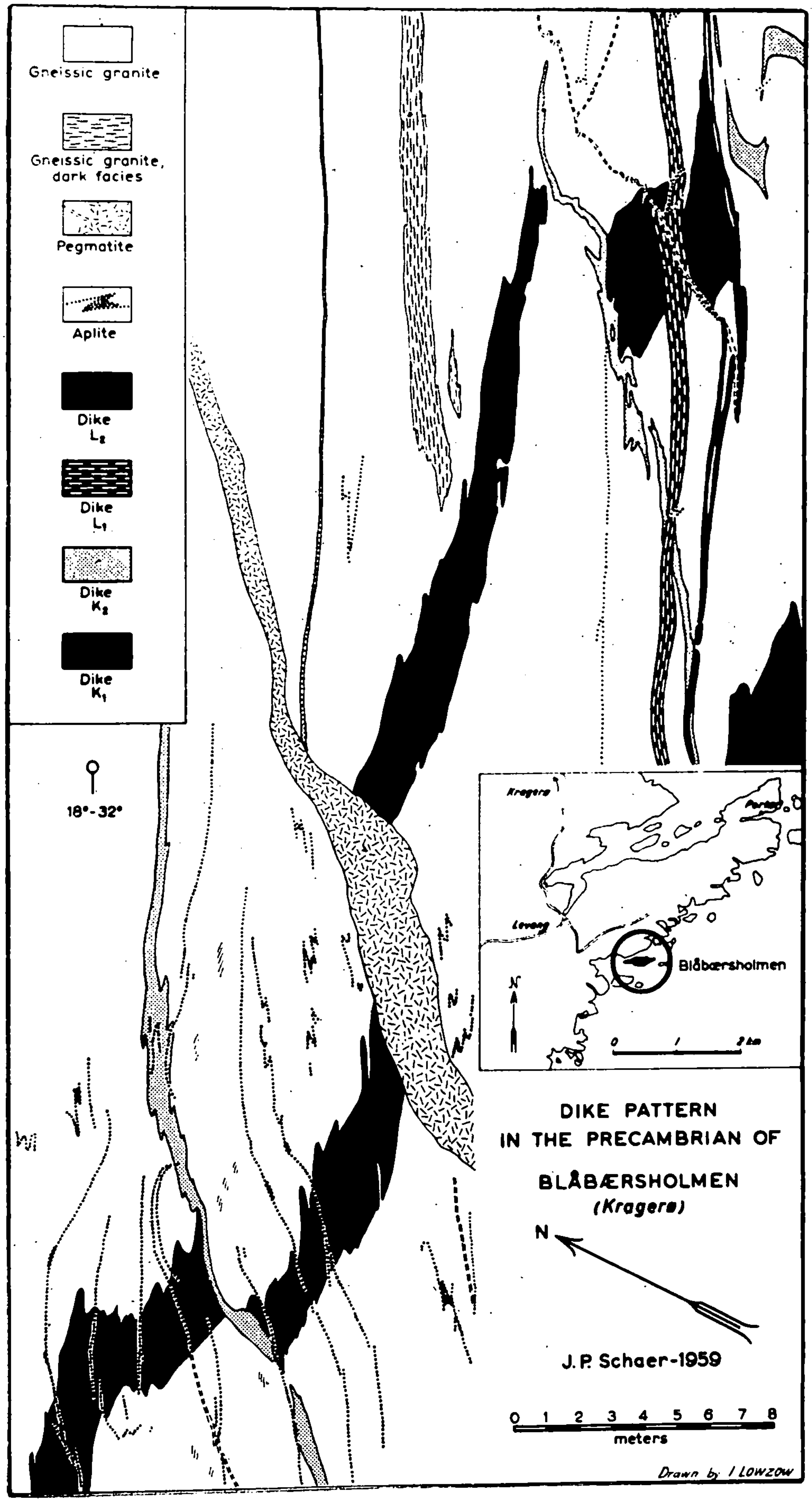


FIG.12

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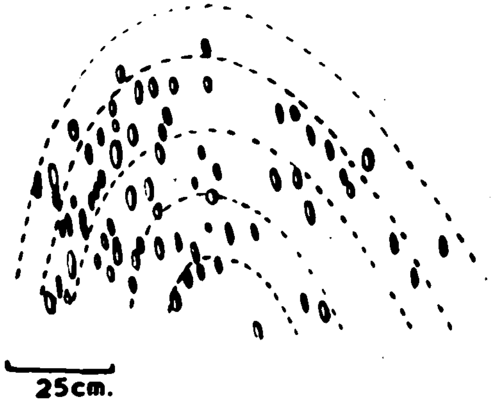
Fig. 13

A. Anticlinal fold in nodular sillimanite gneiss. The long axes of the nodules lie in the axial plane of the fold. Haslum.

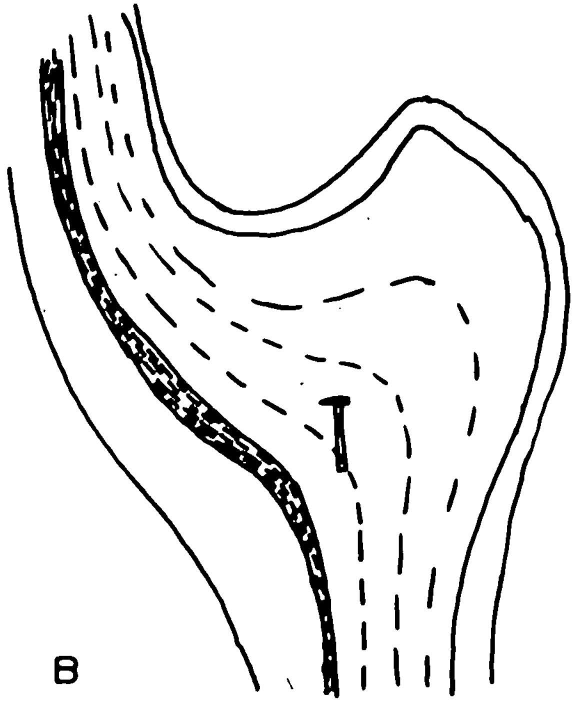
B. Disharmonic minor fold in quartzite. Fiane.

C. Similar fold in micaceous amphibolite. Varpesund.

A



B



C

Pl. 25 which shows a sheared off basic dyke exposed near Portör (believed to be one of the K_2 suite of dykes) should be compared with pl. 26 showing a dyke rock exposed north east of Tonstöl, close to the centre of the main Levang granite.

Garnetiferous amphibolites are fairly common, and these are also thought to have resulted from the metamorphism of both sedimentary and igneous rocks. Pl. 27 shows the way in which the garnets are restricted in their development to particular layers in a series of well foliated, finely banded gneisses exposed south west of Rapen (271 213). These rocks are interlayered with the nodular amphibolite described above. The epidote, quartz, and biotite-rich bands found in these garnetiferous rocks are highly characteristic of para-gneisses. On the other hand, some of the garnetiferous amphibolites, for example that shown in pl. 28 from the north east coast of Langholmen, may well be ortho-gneisses, since they are practically massive and very homogeneous.

Table 5. <u>GARNET REFRACTIVE INDICES AND CELL SIZE</u>

Specimen Number and Locality.	Refractive Index ± 0.002	a^o Cell Size
L.38 - Stabbestad.	1.791	11.56
L.26a - Fiane	1.797	11.58
L.33 - Hovet	1.796	11.53
L.362 - Bekkevika	1.792	11.53
L.26 - Fiane	1.795	11.55

Pl. 25. Showing a sheared out amphibolite dyke in homogeneous grandioritic gneiss. Exposed close to the road, 700 m. south west of Portör.

Pl. 26. Showing a very similar relationship between amphibolite and granitic gneiss to that in pl. 25, this example from an exposure 1 km. north east of Tonstöl farm.

Pl. 27. Garnetiferous amphibolite exposed on the Bekkeviken coast, the garnets unevenly distributed in the strongly banded amphibolite.

Pl. 28. Large garnets evenly distributed through a more or less massive amphibolite exposed on the Langholmen coast 300 m. south of Stölestranden.

The garnets are porphyroblastic and display seive texture, enclosing quartz, plagioclase, biotite, magnetite, etc. In table 5 the refractive indices and cell sizes for several garnets from the amphibolites both north and south of the granite are presented. These data indicate a fairly uniform composition for the garnets, all of which appear to be almandines with up to about 30% of the pyrope molecule.

Those amphibolites which have been described (specimens L.51 and L.143a) may reasonably be designated para-amphibolites. Similarly those narrow, dyke-like bodies, which Wegmann and Schaer have described (1962) from the Portör peninsula, and the amphibolites marginal to the hyperites (see p. 71), are most probably ortho-amphibolites. The majority of the amphibolites exposed on the Levang peninsula, however, can not be confidently assigned to either category, in the absence of less ambiguous field relations.

The Quartzo-Feldspathic Gneisses

The greater part of the Portör peninsula is underlain by a series of steeply dipping, well foliated, quartzo-feldspathic gneisses, interlayered with amphibolites and banded quartz-dioritic gneisses. The range in composition of these felsic gneisses is from quartz monzonitic to quartz-dioritic; a few narrow zones in the migmatites may be truly granitic, i.e. contain potash feldspar in excess of plagioclase.

For the most part these gneisses are a uniform grey colour, though in field mapping the quartz monzonites were distinguishable by their megascopically identifiable pink microcline porphyroblasts.

Specimen L.25 is a grey, medium grained, strongly foliated gneiss exposed on the shore of the peninsula, south east of Ekerne (220 168). In thin section the major minerals are seen to be plagioclase, quartz, biotite, and amphibole, while apatite, zircon, epidote, orthite, opaque ore, chlorite, and calcite occur in accessory amounts. The texture is holocrystalline, sub-equigranular, (maximum grain size ca. 2 mm.), and xenomorphic. The ferromagnesian minerals are lepidoblastic, and the felsic minerals granoblastic. Plagioclase occurs in anhedral, sericitized, grains. Extinction on (010) polysynthetic twinning and the refractive index indicate that it is oligoclase-andesine, An_{30}. The plagioclase developes albite and pericline twinning. Some crystals have bent twin lamellae, and the alteration is markedly irregular, in several grains it is controlled by the twin planes. Rounded quartz inclusions are common in the plagioclase. No antiperthite was observed, and microcline is absent from the rock as a whole. Fairly strongly strained quartz is elongated parallel to the foliation and has recrystallized, showing sutured boundaries. Biotite (X: pale yellow, Y and Z: dark brown) occurs in ragged flakes and is occasionally chloritised. The amphibole is pleochroic, with X: pale yellowish green, Y: green, and Z: slightly bluish green, (absorption of Y and Z very similar in intensity). It is biaxial negative with a low 2V (30° estimated), dispersion is strong, $r > v$, $c \wedge Z = 27^{\circ}$, and $\beta = 1.692$, $\gamma = 1.683$. Apatite occurs in both rounded and euhedral grains, while the less abundant zircon is found only in rounded grains.

The mode of this rock is: plagioclase - 62%, quartz - 25%, biotite - 7%, amphibole - 5%, accessory minerals - 1%.

Although very well foliated, this rock has evidently recrystallized post-tectonically, since evidence for strong shearing and deformation is absent.

The amphibolites with which specimen L.25 is interlayered are the K and L type intrusive dykes mentioned above, and are distinct from the amphibolites of the finely banded quartz-dioritic gneisses exposed in a zone in the central part of the peninsula. The extremely regular banding of these gneisses is shown in pl. 29. The contacts between individual layers are sharp and rectilinear, and individual bands may frequently be traced for several dekametres along the strike. The 2 to 50 cm. thick felsic layers are quartz-dioritic and more or less identical in thin section to specimen L.25. In some zones, however, a small content of potash feldspar shifts the composition towards granodiorite. Very occasionally, narrow bands in which quartz is present in excess of feldspar are observed. The mafic layers, 1 to 30 cm. thick, are composed of amphibole and biotite, with subordinate plagioclase and quartz. Of the abundant accessory minerals common to both rock types, anhedral epidote and sphene, generally associated with the ferro-magnesian minerals, are important. Rounded zircons and apatites, chlorite, sericite, and minor amounts of opaque ore, also occur.

Pl. 29. Extremely regular banding developed between felsic and mafic layers in quartz-dioritic gneisses exposed near Ekerne farm, Portör peninsula.

Pl. 30. Migmatite, Portör.

In the zones of gneisses in which potash feldspar is present in sufficient quantity to produce a quartz monzonitic gneiss, the banding is much less well defined. Typically, the quartz monzonitic gneisses are homogeneous over a width of several metres, or, as shown in pl. 30, migmatitic.

Hofseth, (1942, p.28), mentions that in a zone extending from Levang south westwards over Björkekjærr to Leivann, granitic (i.e. quartz monzonitic) bands are a constituent part of the gneiss. She was of the opinion that this zone possibly represented a zone of more intense granitization. The quartz monzonitic gneisses at Portör Hofseth (<u>op. cit</u>.) has mapped and described as a sharply defined, roughly wedge-shaped, body, the southern contact of which is, on her~~e~~ map, trangressive to the strike of the Portör peninsula gneisses. Mapping carried out in connection with the present study has shown that the Portör quartz monzonite gneisses are, like the similar gneisses in the Levang-Leivann zone, essentially sheet-like, conformably interlayered with amphibolitic and quartz-dioritic gneisses.

The quartz monzonitic sheets with their large pink microcline porphyroblasts have gradational contacts along the strike into rocks with little or no potash feldspar.

Specimen L.3, collected 100 m. north west of Levang (216 172), is representative of the quartz monzonitic gneisses. In hand specimen it is a medium to coarse grained, inequigranular, well foliated, sub-augen gneiss, in which large pink potash feldspar porphyroblasts up to 2.5 cm. long are very prominent. In thin section the major minerals are microcline, plagioclase, quartz, and biotite. Occurring in accessory amounts are apatite, zircon, sphene, epidote, calcite, sericite, and opaque ore.

Xenoblastic plagioclase (An_{20}), with a maximum grain size of 8 mm., is polysynthetically twinned. Alteration to sericite is irregular, sometimes showing preference for a single set of twin lamellae, and in some grains is almost complete. Distinctly twinned antiperthite is well developed in most grains, and an occasional grain is mesoperthitic. The patches of antiperthite extinguish simultaneously within a single grain, and are commonly controlled in their development by the polysynthetic twin lamellae (pl. 31). The twin lamellae are frequently bent and broken.

The fresh anhedral microcline occurs as antiperthite, small interstitial grains, and large porphyroblasts. The larger grains are sometimes indistinctly twinned, probably indicating a certain degree of disordering. Perthite is common; fine and coarse film perthites are found in a single grain, and film perthite not infrequently grades into flame perthite developed adjacent to plagioclase inclusions with which the perthite is in optical continuity. (Pl. 32). Myrmekite is developed at the contact between microcline and oligoclase.

Quartz is sutured in places, elsewhere it is granulated and stretched parallel to the foliation. Bubble trains and fractures are common in the quartz, and most grains are strongly strained. Quartz also occurs as rounded inclusions in feldspar.

Biotite, (X: pale yellow, Y and Z: dark brown), is present in lepidoblastic ragged laths, occasionally altered to chlorite. Apatite and zircon inclusions are common, the latter mineral developing pleochroic haloes. Calcite occurs filling fractures which often traverse several grains.

Pl. 31. Photomicrograph of L.3, showing the partial control of the antiperthite by the polysynthetic twinning in the plagioclase. x 40. Crossed nicols.

Pl. 32. Photomicrograph of L.3, showing flame perthite developing in microcline adjacent to sericitised plagioclase. x 80. Crossed nicols.

The banded nature of the quartz dioritic gneisses has been variously attributed (Barth, 1960; Hofseth, 1962; J. Bugge, 1943; Dietrich, 1960) to primary stratification of supracrustal rocks, lit par lit intrusion of (quartz dioritic) magma parallel to dominant shear planes, and metamorphic differentiation in connection with differential movement.

An intrusive origin for many of the amphibolites may reasonably be postulated, but an igneous origin for the quartz diorites is more difficult to demonstrate. The banding is probably fundamentally derived from a layered sequence of supracrustal rocks which have undergone considerable modification, involving metamorphic differentiation, shearing, and migmatization.

It is characteristic of a large proportion of the Portör gneisses that they are quartz rich, a feature indicative of a sedimentary origin, but have a rather low potassium to sodium ratio. In sedimentary rocks the reverse is normally the case (Pettijohn, 1957).

The very varied nature of the feldspars in these gneisses, where antiperthite, mesoperthite, several types of normal perthite, myrmekite, irregularly twinned microcline, etc., are seen developed in a single hand specimen, is eloquent demonstration of the exceedinly complex history of these rocks. Smithson (1963) has proposed that such phenomena are indicative of mobilisation and at least local potassium metasomatism in the rocks in which they occur. This view is upheld for the gneisses of the Portör peninsula.

The Anthophyllite-Bearing Rocks

Anthophyllite is the orthorhombic amphibole. It is a strictly metamorphic mineral, no varieties being known that have crystallized from a magma, and is of widespread occurrence, particularly in Pre-Cambrian rocks. Cordierite-anthophyllite bearing rocks are common in the Bamble Formation, and according to Bugge (1943) they always occur in connection with gabbroid rocks and amphibolites.

Anthophyllite (gedrite) bearing rocks have been mapped at several localities in the Levang peninsula (see fig. 1), where they occur as completely conformable sheets and lenses interlayered with amphibolites, mica-amphibolites, and mica-schists containing monoclinic amphibole. The anthophyllite (gedrite) rocks probably form continuous horizons, but owing to the sporadic nature of the outcrops, particularly north of the main granite gneiss mass, this is difficult to prove. The exposures of gedrite rock north of Viborgtjern (239 232) and on the Heibö road south of Stabbestad are parts of a horizon extending for over a kilometer, between the quartz-sillimanite rocks and the granite gneiss contact. Similarly, south of the granite, the exposures on the main road near Hovet (215 188) and at Stölestranden, both about 120 m. south of the granite gneiss contact, may be sections of a single partly discontinuous horizon.

In hand specimen all of the Levang minerals were black or greenish black and, in thin section, optically positive. Specimens from the Hovet layer and the Viborgtjern layer gave the following optical data.

L.32 (Hovet) $c^Z = 0^\circ$ Biaxial positive

$\alpha = 1.643$ $\beta = 1.651$ $\gamma = 1.662$.

Birefringence = 0.019.

L.44 (Viborgtjern) $c^Z = 0^\circ$. Biaxial positive.

$\alpha = 1.642$ $\beta = 1.652$ $\gamma = 1.663$.

Birefringence = 0.021.

Rabbitt (1948) presented a table showing the variation in γ refractive index with composition in the anthophyllites. He gave for anthophyllite with $\gamma = 1.662$ to 1.663 a content of 20% ($FeO + Fe_2O_3 + TiO_2 + MnO_2$). More recently, Seki and Yamasaki (1957) have given the relationship between γ refractive index and birefringence and chemical composition, in terms of the $Mg \rightleftharpoons Fe''$ and $MgAl \rightleftharpoons AlAl$ substitutions. On their diagram the Levang orthorhombic amphiboles plot close to the maximum aluminium substitution corresponding to the formula $Mg_5Al_2Si_6Al_2O_{22}(OH)_2$ with 15 to 18% Fe" substitution. The magnesium rich anthophyllites may be distinguished from the magnesium rich gedrites by the optically negative character of the anthophyllites. (Deer, et. al. 1962). The Levang orthorhombic amphiboles appear to be gedrites.

X-Ray diffraction studies were carried out on four specimens using CuKα radiation. With silicon as the internal standard the a_0 cell dimension was determined from the 12.0.0. peak. The results were as follows:

Spec. L.32	(Hovet)	$a_0 = 18.107$ Å
Spec. L.44	(Viborgtjern)	$a_0 = 18.113$ Å
Spec. L.167	(Heibö road)	$a_0 = 18.116$ Å
Spec. L.169	(Stabbestad)	$a_0 = 18.152$ Å

With the exception of data presented by Warren and Modell (1930) on gedrite with $a_0 = 18.2$, these values are appreciably lower than those generally met with in the literature. Howie (1963) has determined the cell parameters for 47 analysed orthopyroxenes from high grade metamorphic rocks, and finds that in general the cell dimensions are each smaller than those determined for igneous ortho-pyroxenes of equivalent composition. In particular the a and b dimensions may be considerably less. These are both apparently affected by the amount of Al in the octahedral position and also by the Fe" Ti Ca and Mn content of the mineral. The variation in the cell dimensions of various orthopyroxenes Howie suggests may be interpreted in terms of variation in alumina content (and paragenesis). The low a_0 values found in the Levang orthorhombic amphiboles may be explicable by analogy with the orthorhombic pyroxenes, particularly since from optical data the Levang minerals are known to be alumina-rich gedrites.

A very frequent association of anthophyllite (gedrite) is with cordierite. Because of the close similarity in their refractive indices, birefringence, and (particularly in (100) and (010) sections) twinning, cordierite and plagioclase (oligoclase) are often difficult to differentiate in thin section. Some accessory minerals, notably zircon and apatite, produce pleochroic haloes (colourless to yellow) in cordierite but not in plagioclase. This test proved adequate to identify cordierite in a number of sections, but where the content of accessory minerals was low confirmation of the presence or absence of cordierite was sought through X-Ray diffraction traces. In table 6 the d spacings for all the peaks produced by the separated fraction of felsic minerals from specimen L.169 are presented, together with the d spacings for cordierite. It will be seen that all of the cordierite peaks are present, the remaining peaks being accounted for by a small content of quartz, apatite, and zircon group minerals.

Forming part of the gedrite bearing gneisses and schists are occasional pods and lenses of monomineralic gedrite 'pegmatites'. These are from 2 to 5 m. thick and up to 30 m. long. Pl. 33 shows the mode of crystallization of the gedrite in one such body at Viborgtjern, in radiating aggregates and rosettes of coarse grain size, with individual grains up to 15 cm. long. This texture may indicate that these masses of gedrite crystallized fairly late in the metamorphic history of the area under conditions of essentially non-directional hydrostatic pressure. This is contrast to the textures exhibited by gedrite in the gneisses where it is markedly nematoblastic, producing a strong B lineation as a result of crystallization under directional stress. On the basis of hydrothermal experiments involving the synthesis of anthophyllite, Greenwood (1963) has suggested that monomineralic zones of anthophyllite are due to the presence of a steep gradient in the activity of H_2O, or a steep gradient in temperature, or both, across the zones.

The Levang gedrite rocks are varied in their mineralogy, the main types being:

Monomineralic gedrite.

Gedrite, cordierite.

TABLE 6

MINERAL IDENTIFICATION - CORDIERITE

Specimen L.169 Stabbestad

dÅ L.169	dÅ Cordierite **	h.k.l.	dÅ L.169	dÅ Cordierite	h.k.l.
8.590*	8.58	110, 200	1.941	1.95	
7.01			1.922		
4.87	4.92	310, 020	1.875*	1.878	
4.64	4.69	002,	1.840		
4.23			1.835		
4.08	4.11	112, 202	1.817	1.805	
3.52			1.796		
3.34	3.38	312, 022	1.706	1.715	
3.22	3.18	222, 402	1.7025		
3.12			1.685*	1.692	
3.03	3.04	511			
2.814					
2.633	2.65	512, 422			
2.511					
2.483					
2.450	2.45	620, 040			
2.331	2.34	004,			
2.275					
2.227	2.24	513,			
2.167	2.18	622,			
2.101	2.11	314, 024			
2.008	2.05	404, 441			

* Broad Peak
** ASTM Card 9.472

Gedrite, cordierite, plagioclase, ± quartz, ± biotite.

Gedrite, plagioclase, ± quartz, ± biotite.

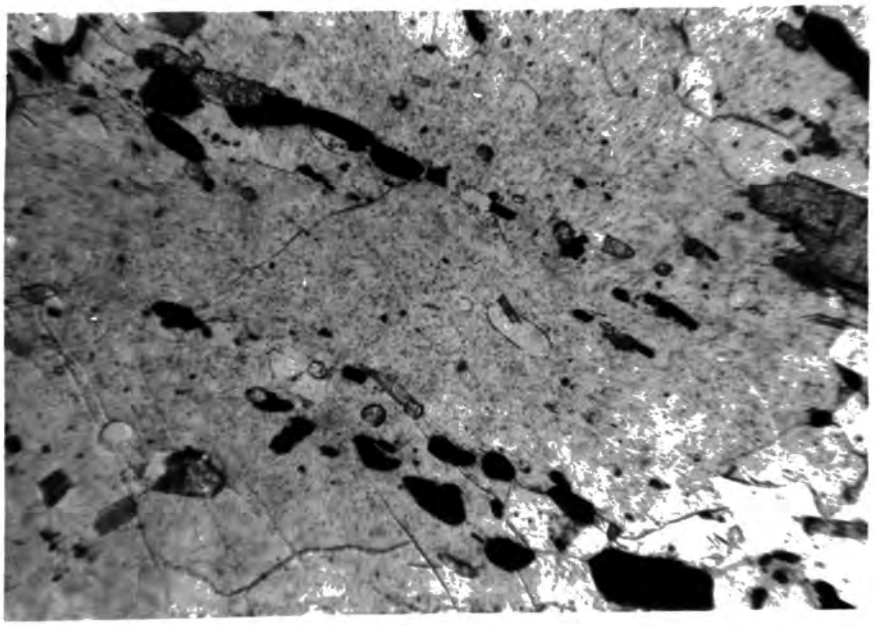
The commoner accessory minerals are apatite, magnetite, rutile, and chlorite, less commonly tourmaline, garnet, and zircon.

Gedrite is generally relatively coarse grained, forming porphyroblastic grains with numerous inclusions of quartz, plagioclase, and accessory minerals. Partial alteration to biotite, and sometimes to chlorite, is common. The biotite is pleochroic according to the scheme X: pale yellow, almost colourless, Y and Z: dark brown or dark greenish brown. Plagioclase is oligoclase-andesine, An_{23-35}. Albite, Carlsbad, and pericline twins are common, and in specimen L.32 from near Hovet secondary deformation twinning is extremely well developed. Some degree of saussuritization is generally to be observed in the plagioclases. Cordierite, which occasionally exhibits polysynthetic twinning, is usually partially altered to an indefinite sericite-chlorite aggregate. Minor accessory minerals, in particular apatite, and rutile, are very commonly well rounded. Pl. 34 shows the distribution of accessory zircon (a strongly metamict variety, probably orangite or malacon) in the gedrite rocks at Stabbestad. Grains of this mineral, and of apatite and biotite, are concentrated into layers and trains which are seen to run through several separate porphyroblasts of gedrite and cordierite. This phenomenom must be a relict sedimentary feature, the original sediment having been a rare heavy mineral concentrate.

The mode of origin of anthophyllite (gedrite) is problematical, and a number of possibilities exist. These have been summarised by Heinrich (1956) as follows:

(1) By magnesian metasomatism of leptites around granitic

Pl. 33. Radiating aggregates of coarse grained gedrite-anthophyllite exposed on the main road, at the northern end of Viborgtjern.



Pl. 34. Photomicrograph of L.169 showing the distribution of grains of metamict zircon (black) and apatite in a gedrite-cordierite gneiss from Stabbestad. x 40. Ordinary light.

and granodioritic bodies.

(2) By moderate to high grade regional metamorphism of peridotites or weathered chloritic greenstones.

(3) By metasomatism of serpentinites.

(4) By contact metasomatism of hornblende schists, gneisses, and amphibolites by peridotites or by granitic pegmatites.

(5) By reaction between amphibolites and dolomitic marbles.

Chromite is a very common accessory mineral in ultra-basic rocks and persists in their serpentinized alteration products. A careful search was made for chromite, but none was found. This, together with the fact that apatite, rutile, zircon, and tourmaline are common, is fairly strong evidence against the possibility of the Levang rocks having resulted from the high grade metamorphism of these rock types. Also, pale coloured alumina poor anthophyllite is the usual orthorhombic amphibole formed from dunites and peridotites, and only alumina rich gedrites have been found on Levang.

There does not appear to be any positive evidence to support an origin for the gedrites through magnesia metasomatism, although this was the view held by Hofseth (1942), who evoked a "metasomatic exchange of alkalies for calcium and magnesium."

Tuominen and Mikkola, (1950), in their work on the anthophyllite cordierite rocks of the Orijärvi region in Finland, maintain that these are found for the most part in the crests and troughs of folds. They consider that, as a result of the metamorphic concentration of magnesium and ferrous iron from the limbs of folds in a series of incompetent argillaceous sediments, anthophyllite-cordierite formed in the regions of pressure 'low' in the crests of folds. The concentration took place under conditions of increasing temperature and loss of water. The reaction which they envisage having taken place is as follows:

$$\underset{\text{Clinochlore}}{5Mg_3Si_2O_5(OH)_4 + 6Mg_2Al_2SiO_5(OH)_4} + \underset{\text{Quartz}}{23SiO_2} =$$

$$\underset{\text{Anthophyllite}}{3Mg_7Si_8O_{22}(OH)_2} + \underset{\text{Cordierite}}{3Mg_2Al_4Si_5O_{18}} + 19H_2O$$

No such structural control appears to have been operative during the formation of the Levang rocks.

The Levang gedrite bearing rocks occur as fairly extensive conformable layers in a series of predominantly paragneissic rocks. One of the layers shows undoubted relict sedimentary structures, and all of the gedrite rocks carry a small amount of rounded accessory minerals of probable sedimentary origin. While some migration of material may have occurred, (for instance, in the formation of the monomineralic lenses), no evidence has been found for any origin for these gedrite rocks other than by essentially isochemical high grade regional metamorphism of magnesia rich chloritic argillites.

The Permian Dykes

Dykes and sills of unmetamorphosed dolerite are exposed throughout the area intersecting all other rock types. They are correlated with igneous rocks of Permian age in the Oslo

Province to the north east. In general these minor intrusives follow sub-vertical fractures, but several flatter lying bodies have been mapped, notably in the region of Levang gård (216 172) and near the northern end of Mörk Vann (198 192). From Rapen a sub-vertical dyke 0.5 to 1 m. thick was traced south westwards for 500 m., trending 065°. The dykes vary in thickness from ca. 20 cm. to 2 m. None of the more felsic Oslo rocks seems to be represented on Levang. The dykes often show well developed columnar jointing and not uncommonly are vesicular. Several appear to have resulted from multiple intrusion of basic magma (pl. 35). The dykes do not display any tendency to follow a particular trend direction.

Metamorphic Facies

The rocks of the Levang peninsula have been subjected to a high grade of regional metamorphism. Hofseth, (1942), considered the metamorphic facies of the main granite gneiss and of the surrounding banded gneisses separately. From a chemical analysis of "a normal rock from the middle of the granite" she derives ACF values (after Eskola) of A 33, C 27, and F 40. These values plotted on an ACF diagram for the amphibolite facies fall within the area where plagioclase and biotite are stable, in the presence of sufficient water. However, on the basis of the observation that epidote, chlorite, and saussuritised plagioclase occur, Hofseth proposes that the granite (gneiss) was formed at a somewhat lower temperature than that of the true amphibolite facies, and approaches epidote amphibolite facies.

Pl. 35. A sub-vertical, vesicular, composite Permian dyke intruding granite gneiss and amphibolite, Myrstrand.

For the banded gneisses, she derives ACF values of A 59, C 33, and F 8, from an analysis of "a sample of a light granite-like band at Levang school". Here again, Hofseth maintains that the presence of clinozoisite and chlorite in the analysed rock indicates that it "like the Levang granite" attained a lower temperature than true amphibolite facies.

Throughout the area amphibolites are interlayered with more felsic gneisses. These basic gneisses give a better indication of the metamorphic grade than the more acidic gneisses employed by Hofseth. Table 7 shows some common mineral parageneses found in the area, a general subdivision being possible into the two assemblages: quartz-microcline-plagioclase-biotite and plagioclase-hornblende, the latter occurring with or without biotite. Of the alumino-silicates, sillimanite is of widespread and common occurrence, but andalusite, kyanite and staurolite are not present in these rocks.

The lower limit of the amphibolite facies has been drawn where plagioclase (oligoclase or more basic varieties) breaks down to an equilibrium assemblage of epidote and albite. (Turner, 1958). Ramberg, (1952) would define the lower limit as the P-T conditions under which plagioclase of composition An_{30} is in equilibrium with epidote. Many of the amphibolites of the Levang area do not contain any epidote minerals, the plagioclase present usually being andesine. The epidote which has been noted is present as a retrograde metamorphic mineral, resulting from the breakdown of plagioclase, and ferro-magnesian minerals. Similarly, in the granitic gneisses, epidote is of fairly common occurrence as a diaphtoretic alteration product.

The presence of sillimanite-potash feldspar-quartz-biotite-

TABLE 7

COMMON MINERAL PARAGENESES

Plagioclase An Content	Quartz	Microcline	Biotite	Amphibole	Muscovite	Diopside	Garnet	Sillimanite	Chlorite	Sphene	Opaques
4	X	-	+	-	+	-	-	-	-	-	+
8	X	X	X	-	X	-	-	X	+	-	-
9	X	X	+	-	+	-	-	-	-	-	+
11	X	-	+	X	+	-	-	-	+	-	+
20	+	+	X	-	+	-	-	-	+	+	+
24	X	X	X	+	-	-	-	-	-	+	+
30	X	-	+	+	-	-	-	-	-	-	+
38	X	-	X	-	-	-	+	-	+	-	+
41	+	-	-	X	-	-	+	-	+	-	+
49	+	-	+	X	-	-	-	-	+	+	+
51	-	-	-	X	-	X	-	-	-	-	+

X present in Major amounts

\+ present in Minor amounts

\- absent

muscovite and of calcic plagioclase-hornblende-almandine parageneses indicates that the rocks of the area have attained a maximum grade of metamorphism well above the lower limit of the amphibolite facies. The upper limit of the amphibolite facies is denoted by the following reactions:

$$\text{Biotite} + \text{Quartz} = \text{Hypersthene} + \text{K-feldspar} + H_2O$$

$$\text{Biotite} + \text{Sillimanite} = \text{Garnet} + \text{K-feldspar} + H_2O$$

Pyroxene granulites (charnockites) are found in the region of Arendal, south west of Levang (Bugge, 1943). None of the Levang rocks show any signs of having attained a facies level higher than sillimanite almandine facies. Typical Granulite facies minerals are not found, with the exception of some of the better preserved hyperites which are noritic; but these are a special case and are not relevant to the facies problem.

The sub-facies of the amphibolite facies are staurolite-almandine, kyanite-almandine-muscovite, sillimanite-almandine-muscovite, and sillimanite-almandine-potash feldspar (Turner, 1960). The complete absence of staurolite and kyanite has already been noted. Turner (op. cit.) points out that the mineral assemblages of the high grade amphibolite facies tend to be complicated due to reactions taking place in response to falling temperature and variable water pressure. Sillimanite, muscovite, and potash feldspar may be found in one rock, and partial replacement of early formed mica by sillimanite and "sericitization" of sillimanite may be observed. This is exactly the case in some of the sillimanite-bearing gneisses of Levang, where the alumino-silicate is seen to be replacing biotite and/or muscovite. For this reason it is not possible to state precisely which of the two upper amphibolite facies sub-facies, the sillimanite-almandine-muscovite or the sillimanite-almandine-potash feldspar, is the correct one for the Levang rocks.

The anorthite content of the plagioclases has been commonly recognized to increase with increasing grade of metamorphism (Ramberg, 1952). Francis (1956) gives An_{40} as the maximum anorthite content for plagioclase in the lowest grade of the amphibolite facies, the staurolite-quartz sub-facies. In table 7 the parageneses of several of the Levang gneisses are presented, together with the anorthite content of the plagioclases. The general range for the plagioclase compositions is from An_4 in quartzites to An_{51} in diopside amphibolites. Average values are in the region of An_{22} for granitic gneisses and An_{30-35} for quartz-plagioclase gneisses and amphibolites. The table shows that the anorthite content of the plagioclases is relatable to variation in the bulk chemistry of the gneisses rather than to variations in metamorphic grades.

The Levang gneisses appear to have attained a degree of equilibrium under P-T conditions approximating to the sillimanite-almandine sub-facies of the amphibolite facies of regional metamorphism, and suffered subsequently a certain amount of retrograde metamorphism which lead to the production of epidote group minerals and chlorites.

CHAPTER 4

STRUCTURAL ANALYSIS

INTRODUCTION

A considerable amount of work has been done by Norwegian and foreign geologists on this interesting and relatively well exposed tract of Pre-Cambrian rocks, but these studies have been concerned almost exclusively with mineralogical and petrological questions, and little has been written about the structure of the region. As recently as 1950, Selmer-Olsen expressed the opinion that folding was rare in the Bamble Formation, being almost confined to mica-schists.

Barth, (1947,a), working on the Iveland-Evje amphibolite north of Kristiansand, recognized two periods of folding, an earlier one about north west - south east axes, and a later phase about north - south axes.

Wegmann, (1960), was of the opinion that the Bamble Formation, which he described as an old sedimentary formation of quartzites, greywackes, schists, limestones, and basic intrusives, had been folded at different times in different ways, and he postulated three main phases of deformation. The oldest phase involved folding and metamorphism at a relatively shallow level in the earth's crust, together with intrusion of ophiolites and granodioritic rocks (gneiss-granite). The second phase took place at a much deeper level within the front of migmatization, refolding of the earlier folds resulting in extremely complex structures.

This deformation Wegmann believes to have been accompanied by intensive and extensive granitization, giving rise to a series of granitic rocks ranging from true intrusive types to augen gneisses with big orthoclases. In the Arendal region, a series of rocks which included granites and pegmatites was folded, during the first phase, about axes trending more or less north - south. The superimposed younger folds of the second deformation are folded about roughly north east-south west trending axes. Wegmann states that the sub-stratum of the sedimentary series has probably been completely mobilised and is now no longer descernable. The last movements of this second phase were cataclastic, leading to the final period of movements which are believed to have occurred at a relatively high level in a rather stiff basement. This phase is manifested by extensive zones of mylonitization, the result of widespread faulting and thrusting which dissected the area into a series of rhomhohedral slices. The last of the more important displacements were probably of Caledonian age, and some movements along these zones may have recurred in Permian or even Tertiary times.

Elders, (1961), makes the observation that the general strike of the rocks throughout the major part of south east Aust-Agder trends 030°, especially in the eastern part. North east of the Herefoss granite there is a complex of major, apparently cylindroidal, almost isoclinal folds, with sub-vertical axial planes striking east of north, the axes of which plunge south south west at angles up to 45°. Elders (op. cit.) believes that in the Bamble Formation as a whole major folds, with moderate plunges and steeply dipping axial planes almost parallel to the general strike of the gneisses, are commonly developed. These folds appear to be older than the migmatization and are believed to be the oldest structures in the area.

As far as the Levang peninsula in particular is concerned, there has not been any work done on the structure of the area. Hofseth, (1942), failed to recognize the presence of any of the major folds within the main mass of the Levang granite-gneiss. She states that "the structure is clearly seen on the map, on the surface of the rock in the field, in hand specimen, and in thin section.......The direction of the (foliation) planes is always more or less vertical with dips towards the north. The surface of the rock consequently shows a striation which varies a little in the different parts of the granite." She also states that, "this vertical foliation suggests an upward movement of the granite." The existence of a fold complex within the Levang granite gneiss was first deduced from an examination of the aerial photographs of the area, and these subsequently proved invaluable during field mapping, all of which was carried out on the basis of photographs enlarged to a scale of 1:10,000. The topographical maps of this part of Norway are poor, and this, coupled with the fact that Hofseth did not have aerial photographs at her disposal, may help to explain her neglect of this aspect of the geology of Levang.

Methods of Analysis

The method of presentation of structural data makes use of the stereographic projection on the lower half of a Lambert

Equal Area net of the various structural elements, viz., poles to the planes of foliation, lineations, and minor fold axes. The poles to the foliation, S, are termed πS. The inferred plane of symmetry for the fold may also be entered in the πS diagram. In a symmetrical fold this is a line which passes through the centre of the stereogram, that for an asymmetrical fold being a line passing through the plotted β axis of the fold.

The following extract is taken from a paper by McIntyre and Christie, (1957, p.646) - "The fold axis can.......be defined as the nearest approximation (for we are dealing with real folds) to the line which, moved parallel to itself, generates the fold.......any structures which can reasonably closely be defined in terms of a rectilinear generator and which are therefore homogeneous with respect to the fold axis, are said to be cylindroidal. An area can be tested for this homogeneity by plotting the normals to the bedding (or foliation in a metamorphic terrain) on a standard stereographic projection. The more nearly cylindroidal the structure, the more closely will the normals to the bedding lie on a great circle, the pole of which defines the trend and plunge of the fold axis."

In a cylindroidal fold (i.e. one which can be described by the rotation of a plane about the rectilinear axis β) all the linear structures would be expected to be parallel to the fold axis. In nature, however, folds are not persistent in the plunge or bearing of the axis, and the profile changes constantly as it is traced for any distance. If the data from a large area having a complex structure are plotted stereographically, in the resulting πS diagram the structural elements will not be concentrated systematically about a great circle girdle for πS and a pole position for **B** lineations, and the diagram will have triclinic symmetry.

It follows that in order to demonstrate adequately the structure of an area, it must be divided into a number of sub-areas, within which πS can be related to discernable folds so as to produce monoclinically symmetrical πS diagrams. Each sub-area must be of such size that the πS plots are statistically distributed about β, when the part of the fold concerned can be considered to be cylindroidal. The relationship between πS and 'a' and **B** lineations can later be determined by entering the plots of the latter in the πS diagram. It is only by a process of sub-division and examination of distinct sub-areas that the inter-relation of the folds in the whole area can be determined.

Where two or more sub-areas are seen to be related, the data from each can be combined in a single synoptic diagram which shows foliations, lineations, or both. πS diagrams are also plotted for sub-areas within which no discernable fold culmination had been observed in the field, all lineations and minor fold axes also being included.

In this account reference will be made to three different classes of symmetry in the πS diagrams. Those diagrams with orthorhombic symmetry have a distribution of πS plots which possesses three, mutually perpendicular, planes of symmetry, (mmm). The πS diagram fig. 18, for sub-area 8, the Tonstöl Lakes area, is an example of this type. Diagrams with monoclinic symmetry have a single plane of symmetry, corresponding to a great circle in the stereographic net, which passes through the plots of the poles to the foliation, (see, for example, fig. 15C, for sub-area

3 in the Heligesvann antiform.) In diagrams with triclinic symmetry, no planes of symmetry can be drawn through the πS plots. Fig. 29A, which is a synoptic diagram for the foliations in the eastern part of the Myre Dome, is an example of this type. A fourth class, termed axial symmetry, is found in fabric analyses but not in folds. In it the plots have the symmetry of a cylinder, that is, in projection there is a unique axis which is the line of intersection of an infinite number of planes of symmetry, and is normal to another plane of symmetry. Fairbairn, (1949), points out that in tectonites this type of symmetry would require flow within cylindrical walls, and that it is thus probably of greater significance in problems of magmatic flow.

The Regional Foliation S.

In this account, the term foliation is synonymous with schistosity, and, following Turner and Verhoogen, (1951), it has been used in a non-genetic sense to include all megascopically discernable parallel fabrics which tend to impart a certain degree of fissility parallel to their planes in the rocks in which they occur.

A concept which is of considerable importance in structural geology, the S surface, includes both the type of foliation defined above, and also all statistical surfaces indicated by the lattice orientation of any fabric element. Fairbairn, (1949), is of the opinion that the classification of tectonites by Sander into S tectonites, (in which there is one S surface), and B tectonites (which have several S surfaces), is not necessary because of the increasing number of unclassifiable examples now known.

Only rarely do the metamorphic rocks of the Levang peninsula fail to exhibit a well developed foliation. In the purer quartzites a foliation is occasionally difficult to discern in the field, but this is due to the low content of mafic minerals, and the rock is seldom, if ever, massive.

All the rock units are lens-shaped on a large scale, probably for the most part the result of differential competency in adjusting to stress during deformation. However, the foliation is found to parallel lithological boundaries on both a local and regional scale, and, as such, is believed to coincide essentially with the original depositional layering in the para-gneisses, these making up by far the greater part of the metamorphics. Secondary S surfaces which transgress this depositional foliation have been met with. Fig. 13A illustrates a small anticlinal fold in sillimanite gneiss in which the sillimanite nodules can be clearly seen to have their long axes in the plane of a secondary axial plane foliation.

Hofseth, (1942, p.20), states, that, "the Levang granite (gneiss) is foliated along the whole area, a little weaker in the centre, but there are also a few small, unfoliated, coarse-grained parts," concluding that, "the rock must be called a gneiss granite". She does not specify the localities of the unfoliated parts of the granitic rocks, and in the course of the field work connected to the present study some degree of preferred orientation of the constituent minerals was invariably noted, (although occasionally difficult to discern), throughout the mass, and the granite gneiss was never observed to be massive.

The factors contributing towards a foliation in the Levang granite gneiss were as follows:

(1) There is a marked parallelism of the potash feldspar 'augen', where these occur.

(2) Preferred orientation of the platy mafic minerals, particularly biotite, and of the nematoblastic amphibole.

(3) A banding, the result of marked compositional differences between adjacent horizons in the granite gneiss is frequently prominent, (see pl. 10).

(4) Stretching of xenoblastic quartz and, to a lesser extent, plagioclase.

(5) Parallelism of basic 'inclusions' to the foliation of the granite gneiss.

Fig. 35 illustrates the various structures found in the granite, viz. foliation, lineation, and banding (with lineation). Not represented a fourth commonly occurring structure, a combined foliation and lineation.

The commonest linear structures found in this area are minor fold axes, preferred orientation of minerals, and striations; less common are crenulations, necks of boudins, and mullions.

The discussion of the origin of the linear structures and of the foliation in the granite gneiss will be deferred until the structural geometry of the area has been described.

THE GEOMETRY OF S IN THE GRANITE GNEISS

The Heligesvann Antiform

This structure is unique among those found within the Levang granite-gneiss, in that it shows a distinct and almost continuous marker horizon, analogous to those described by A. Berthelsen from the Tovqussaq region in western Greenland, (1960). This horizon is represented in Heligesvann by a micaceous amphibolite, while the Greenland rocks are pyrobolites, i.e. plagioclase-bearing rocks in which orthorhombic and clinopyroxenes about equal or exceed the hornblende in amount. The general form of this fold is that of a somewhat asymmetrical doubly plunging anticline. The ratio of length to breadth, as defined by the marker amphibolite, is approximately 4:1.

The series of rock-types exposed in this antiform has been described above (p. 21). The whole of the central area is occupied by a light grey quartz-rich rock, in which the mafics are low and microcline is absent or present in only accessory amounts of less than 2%. Foliation is well developed, but is not easily seen in the field because of the low content of mafics.

Forming a cover to the quartz-plagioclase gneiss is a sheet of micaceous amphibolite, which varies in thickness from 50 to 100 m. The otherwise completely continuous amphibolite exposure is interrupted in the north east by the small lake of Heligesvann, but the outcrop pattern is such that it is reasonable to assume that the body is a continuous one.

The next layer in the sequence is a relatively coarse-grained rock, with a high content of mafic minerals, containing pink potash feldspars together with abundant garnets. Between the limit of this rock-type on the north limb of the fold and the amphibolites and mica-schists of the 'envelope', a lighter, non-garnetiferous granitic gneiss is exposed. To the south the relations are complicated by the proximity of the Kapel 'Basin' folds, and by the presence of a thick amphibolite gneiss the equivalent of which is not seen on the north side of the axis.

For the purpose of analysis, the Heligesvann antiform has been divided into six sub-areas, the limits of which are shown in figs. 14 and 17. The stereographic πS diagrams appear in fig. 15.

Sub-Area 1.- This sub-area covers that part of the fold where the general plunge of the axis is towards the south west. Its size and location are shown in fig. 14.

The rock-types involved include all those mentioned above. The amphibolite layer can be seen clearly on the aerial photographs to close around the nose of the fold. It is about 80 m. thick in the northern limb, but is 130 m. thick in the southern, where it is split by a lens of garnetiferous granite-gneiss. This lens can be followed for 900 m. along the strike within the amphibolite. These complex relationsships may be an indication of very early isoclinal folding, later re-folding resulting in the formation of the present non-isoclinal structures.

The trend of the foliations in the northern limb is 030°, with dips of 50 to 60° towards the north west at the level of the marker horizon. As the axial zone is approached, the strike

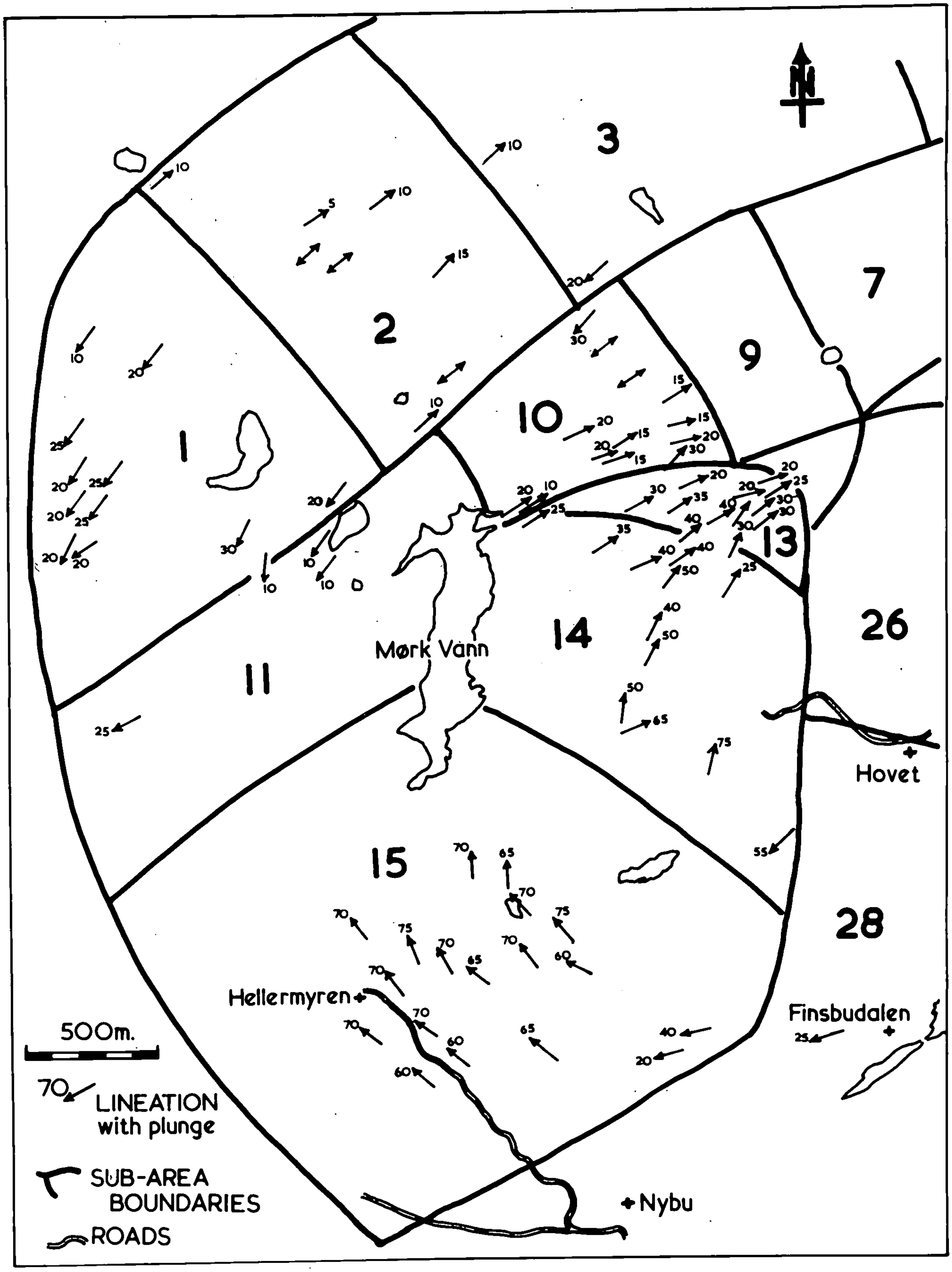
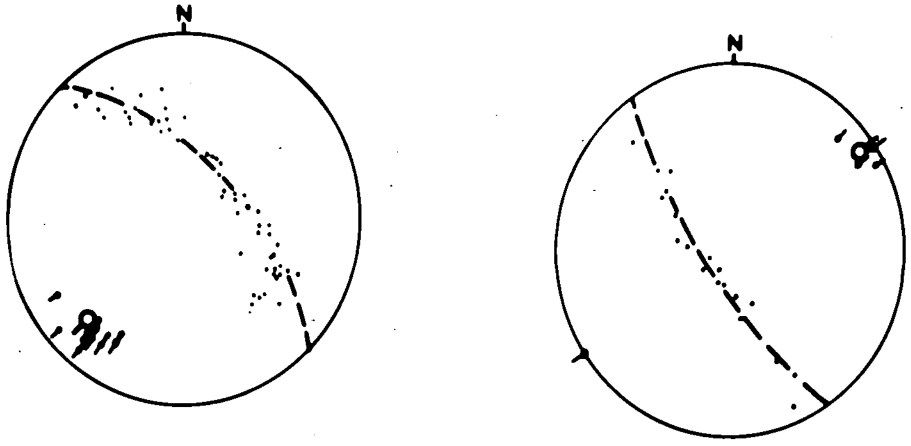

N
1
2
3
7
9
10
11
13
14
15
26
28
Mørk Vann
Hovet
Hellermyren
Finsbudalen
Nybu
500m.
70
LINEATION with plunge
SUB-AREA BOUNDARIES
ROADS

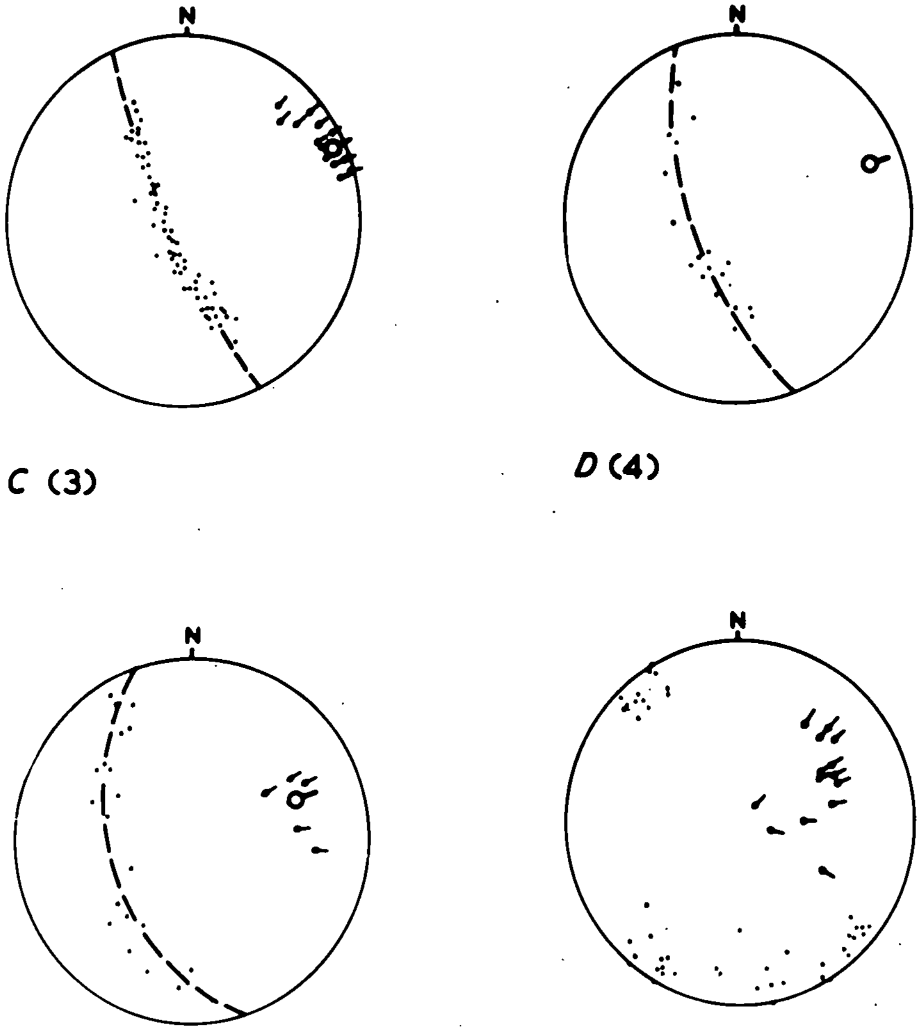
FIG. 14



A (1)

B (2)

HELIGESVANN ANTIFORM



C (3)

D (4)

E (5)

F (6)

FIG. 15 πS DIAGRAMS

swings smoothly to 005° dipping 35 to 40° due west, then the foliation is bent abruptly over the hingle line, where the minimum dip is 20° to the southwest, again at the level of the basic gneiss. The southern limb with its more complex 'layering' trends due east with a dip of 45 to 50°, then turns to strike 050° at a point south of the small lake, (192 198).

There is a concentration of granitic pegmatites in the hinge zone, particularly at the level of the amphibolite. Probably they occupy tensional low pressure regions, especially in the relatively competent basic rock.

The πS diagram, fig. 15A shows 54 poles to the foliation, evenly distributed on both limbs, and displaying a high degree of symmetry. The poles define very readily a great circle, the axis of which plunges 25° bearing 225°. This is the β axis of the fold which can be said to be statistically cylindroidal within the given sub-area, since the symmetry of the πS diagram is monoclinic. The plots of the linear structures cluster around the plotted axis, indicating that these are **B** lineations.

The twelve linear structures measured were all produced by a preferred mineral orientation.

The fold thus defined is an asymmetrical plunging anticline, the southern limb being the steeper, and the axial plane dips at about 80° towards the north west.

<u>Sub-Area 2</u>.- This sub-area is over that part of the Heligesvann antiform where the foliation is beginning to close about a roughly north east trending axis.

Within this sub-area, the limits of which are shown in fig. 14, the northern limb has a more-or-less constant trend at the marker horizon of 060°, with a dip of 50° northwest. The trend of the foliation changes smoothly over the axis, dipping shallowly to the north east, and in the southern limb strikes 050°, at a 60° dip.

The πS diagram, (fig. 15B), on which 19 poles to the foliation have been plotted, possesses monoclinic symmetry about a β axis plunging 10°, bearing 054°. Four B lineations, all measured on foliation planes in the central quartzose gneiss, correlate closely with the statistical axis.

The structure here is that of an asymmetrical anticlinal fold, plunging north east, and with a sub-vertical axial plane.

Sub-Area 3.- This sub-area is situated around and to the west of Heligesvann, (fig. 17). Within it the eastern termination of the basic 'marker horizon' is situated, the two ends of the sheet running into the north and south shores of the lake, which is 150 m. wide at that point, concealing the hinge zone.

Exposed in the outer part of the southern limb are two thin biotite amphibolite layers, 'interbedded' with the garnetiferous granite-gneiss. These are not seen at the equivalent stratigraphical horizon in the other limb.

The closure of the gneissic foliation to form this fold is very clearly seen on the aerial photographs.

The strike of the foliation in the northern limb away from the axial region is 075°, turning to 090° just north of the lake. The dip at the marker horizon is 35 to 40°, towards the north, increasing to 55 to 60° at the edge of the sub-area. The foliation swings very abruptly over the hinge to trend 055° to 065° in the southern limb, with dips of 50 to 60° in the amphibolite.

65 poles to the foliation have been plotted in the πS diagram, fig. 15C. These define, with the minimum of ambiguity of interpretation, a β axis plunging 10°, bearing 065°.

The 13 linear elements plotted are all interpreted as **B** lineations. The observed scatter biased to the north of the statistical axis reflects the general change in the trend of the structure as a whole towards an east-west strike. Compared with the last sub-area, the bearing of the axis has changed from 054° to 065°. The plunge is the same, at 10°, but the fold style is tighter while retaining the same degree of asymmetry.

<u>Sub-Area 4</u>.- Lying entirely within an area of garnetiferous granite-gneiss, this sub-area is much smaller than the others so far examined. It is situated immediately east of Heligesvann, (see fig. 17). (Its small size is dictated by the fact that east of the lake the plunge of the fold axis begins to change rapidly.)

No basic gneisses were mapped within the well foliated granite-gneiss.

The northern limb of the fold trends around 110° to 130° with dips of 35 to 40° to the north east. The foliation in the southern limb strikes 060°, dipping south east at about 50°. When the 18 poles to the foliation have been plotted on the πS diagram, fig. 15D, they define a great circle, the pole of which plunges 20°, in the direction 069°.

The general structure of the region to the north and east of Heligesvann is suggestive of the development of a 'box' type fold. The second fold axis would trend roughly due north, through Heibø farm, (210 222), with a steeply plunging axis at around 50°. The northern limb of the main Heligesvann antiform, as just described in sub-area 3, would thus be the 'middle' limb of this partly developed box fold, and the trends for the three limbs would be 075°, 130°, and 060°, for the northern, eastern, and southern, respectively.

Sub-Area 5.- The limits of this sub-area, shown in fig. 17, were chosen so as to cover the easternmost extension of a recognizable anticlinal structure in the Heligesvann region.

A biotite amphibolite gneiss carrying accessory garnet has been mapped as a conformable sheet in the southern limb of the fold, extending into the hinge zone. Over the rest of the sub-area, granitic gneiss, with a variable garnet content, is exposed.

Although the fold trend is easily seen on aerial photographs, the strike and dip of the foliation were not easy to measure in the field, especially in the axial zone. A mineralogical lineation was the most obvious structural element. A certain amount of recrystallization during deformation of the constituent minerals parallel to the axial plane of the fold, might be sufficient to obscure the pre-existing foliation in a rock which lacked marked differences in composition between layers, without necessarily producing a well defined axial plane foliation.

The northern limb of the fold strikes 120° to 130°, with a dip to the north east of 55 to 65°. The southern limb trends at 060°, and dips 70 to 80° at the limits of the sub-area.

The poles to the foliation shown in fig. 15E, do not show an even spread because of the deficiency in readings from the hinge of the fold, but they nevertheless are concentrated about a girdle, the pole of which plunges 38°, in the direction 076°. This is the computed β axis of the fold.

Five lineations, produced by a preferred mineralogical orientation, are grouped around this axis.

The fold thus defined is an asymmetrical anticline, with a very steeply dipping southern limb and an axial plane inclined at a high angle, at least 70°, towards the north.

<u>Sub-Area 6.</u>- This sub-area lies immediately to the east of sub-area 5, (see fig. 17), and within it the structures are extremely complex.

The southern limb of the anticline steepens from 60° to 80°, and further north east to vertical, as the trend changes from 060° to 040°. The foliation thus shows no tendency to close over an axis.

The northern limb, as it is traced from the region of Heibø farm, turns from 110° to trend 130° as the dip steepens to 75 to 85°, and then at the axial zone, (projected north east from the last sub-area), swings abruptly to strike parallel to the foliation in the southern limb.

These relationships are clearly seen on the aerial photographs in the trends of the topographic features.

The πS diagram, fig. 15F, in which 45 poles to the foliation have been plotted, possesses a low order of symmetry, viz. triclinic, and the poles do not define a single girdle. It is possible to draw a great circle through the poles grouped in the lower part of the diagram, to define a pseudo-synclinal axis trending due north, enclosed within the northern limb as described above.

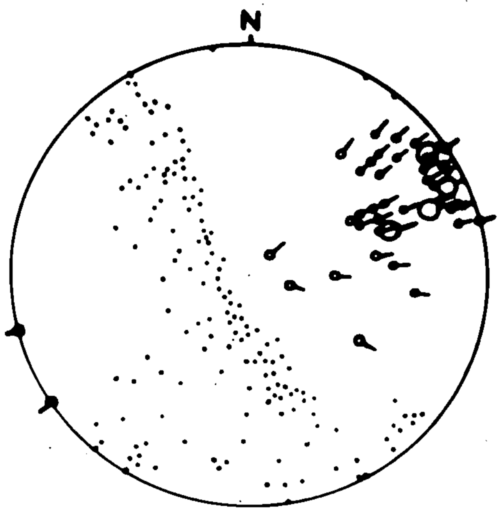
The deficiency of poles in the western section of the diagram can be attributed to an absence of north-south trending, easterly dipping foliation planes.

The linear structures are scattered about 90° of arc, and vary in plunge from 30 to 80°. Some may be β lineations for the synclinal axis.

Garnetiferous granite-gneiss is exposed in the (extrapolated) axial zone, and a large body of dark amphibolite, poor in felsic minerals, is observed to follow the swing towards the north east in the northern limb.

The synoptic diagram combining πS diagrams B.-F. is shown in fig. 16. This illustrates the marked change in trend of the structure as a whole, which amounts to over 30° when the south west plunging axis is taken into account, (it is not shown in the synoptic diagram).

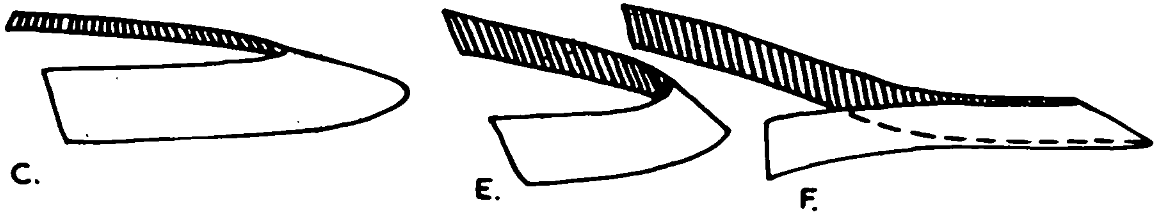
The proposed interpretation of the structure in sub-area 6 is that here the antiform is extremely tightly appressed into an isocline, the hinge of which has been sheared out and/or obscured by an axial plane foliation. The attitude of plunge of the axis of the isocline is conjectural, but the linear elements in the region suggest a plunge of approximately 40° bearing 040°.



SYNOPTIC DIAGRAM B.→F.

FIG. 16

EASTERN HELIGESVANN ANTIFORM.



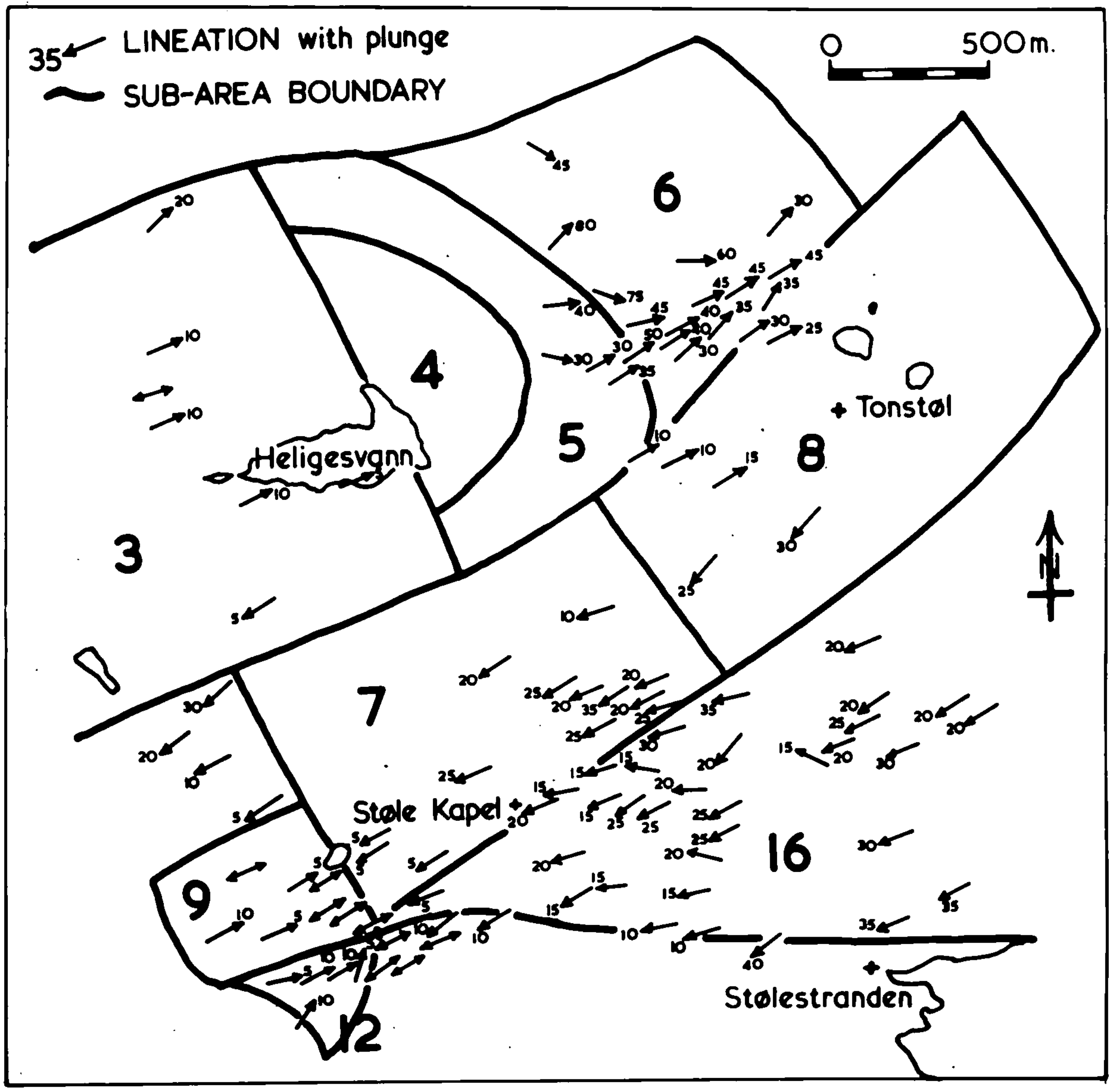

35 LINEATION with plunge
SUB-AREA BOUNDARY
0 500m.
N
3
4
5
6
7
8
9
12
16
Heligesvann
Tonstøl
Støle Kapel
Stølestranden

FIG. 17

In fig. 16 schematic representations of the general foliation trends in sub-areas 3, 5, and 6, are presented, showing how the isoclinal folding in area 6 is developed.

The close proximity of the large and very rigid mass of the Heibø hyperite may have been at least in part responsible for the tightening of the Heligesvann fold to the south east, since the fold form and trend suggest that it was formed as a result of shortening about a north west - south east direction.

The Kapelen Basin

This structure lies to the south of, and is complementary to, the Heligesvann antiform. The structural centre is marked topographically by a small lake, (212 201).

It has, for convenience, been called a 'basin', but should more accurately be termed a doubly-plunging syncline. The ratio of length to breadth, is, as in Heligesvann, approximately 4:1.

Basic rocks, amphibolites, and biotite amphibolites, are exposed over large areas, particularly in the central and eastern parts of the structure. The granite-gneiss is for the most part garnetiferous. All these rock types are well foliated, with the exception of the central amphibolite and the granite-gneiss in a small area in the eastern part of the synform, between Støle Kapel and Tonstøl, so that even in the absence of a 'marker' horizon the fold form can readily be recognized in the field.

In order to analyse the structure, the region has been divided into five sub-areas, two covering that part of the fold which plunges westwards, and three the eastwards plunging axis.

The eastern part of the fold will be dealt with first.

Sub-Area 7.- The location of this sub-area is shown in fig. 17. The northern limit has been arbitrarily drawn halfway between the respective hinge zones of the synform and of the Heligesvann antiform, since the common limb has a more-or-less constant strike and dip for a distance of several hundred metres, measured perpendicular to the strike. The southern limit can be much more exactly defined, because there is a rapid change in the strike of the foliation from the synform into the nose of the westwards extension of the Grönsvik anticline, to the east of Stöle Kapel. The western limit is drawn through the lake, mentioned above, and the eastern boundary encloses the limit of the area where a fold 'closure' can still be mapped.

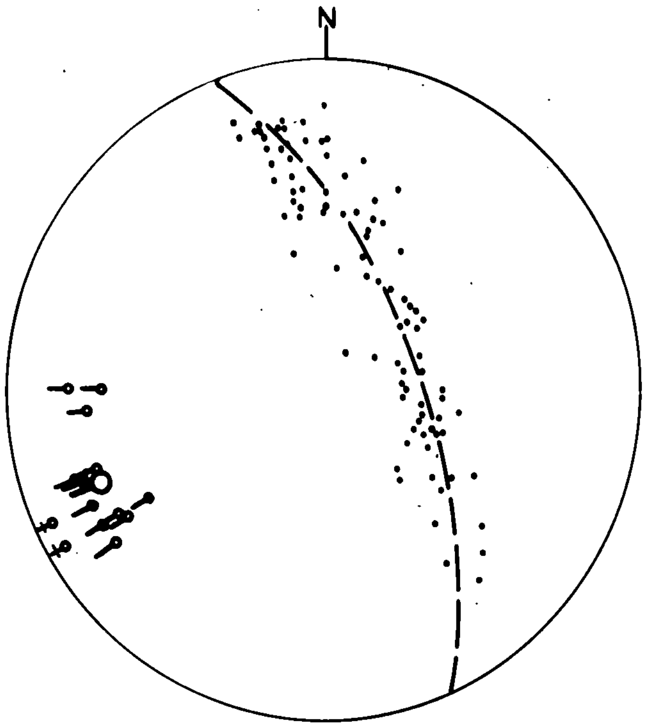
A mesocratic amphibolite gneiss with about equal proportions of common hornblende and andesine plagioclase, together with accessory quartz and biotite, is exposed in the centre of the 'basin'. A strong lineation, caused by the parallel alignment of the nematoblastic amphibole, is the main structural element in this rock, the foliation being very ill-defined or absent. Surrounding this basic gneiss is a foliated granitic gneiss, frequently garnetiferous, which shows a very complex 'migmatitic' relationship to the amphibolites and biotite amphibolites exposed around, and to the north of, Stöle Kapel. The exposure pattern of these latter rocks is that of a series of crescentic arcs, broad in the axial region of the fold and thinning rapidly in each limb. The broadening of the outcrops is in part due to the decrease in the angle of dip of the foliation, but there does also appear to be a definite thickening of the individual units in the hinge zone. Similar crescentic outcrop patterns are seen in the amphibolites of the western part of the synform, and it seems probable that the rapid attenuation of these mafic masses is due to shearing in the limbs of the fold.

Also outcropping within this area is a sheet of biotite amphibolite which can be traced with certainty for over 3 km., from the north eastern edge of this sub-area to a point west of Mørk Vann, (198 192). It forms parts of the northern limb of the fold, and here attains a maximum thickness of about 35 m.

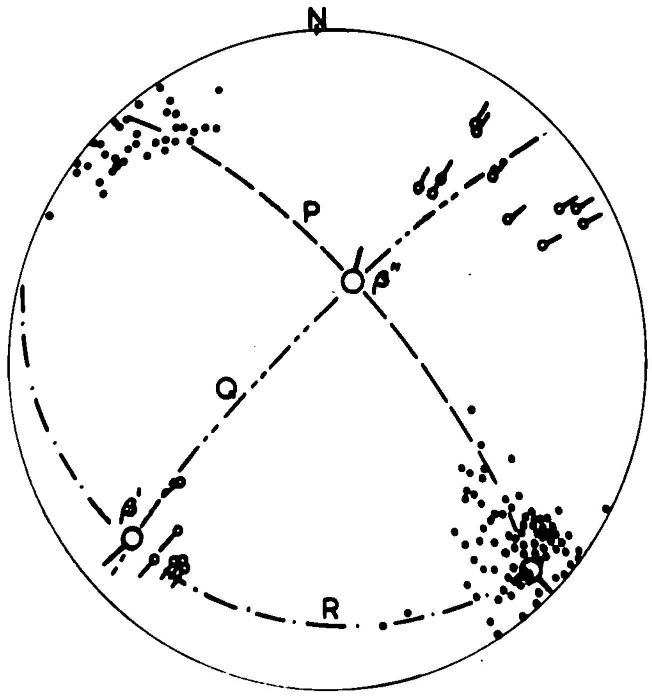
In the πS diagram, fig. 18, 92 poles to the foliation have been plotted, there being fewer readings from the southern limb of the fold as compared to the northern. This is because, apart from a concentration in the hinge zone, readings were taken from localities evenly spread over the sub-area, and the southern limb is not developed as fully as the northern, because of the close proximity of the anticlinal Grønsvik axis. The poles define, without any ambiguity, a great circle the axis of which plunges 25° in the direction 250°.

It should be noted, that in as far as the sub-area includes those central parts of the structure in which the foliation is flat-lying, i.e. in the centre of the 'basin', the degree of pitch of the statistical β axis is an average value.

A total of 14 linear structures have been plotted, and these correlate fairly closely with the computed axis, indicating that they are B lineations. The two lineation plots denoted by a crossed symbol were measured in the central amphibolite.



EASTERN KAPEL BASIN



TONSTØL LAKES AREA

FIG 18 πS DIAGRAMS

The symmetry of the πS diagram is monclinic, and the fold is statistically cylindroidal. The fold thus defined is a symmetrical syncline with a sub-vertical axial plane, and an axis trending 250°.

<u>Sub-Area 8</u>.- Tonstøl farm, (227 215), lies at the centre of this sub-area, which is situated north east of sub-area 7 (fig. 17).

Within it, particularly in the region around the Tonstøl lakes and to the north east, there is a very complex relationship between the mafic and felsic gneisses. Elaborate interdigitating of the two rock types as in typical migmatites is seen. The granitic gneisses in part contain garnets, as does one of the larger amphibolite lenses. The mafic units are amphibolites, bi-amphibolites and hornblende biotite schists.

In general the rocks are well foliated, with the exception of a basic sheet presumed to be metadiabase which can be traced in intermittent exposures for a distance of several hundred metres, parallel to the foliation of the gneisses. It is well exposed where it crosses the track from Tonstøl to the main road.

The dip of the foliation is steep throughout the area. There is a general north west dip in the gneisses in the south eastern part of the sub-area, but in the central and north western section dips are vertical or towards the south east.

A total of 117 poles to the foliation have been plotted on the πS diagram (Fig. 18). These are concentrated in the south east and north west sections of the diagram, reflecting the constancy of strike and the absence of shallow dipping foliation planes.

The poles do not define a single girdle, and the symmetry of this diagram, without taking into consideration the linear structures, approaches orthorhombic. It is thus possible to draw three different planes of symmetry, all mutually inclined at 90°.

On the basis of the slight asymmetry of the grouping of the poles, the great circle P has been drawn (see fig. 18) to represent a possible plane of symmetry. The pole to this great circle, β', plunges 20° in the direction 230°. At right angles to the plane P, the great circle R is the trace of a second plane of symmetry. Its pole, β'', plunges 70° bearing 020°. The third plane is represented by the great circle Q, the pole of which pitches 10°, in the direction 140°. This third axis lies within the greatest concentration of πS plots, and as such need not further be considered since it cannot possibly represent a β tectonic axis of rotation for a fold structure with the given distribution of foliation planes.

There are four possible fold forms with reference to the remaining two axes, based on the assumption that the fold is synclinal, there being four similar possibilities for an anticlinal structure.

Firstly, the rocks could be isoclinally folded about the gently dipping axis, β'. The limbs of the fold would be tightly appressed and the hinge very sharply overturned. The axial plane, which is represented by the great circle Q, dips very steeply towards the north west.

Secondly, monoclinal folding could have taken place about the β' axis. The implication here would be that this folding was produced by minor variations in the dip of the beds in one limb of a much larger structure, (? the Myre Dome).

Thirdly, the rocks are isoclinally folded, but about the β" axis. The fold form would be similar to the first case, but the axes are steeply plunging. The great circle Q would again represent the trace of the axial plane.

Lastly, the rocks could be monoclinally folded about the steeply dipping β" axis. The fold form would thus be an extreme example of an 'open' fold. These again could represent gentle flexures, possibly about axes corresponding to the 'a' direction, in the limbs of a much larger structure.

On examination of the πS diagram, it is found that the pole to the first plane, β', correlates well with a group of lineations pitching at around 25° towards the south west. The second axis, β", does not make any such correlation.

Most of the linear elements measured were of the mineralogical type, but several were minor isoclinal folds. A minor fold exposed on the main road south of Tonstøl, plunging 30°, bearing 045°, is probably the one mentioned by Hofseth (1942) as having been 'preserved' in the basic gneiss. The maximum plunge of any of the lineations is 40°, and the majority plunge at angles of 25° or less. The general trend of the linear structures is constant, but the direction of pitch varies, 11 plunge towards the north east, and 6 south west.

The interpretation proposed is that within this sub-area, the open fold form recognized in sub-area 7 has tightened into an isoclinal type, with long parallel limbs and a very sharp overturning at the hinge, the folding having taken place about a shallow dipping axis, e.g. the β' axis in the πS diagram, fig. 18. It is possible, that the variable attitude of the linear structures may indicate that the β tectonic axis also varies in its direction and degree of plunge. It should be noted that the tightening of the Kapelen synform takes place in the area exactly due south east of the isoclinal section of the Heligesvann antiform.

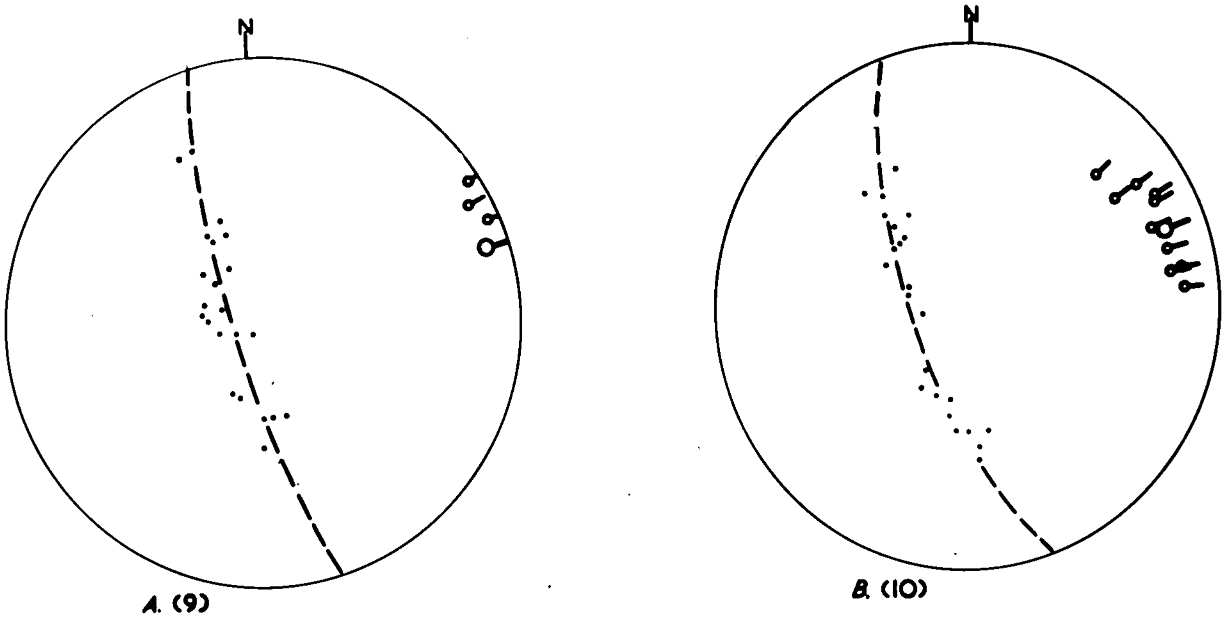
Sub-Area 9.- This is a small sub-area, situated immediately to the west of the lake, (212 201), and covers the central part of the north eastwards plunging fold.

The rock types are the same as those of sub-area 7; weakly foliated amphibolite in the centre, surrounded by more strongly gneissic granitic rocks, and a lens of biotite amphibolite in the northern limb.

In both sub-areas, 9 and 10, a fold closure can clearly be seen in the trends of the features on the aerial photographs.

In the πS diagram, fig. 19A, 22 poles to the foliation have been plotted. These can be unambiguously interpreted as describing a single girdle, and the diagram has monoclinic symmetry. The pole to this great circle plunges 10° in the direction 075°. Three lineations with similar dips have been measured bearing 060° to 070°, and these are B lineations.

The fold form within this sub-area is that of a symmetrical syncline, plunging 10° bearing 075°, and with a vertical axial plane. The foliation does not swing abruptly over the hinge, and the fold is a similar shear fold.



WESTERN KAPEL BASIN.

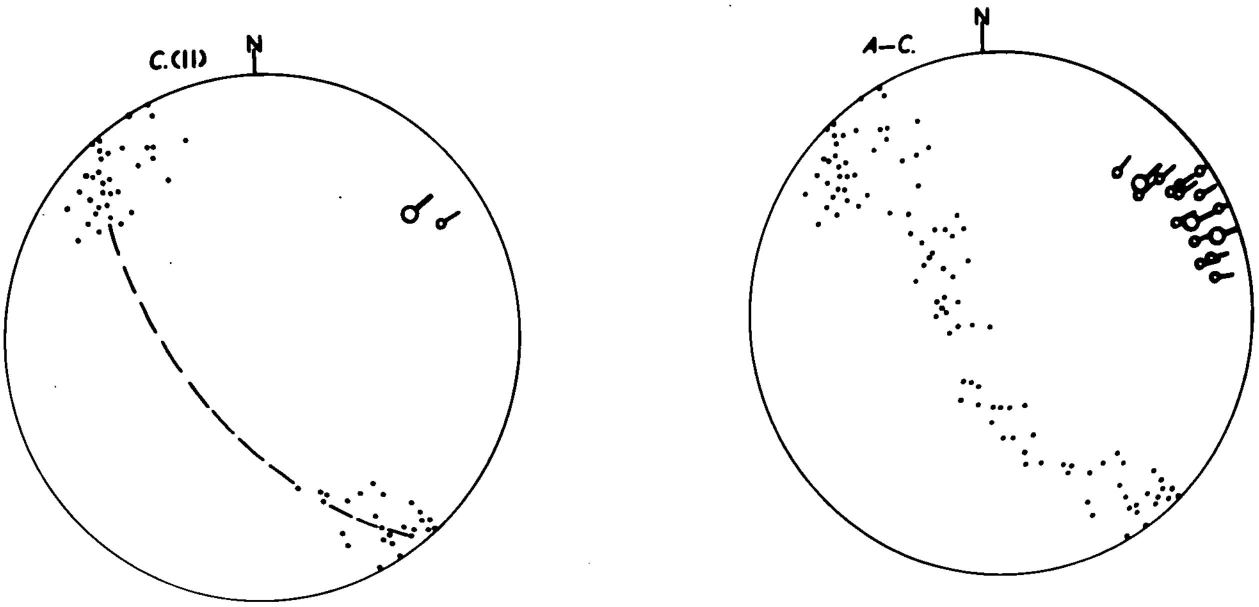


FIG.19 πS DIAGRAMS

Sub-Area 10.- Situated due west of sub-area 9, this triangular area has its apex at the north end of Mørk Vann, (198 192). The northern limit is again arbitrary, but the southern limit can be more exactly fixed against the changing strike over the anticlinal Mørk Vann axis.

It encloses that area where a definite fold closure can be demonstrated in the field.

In the eastern part of the area the amphibolite lens mentioned as outcropping in area 9 wraps around the hinge of the fold, and in the southern limb a thin sheet of very micaceous amphibolite which can be traced for over 700 m. is exposed. The latter sheet attains a maximum thickness of about 15 m.

The granite-gneiss in the central areas is non-garnetiferous, but that along the northern and southern margins, the 'lower horizon' stratigraphically speaking, is rich in garnets.

The northern limb has a general strike from 045° to 055°, with dips to the south west of 50°. The swing of the foliation over the hinge is gradual in the east, but becomes rather more sharp towards Mørk Vann. The southern limb trends east-west, with dips of about 50° towards north at the limit of the sub-area.

In the πS diagram, fig. 19B, 24 poles to the foliation have been plotted. The diagram is monoclinic in its symmetry, the poles defining a great circle the axis of which plunges 20° bearing 070°. Compared to the previous sub-area, the plunge has increased by 10° and the trend is slightly different, 5° nearer due north.

Of the 10 linear structures plotted, 6 were readings taken on flat, open, sinusoidal folds, with an amplitude of 10 to 30 cm.

These occured in thin bands of biotite amphibolite in the granite-gneiss (thickness of the bands generally less than 10 cm.) in the central and eastern parts of the sub-area, close to the hinge zone. These folds are congruous minor drag folds with the same attitude as the major fold. The remainder of the lineations plotted were caused by a preferred orientation of the minerals. The plots of the lineations correlate fairly well with the computed axis for the major fold, and they are thus interpreted as B lineations. There is no evidence of the formation of an axial plane cleavage in this area.

The structure is that of a symmetrical synclinal fold, plunging in the direction 070°, the average plunge within the area being 20°, and the axial plane is sub-vertical.

Sub-Area 11.- This sub-area lies around the northern end of Mørk Vann, and extends to the limit of mapped ground to the west (fig. 14). The boundaries are arbitrary; the northern one has been drawn through the small lake (196 197), parallel to the trend of the foliation, and the southern, also paralleling the strike, from an origin on the west side of Mørk Vann, (198 190). Over much of the area the strike of the foliation is close to 060°, although the northern end of Mørk Vann strikes from 035 to 070° have been measured. The dip of the foliation is steep throughout.

Garnetiferous granite-gneiss is the major rock type exposed, while the important micaceous amphibolite mentioned above (p. 151) as being traceable for over three kilometers merges north west of Mørk Vann with the broad complex of basic gneisses and schists seen to extend a further two kilometers to Leivann.

North of the main zone of basic gneisses the foliation dips steeply towards the south east, within this zone it is vertical or nearly so, while the rocks to the south dip steeply north westwards.

In the πS diagram, fig. 19C, a total of 61 poles to the foliation have been plotted. They are grouped in two restricted areas, in the north west and south east of the diagram, and do not define a single girdle. The symmetry is approximately orthorhombic. The diagram is similar to that for sub-area 8, fig. 18, and an interpretation using the same line of argument is therefore relevant and need not be repeated. Only one lineation has been measured in this area, and it plunges 20°, bearing 070°.

The structure on a major scale is believed to be that of an isoclinal synform, the limbs of which have been tightly appressed, folding having taken place about an axis with a fairly shallow dip towards the north east. The axial plane of the fold is vertical. In the πS diagram a great circle has been tentatively drawn, as a possible plane of symmetry for the observed distribution of poles to the foliation, the pole of which corresponds approximately to the proposed β axis for the fold.

This fold thus represents a symmetrical isoclinal extension for the more open synclinal fold of sub-area 10 to the north east. A line of extension south westwards for the computed axial zone of the latter fold divides fairly well north dipping from south dipping foliations. As in the Tonstøl Lakes area, the region where the hinge of the isocline is thought to lie is one of complex petrological relationships of the 'migmatite' type.

The synoptic diagram, fig. 19 A-C, does not depart far from monoclinic symmetry, indicating that there is no marked variation in the general trend of the structure as it is traced through the three sub-areas, and the axis of folding has a shallow dip throughout that part of the fold which has been mapped.

The Mørk Vann Antiform

This complex structure is situated to the east and south east of the large lake of Mørk Vann. It is notable for its comparative lack of basic rock units, particularly in the eastern part of the fold. Lying immediately to the south of the Kapelen synform, this structure is complementary to it. Over most of the area, the felsic gneiss contains potash feldspar, but garnet is not common. The gneisses are well foliated in the region of Mørk Vann and towards the boundary of the granite-gneiss, but in the central parts of the structure the trend of the foliation with reference to the major fold is frequently totally obscured by very complex minor folding.

For the purposes of analysis, the Mørk Vann antiform has been divided into four sub-areas, the limits of which are shown in figs. 14 and 17.

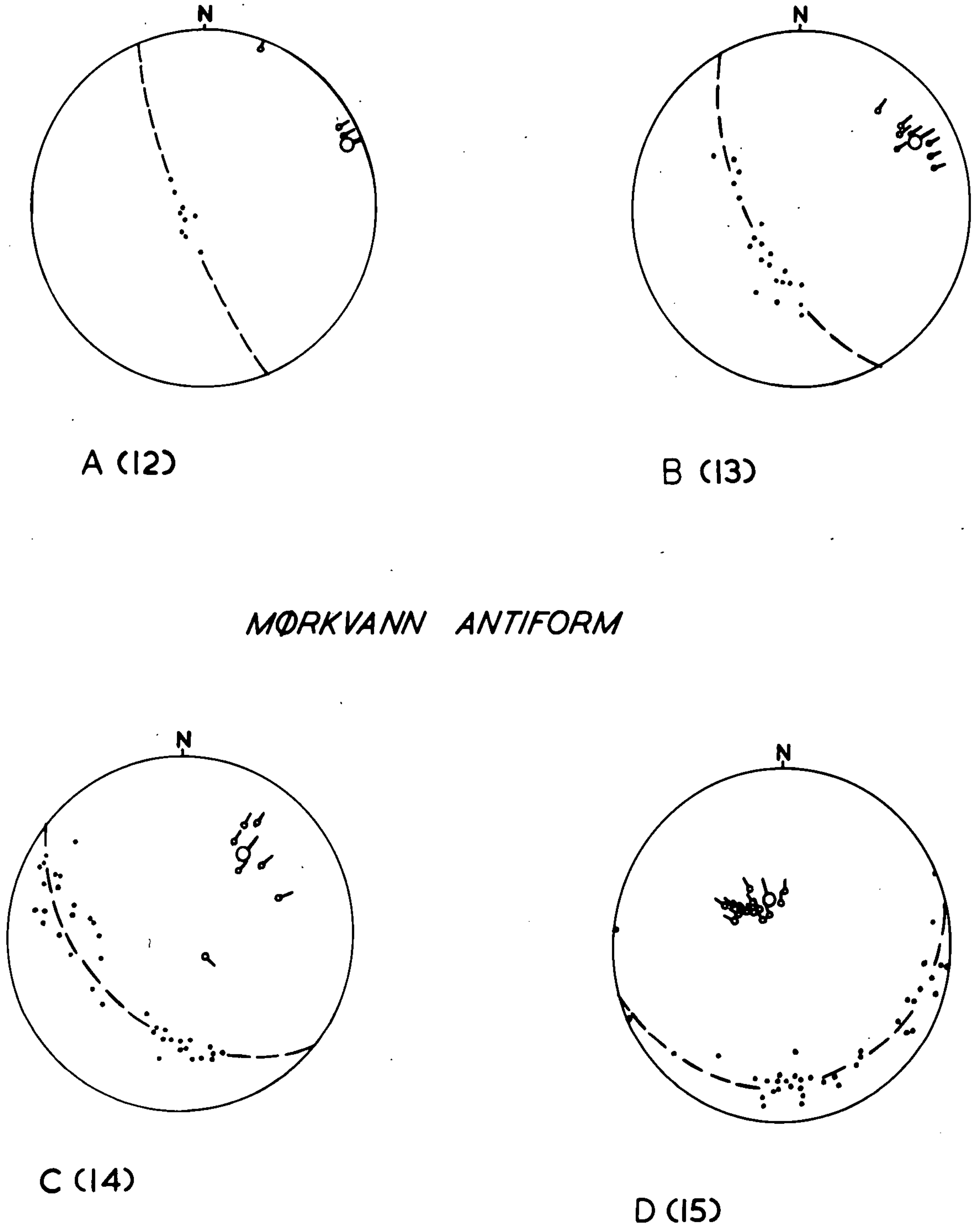
Sub-Area 12.- This is a very small sub-area, situated to the south west of Kapelen, on the nose of the fold. It covers the limit of closure of the foliation about a roughly north eastwards trending structure, the fold merging into an area of horizontal foliation in the structural 'col' around Stavsengen farm, (212 198). This part of the fold is clearly visible on the aerial photographs in the trends of the features.

The northern limb of the fold strikes east-west, with a dip of up to 20° to the north. The foliation swings gradually over the hinge, and the eastern limb trends 010°, also with a dip of 20°, to the east. Only granite gneiss is exposed in this sub-area and it is well foliated.

In the πS diagram, fig. 20A, nine poles to the foliation have been plotted. Because the maximum dip within the area is only 20°, the plots are restricted to the centre of the diagram, but they nevertheless define fairly well a single girdle, giving the diagram monoclinic symmetry. The pole to this girdle plunges 10°, in the direction 070°. The attitude of this β axis thus closely parallels that of the Kapelen synform to the north, which plunges 10° bearing 075°. Two mineralogical lineations correlate well with the computed axis, and these are thus B lineations.

The fold form is here that of a symmetrical anticline, plunging at a very shallow angle east-north-east, and the axial plane is vertical.

Sub-Area 13.- The strike of the fairly well defined foliation in the granite gneiss of the northern limb of the fold is east-west, with dips to the north of 45 to 50°. At the highest stratigraphic horizon in this part of the fold the granitic gneiss is garnetiferous. The foliation can be seen to swing smoothly over the



MØRKVANN ANTIFORM

FIG.20 πS DIAGRAMS

axial zone into the eastern limb, which trends 030°, with dips of up to 45° to the east.

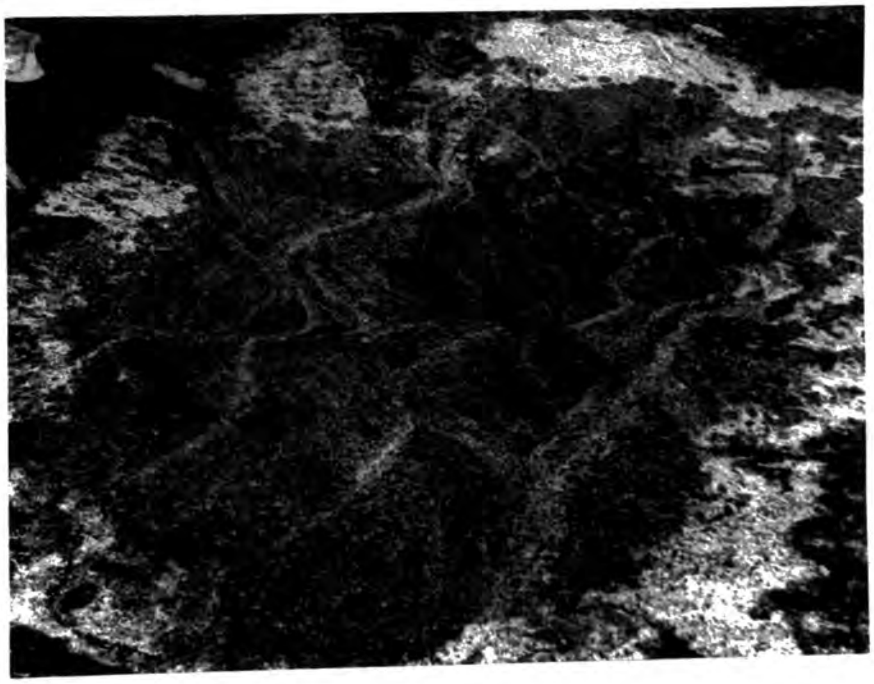
A total of 21 poles to the foliation have been plotted in the πS diagram, fig.20B. These describe a single girdle, and the diagram possesses monoclinic symmetry, indicating that the fold is statistically cylindroidal within this sub-area. The girdle defines a β axis plunging in the direction 063°, at 23°.

Eight linear structures were measured and these when plotted are closely grouped around the computed axis. These lineations were seen on foliations, and represent preferred orientation of the minerals on recrystallization in the B direction.

The structure is that of an open symmetrical anticline, the limbs of which have only a moderate dip, trending about 063° at a plunge of 25°.

Sub-Area 14.- Mørk Vann forms the western limit for this sub-area (fig. 14), and along its shore a number of narrow units of biotite amphibolite are exposed. These are conformable to the foliation in the granite gneiss, but as they are traced further east they lens out short of the axial zone of the fold.

The northern limb of the fold trends 060 to 070°, with dips of 60 to 65° towards the north west. The well defined foliation of this part of the fold becomes more obscure as it is followed into the axial zone. Pl. 36 illustrates the type of elaborate minor folding of the granitic gneiss foliation which makes the determination of the true strike and dip so difficult. Towards the eastern edge of the sub-area the foliation is again more



Pl. 36. Very complex minor folding of the granite gneiss foliation near the centre of the Mork Vann antiform, 600 m. north east of Hellermyren farm.

easily measured, and the southern limb of the fold trends 030° with steep dips of up to 80°.

The 39 poles to the foliation plotted in the πS diagram, fig. 20C, define a great circle the pole to which plunges 43° bearing 039°. The scarcity of plots in that part of the diagram corresponding to the axial region of the fold has already been explained. Of the 7 linear structures plotted, 6 are grouped around the β axis, while the seventh, measured on open minor folds of low amplitude in the southern limb, has a bearing at right angles to the others, reading plunge 75° in the direction 130°. These are interpreted as minor folding about the 'a' direction. Other minor folds with similar trends were seen, but their attitude could not be determined because they were exposed in only two dimensions.

The fold form is here that of an asymmetrical antiform, with a moderately dipping northern limb and a very steep southern limb. The fold plunges 45°, bearing 040°, and the axial plane is inclined steeply towards the north west.

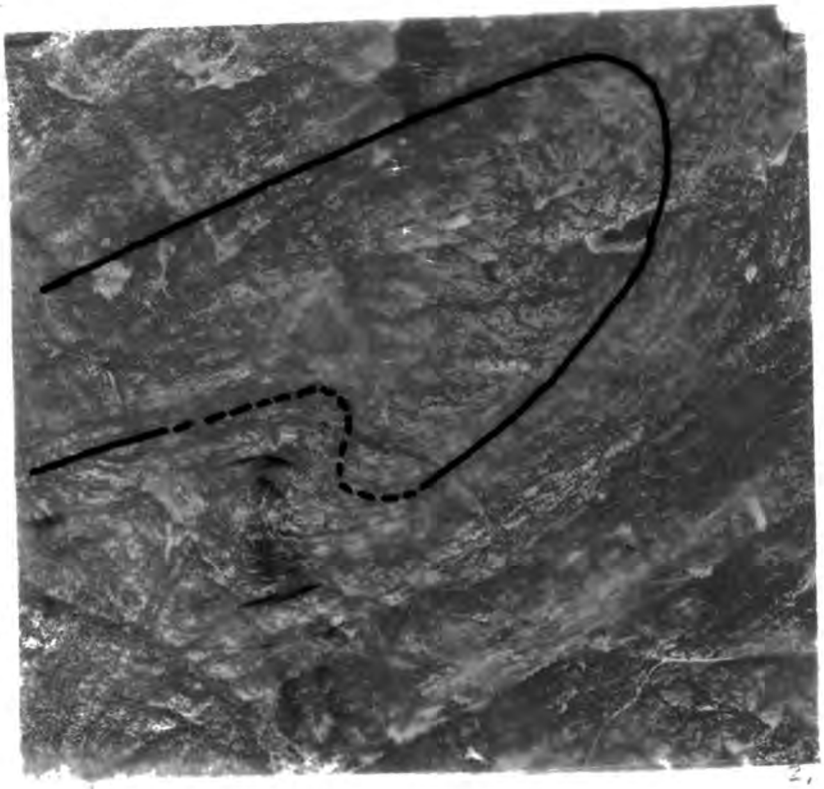
<u>Sub-Area 15</u>.- This sub-area covers the remainder of the mapped portion of this structure, and has the farm of Hellermyren (196 180) near its centre (fig. 15). The northern limit of this sub-area is shared by sub-area 11 and has been arbitrarily drawn parallel to the foliation. The north eastern boundary has been drawn to exclude that part of the structure within which a north eastwards trending fold could be domonstrated in the field, this having been dealt with in the previous three sub-areas. The southern and western boundaries extend to the granite gneiss 'contact' and

to the limit of mapped ground, respectively.

On aerial photographs the trends of the features can very clearly be seen to describe a fold form approaching a chevron type, i.e. with a 'Z' form in plan view, and with roughly north east - south west striking axial planes (see pl. 37). In the field, however, it proved extremely difficult to determine the strike of the foliation in the axial zones and in the 'middle' limb. As was the case further to the north east, minor folding on an elaborate scale is again responsible. The minor folds have steep plunges which are difficult to measure because they are generally only exposed in a horizontal plane. Pl. 38 illustrates the type of minor folding typically developed in this region. The minor folds are generally asymmetrical, and in most of the better exposed examples the longer limb was seen to be parallel to the main trend of the limb in which it occurs. These minor folds on the flanks of the major folds may be interpreted as congruous drag folds, the attitude of which reflects on a small scale that of the major structure. However, since minor folds are also extremely well developed throughout the axial regions of the major folds, these must be parasitic folds in the sense of de Sitter (1958).

In the last sub-area, the southern limb of the fold had a dip close to vertical. Further south west, in this sub-area, it 'overturns' to dip towards the north west at between 50 and 70°, shallowest near the granite gneiss 'contact', striking 060 to 070°. The northern limb of this complex fold has a similar trend, but slightly steeper dips at 60 to 80°.

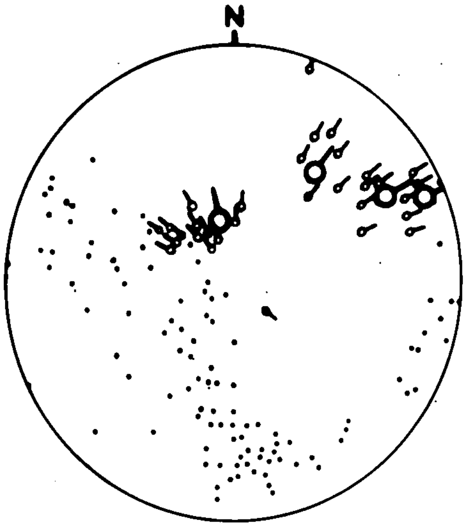
In the πS diagram, fig. 20D, the 38 poles to the foliation



Pl. 37. Aerial photograph of the Mörk Vann antiform. On the overlay the trace of the granite gneiss foliation as determined on the ground is shown by a solid line, the broken line indicates the part of the structure where minor folding obscures the strike and dip of the foliation.

Pl. 38. Minor folding in the granite gneiss at Hellermyren. Note the similarity in profiles of this fold and the major fold as seen on the aerial photograph.

MØRKVANN ANTIFORM



A→D

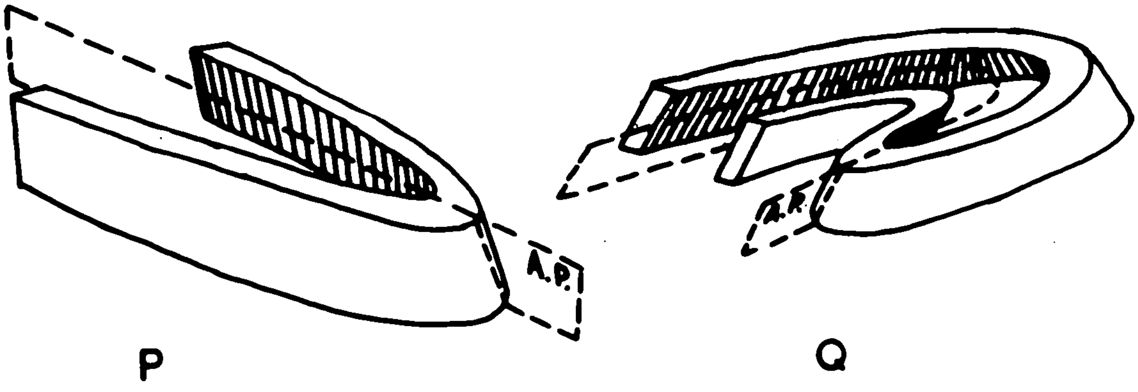


FIG. 21

are confined to a great circle close to the primitive, and the pole plunges 69° in the direction 345°.

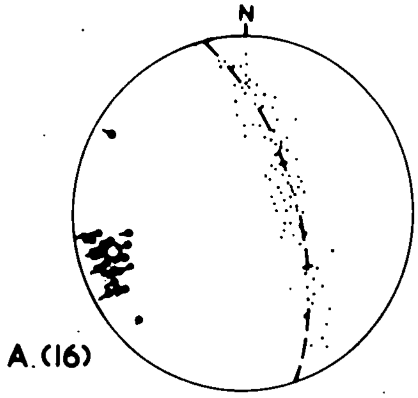
The 14 lineations plotted were measured on the axes of different sets of minor folds, and these have a markedly constant trend and plunge. They group closely around the statistical axis and are probably B lineations.

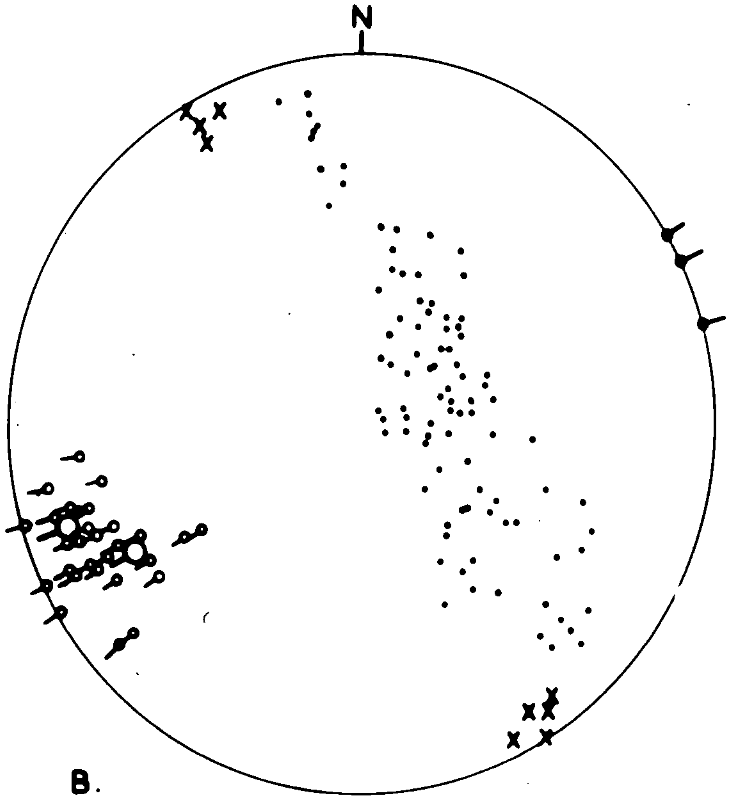
The conclusion is drawn that the fold form in this sub-area is that of a pair of folds of chevron type. The northern limb trends 070°, the middle limb trends 045° approximately, and the southern limb 070°. The β axes of both folds plunge at a steep angle, about 70°, towards north west or north north west, and the axial planes are also inclined steeply on a bearing slightly west of the trace of the axes.

The Grönsvik Antiform

The structural 'col' at Stavsengen (212 198) has the basinal Kapelen synform to the north, the Mörk Vann anticline to the south west, and this antiformal structure to the east. In the original analysis, the structure was divided into three sub-areas, but it was found that the general trend and plunge of the fold was very constant over the whole area, and the sub-areas were merged into a single unit, one πS diagram, fig. 22A, being presented here.

Sub-Area 16.- The limits of this sub-area are shown in figs. 17 and 23.





SYNOPTIC DIAGRAM

WESTERN MYRE DOME

SUB-AREAS 17 & 18

FIG. 22

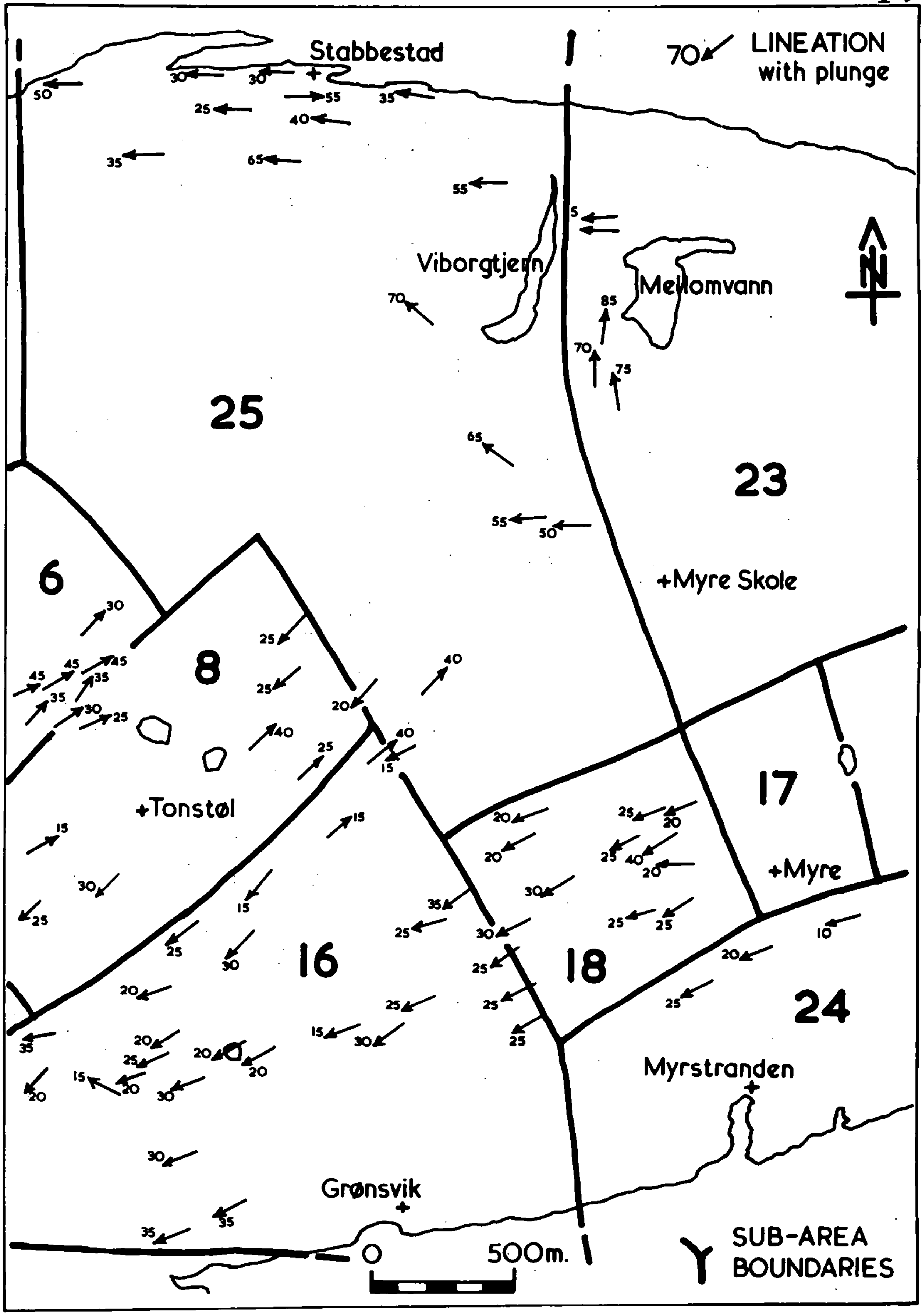

Stabbestad
70 LINEATION with plunge
Viborgtjern
Mellomvann
N
25
23
6
8
+Tonstøl
+Myre Skole
17
+Myre
16
18
24
Myrstranden
Grønsvik
0
500m.
SUB-AREA BOUNDARIES

FIG. 23

Granite gneiss is exposed over most of the area, and basic rock units are very largely confined to the northern limb of the fold. These latter comprise amphibolites and micaceous amphibolites, occurring in the usual sheet-like conformable masses, with the exception of bodies exposed 200 m. north of Ødegården farm, (226 202), in the hinge zone of the fold. These are three small pod-like masses, the largest measuring 60 m. by 40 m., of weakly foliated amphibolite gneiss, which appear to be discordant to the foliation of the granitic gneiss. These may be amphibolitized hyperites, intruded into the axial zone of the fold syn- or post-tectonically.

The clarity of the foliation in this fold is very variable, this being the only major fold which was not recognized during the preliminary examination of the aerial photographs of the area, prior to the first field season. The poor definition of the foliation on the photographs is thought to result from its being obscured by a later secondary 'foliation' the trend lines of which show up better than those of the para-gneiss foliation in the axial region. In parts of the fold the only reliable structural element which could be measured was a B lineation, plunging towards the west at shallow angles. This lineation was, in most cases, mineralogical, involving the extension of the long axes of the feldspar augen. Over a large area north west of Myrstranden, where the granitic gneiss lacked strong compositional variations perpendicular to the foliation, the re-orientation of the mafics, and to a lesser extent the feldspars, resulted in the complete obliteration of the earlier gneissic structure, and a vertically dipping axial plane 'foliation' now predominates.

In the central part of the area, where the foliation is clear, the northern limb strikes 040° to 050°, with a dip to 40 to 50° to the north west. The foliation is hinged fairly sharply over the axis to trend east-west in the southern limb, with steeper dips to the south of 60 to 70°. Further west, in that part of the fold close to the 'col' the dips of the northern and southern limbs decrease to 20 to 30°, and 35 to 40° respectively.

In the πS diagram, fig. 22A, a total of 92 poles to the foliation have been plotted, and these are confined to a single girdle. Since these readings were collected from localities fairly evenly spread over the structure, the diagram possesses monoclinic symmetry, and the fold is statistically cylindrical within the given sub-area. The pole to the girdle defines a β axis plunging 25°, bearing 252°. This is the attitude of the axis over the greater part of the area, but in the extreme western end the plunge becomes gradually horizontal, and subsequently plunges in the opposite direction in the Mörk Vann anticline. Readings taken on that part of the fold with a shallow axis are represented by a special symbol in the πS diagram.

The linear structures group closely around the computed axis, indicating that they are probably B lineations. The measurements were taken on feldspar 'augen', and on congruous minor folds, the latter being broad 'open' corrugations of low amplitude.

The fold form within this area is that of an asymmetrical anticlinal fold, plunging at a shallow angle, about 25°, in the direction 250°. The northern limb has a moderate dip, the southern limb a very steep dip. The axial plane of the fold probably dips steeply towards the north.

The Myre Dome

This fold was the largest single structural unit to be mapped within the main Levang granite gneiss, and it is also the most important.

The eastern part of the fold approaches a true domal form, with quaquaversal dip of the foliations, but the extension westwards of this structure is the broad anticlinal fold described above as the Grönsvik Antiform.

The dome, which is distinctly elongated in a roughly north east - south west direction, is centred just north of Myre farm, (247 213), the small lake of Myren, (251 214), marking topographically the exact centre of the structure.

Basic rock units are almost entirely confined to the northern limb and axial region of the westwards plunging part of the fold.

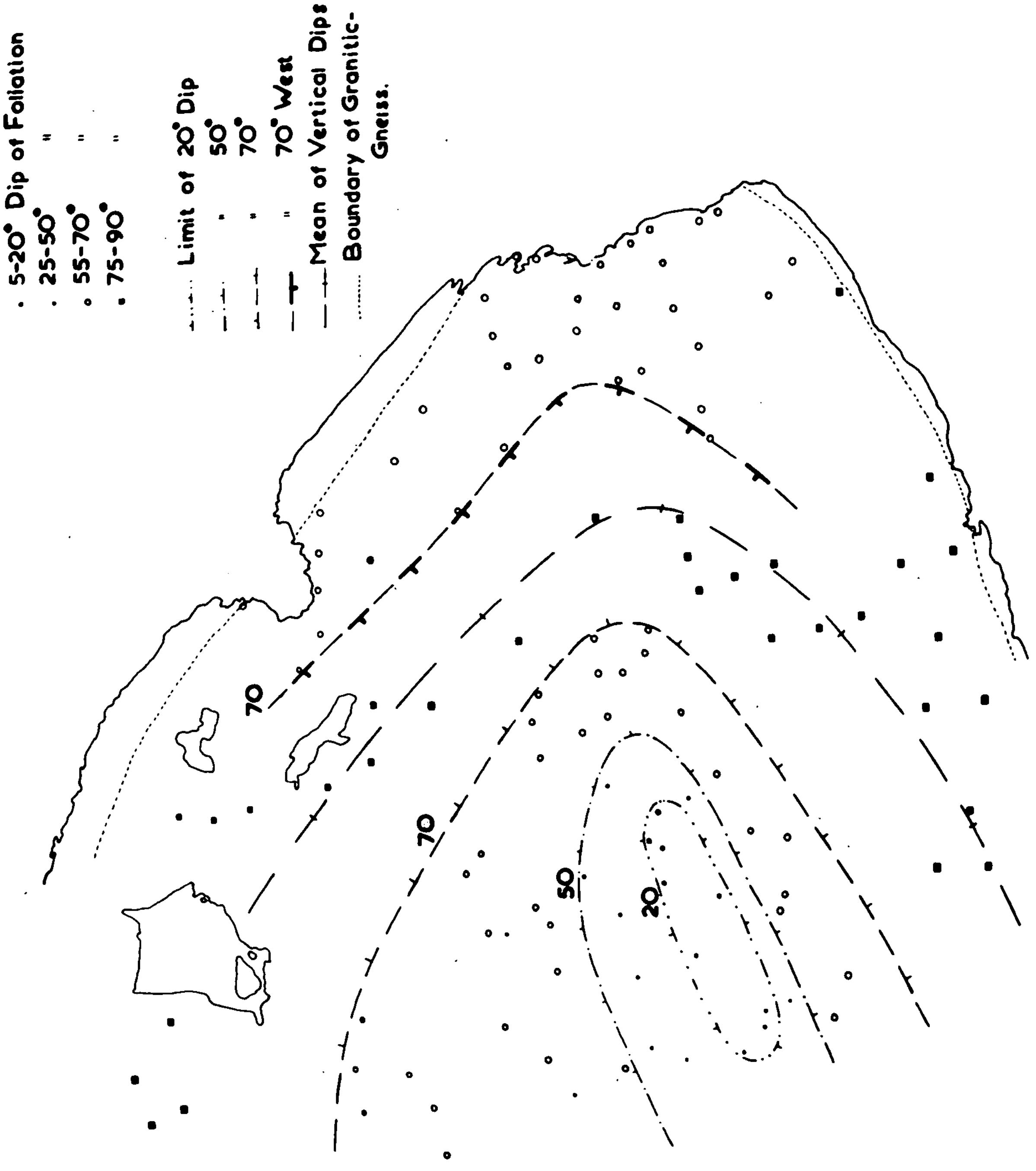
For the purposes of analysis, the structure has been divided into nine sub-areas. Six of these are confined to the hinge zone of the fold, while the remaining three sub-areas, two in the north and one in the south, extend to the coasts of the peninsula, covering the flanks of the structure. Sub-areas 17 and 18 are in the axial region of the western part of the dome, linking up with the Grönsvik sub-area 16, and sub-areas

19, 20, 21, and 22 cover the eastern axial zone. Each of these six sub-areas could not be made to extend from the north to the south coasts, perpendicular to the axial trend of the dome, because the fold is somewhat asymmetrical, and such sub-areas would not produce monoclinically symmetrical πS diagrams. Fig. 24 illustrates this asymmetry. In it, 'contour' lines have been drawn enclosing the maximum extensions of various attitudes of dip of the foliation, these being at 20°, 50° and 70°, for planes dipping outwards from the centre, and at 70° for the inner limit of foliations dipping towards the centre. The line for a vertical attitude is a mean through the zone of steepest dips. The distribution of the 'contours' in this diagram shows clearly that the dip of the foliation steepens much more rapidly in the southern limb compared to the northern, and that north of the axial region the 70° outwards dipping trace is displaced markedly relative to the 50° trace. The 70° trace for the inward dipping planes terminates in the regions, south east of Bjelkevann (250 230), and south west of Rapen (271 213), where all the foliation planes are dipping close to the vertical. Further indication of this asymmetry will be presented in the πS diagrams for the various sub-areas.

<u>Sub-Area 17</u>.- The limits of this sub-area are shown in fig. 23. Within it the granite gneiss is well foliated and non-garnetiferous.

Basic rock units are very common in the northern limb of the fold, where they comprise amphibolites and mica-amphibolites,

Fig. 24. The central and eastern part of the Myre Dome. 'Contours' have been drawn at the limits of granite gneiss foliations with dips of particular values, demonstrating the attitudes of the foliations and the asymmetry of the structure.


. 5-20° Dip of Foliation
. 25-50° "
○ 55-70° "
■ 75-90° "
Limit of 20° Dip
" " 50°
" " 70°
" " 70° West
Mean of Vertical Dips
Boundary of Granitic-Gneiss.
70
70
50
20

in part garnetiferous. Pl. 39 is taken from a locality close to a small farm (247 215), and shows the complex migmatitic relationship between the basic and acidic gneisses. A comparison should be made between these rocks and those illustrated in pl. 40 of the mixed gneisses from the Portör Peninsula.

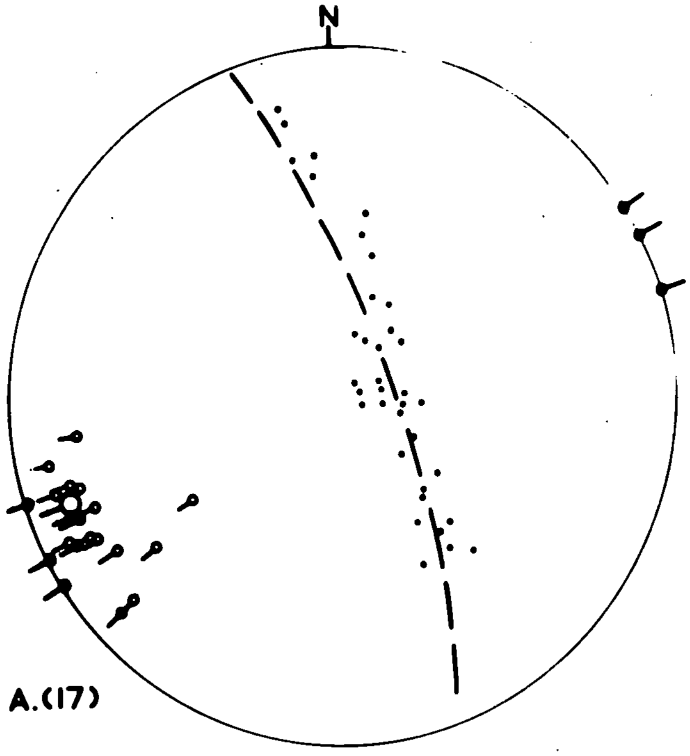
In the southern limb, only one narrow but persistent basic gneiss horizon has been traced. It is an amphibolite sheet some 4 m. thick in the outcrops where it crosses the road 130 m. south of Myre farm, and thinning gradually eastwards. There is a broad gap in the exposure over the axial region of the fold to the west of Myre, but it seems probable that this sheet is continuous in depth over the hinge and can be correlated with one of the basic units of the northern limb.

The northern limb strikes 060°, with a maximum dip within the sub-area of 50°. The foliation swings smoothly over the hinge line, to trend 080° in the southern limb, where the steepest recorded dip was 75°. The northern and southern boundaries of this sub-area are equidistant from the hinge zone, showing that the asymmetry noted above as occurring in the eastern part of the fold can also be discerned in the west. 50 m. south of the small lake (251 214) mentioned above (p. 175) a dip of 65° for the foliation was recorded, while the equivalent distance north of the lake the dip was only 25 - 30°.

In the πS diagram, (fig. 25A), the poles to the foliation define a single girdle, the axis of which plunges 13° in the direction 252°. The true average figure for the plunge is nearer 10°, since the foliation is horizontal at the eastern

Pl 39. Migmatitic relationship between granitic gneiss and amphibolite. The exposure is 200 m. north of Myre farm.

Pl. 40. Migmatites exposed 500 m. north of Portör, at the north eastern extremity of the peninsula.



WESTERN MYRE DOME

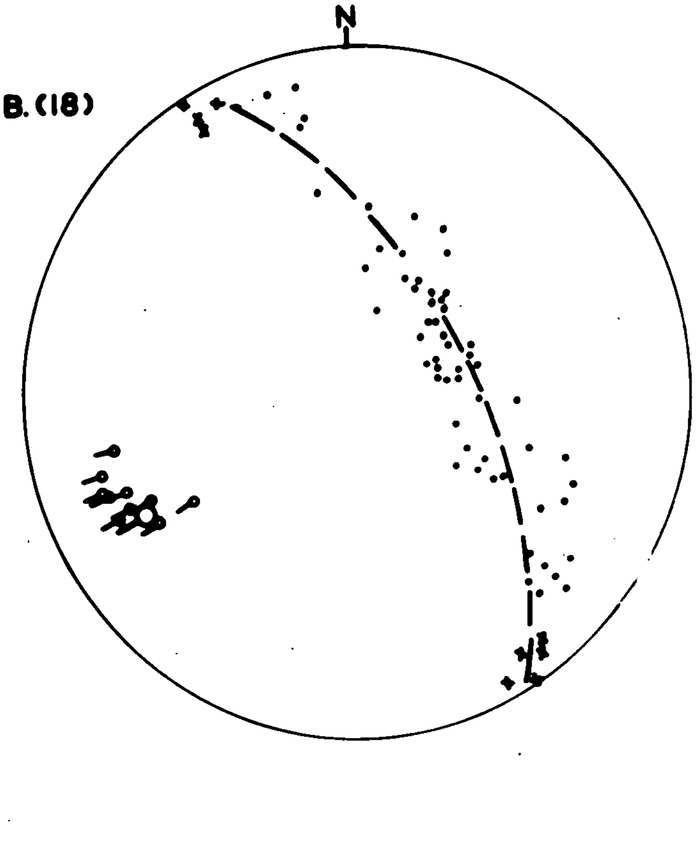


FIG. 25

margin of the sub-area, and 20° is the minimum dip of the foliation in the hinge zone at the western margin.

A total of 20 linear structures have been plotted on the diagram. All the readings were taken on mineralogical lineations in both the acidic and basic gneisses. These plots group fairly closely around the computed axis, although there is a scatter to the south west which probably reflects a change in trend of the fold axis within the sub-area towards the south west, the plot of the axis for the sub-area immediately to the west having a bearing of 242°, compared to 252°, for this sub-area. All the observed structures are interpreted as being B lineations.

The fold form here appears to be that of a markedly asymmetrical anticlinal fold, the axis trending 250° with a plunge from horizontal to 20°.

Sub-Area 18.- Fig. 25B shows the location and size of this sub-area. The various rock types, and their distribution, are broadly similar to those of sub-area 17. With the exception of the south western part of the region, the granite gneiss is well foliated. In the northern limb of the fold several of the higher horizons are garnetiferous. A sub-vertical dyke-like body of biotite amphibolite, which attained a maximum width of 2 m., was traced for a distance of over 200 m., trending roughly parallel to the fold axis with a strike around 230°. It was exposed near the western margin of the sub-area some 100 m. north of the hinge zone of the fold. It therefore cut obliquely across the foliation of the granitic gneisses. It is probably a meta-dolerite dyke. Its trend closely parallels that of the dykes at Kapelen, (see p. 67). Like them, it can possibly be correlated with one of the dyke phases recognized by Wegmann (1962) on the Portör Peninsula.

This dyke was the only discordant basic rock unit to be mapped within this sub-area. Other amphibolites and mica-amphibolites occur as broad lens-shaped conformable sheets in the northern limb, and folded over the axis. One sheet can be followed from the northern limb through the hinge zone and for a distance of 800 m. into the southern limb. It is well exposed on the east side of the road, 320 m. south of Myre farm.

The northern limb of the fold strikes 045 to 050°, with a maximum dip of 65 to 70°. In the eastern and central parts of the area, the foliation can be seen to swing smoothly over the hinge, with minimum dips of the order of 20 to 30°, and the southern limb trends 080°, the maximum dip compared to the other limb being somewhat higher at 80°. The western boundary of the sub-area traverses a region of poorly defined foliation. As has been explained in the description of the eastern part of the adjacent sub-area 16, in the hinge zone of this part of the fold, the (presumed) primary gneissic foliation has been obscured by the superimposition of a secondary sub-vertical axial plane 'foliation'. In the πS diagram, fig. 25B, the plots indicated by a crossed symbol do not represent, as might be supposed from their position in the diagram, steeply dipping foliation planes on the outer limbs of the fold, but are readings taken in the axial zone north west of Myrstranden (246 203) on the secondary 'foliation'. The minimum dip of these S_2 planes was 80°.

57 poles to the foliation have been plotted in the πS diagram. There is a relative deficiency of plots from the southern limb, but the poles define fairly clearly a single girdle, the pole to which plunges 27° in the direction 242°. The plots in the central part of the girdle, since they are from the hinge zone excluding the western part, probably give a bias towards slightly too low a mean for the plunge of the axis within the sub-area as a whole. However, the plunge of the fold in sub-area 16 was only 25°, so that it appears likely that the fold does not plunge at an angle appreciably greater than 30° at any point between the centre of the 'dome' and the structural 'col' at Stavsengen (212 198).

The plots of 11 mineralogical lineations show a high degree of correlation with the computed fold axis and are interpreted as being B lineations.

The analysis indicates that the fold form here is an asymmetrical anticline, plunging about 25°, bearing 240°, the southern limb being the steeper of the two.

In the synoptic diagram, fig. 22B, the πS diagrams for these last two sub-areas have been combined. It shows that as the plunge of the axis steepens from ca. 10° to ca. 25°, the trend changes from 250° to 240°. Further to the west, in sub-area 16, fig. 22A, the mean dip is approximately the same, but the fold trend has swung back to a bearing of about 250°.

Sub-Area 19.- This sub-area has its western margin running due west of north through the small lake, (251 214), and covers the first part of the eastwards plunging domal axis. For the location and size of the area see fig. 26.

Granitic gneiss, which does not carry garnet, is exposed over much the greater part of the region. In the northern limb the eastern terminations of three large basic sheets are seen, and to the south, the narrow but persistent amphibolite mentioned above (p. 178) lenses out near the eastern margin.

The maximum dip of the northern limb of the fold, which strikes around 085° to 090°, is 65°. The foliation, which is fairly easily discerned in the field, curves smoothly over the hinge to trend 070° in the southern limb, the maximum dip here being 80°.

In the πS diagram, fig. 27A, 35 poles to the foliation have been plotted. These will be seen not to define very clearly a single girdle, probably because the sub-area chosen was a little large. However, 90% of the poles plot within the traces of two planes of symmetry, one vertical and the other dipping 55° towards the west, the poles to the great circles of these planes having the same trend. The approximate mean great circle which has been drawn has a pole which plunges 20°, bearing 070°. This computed axis has a reasonably accurate trend, with reference to the fold in the fild, but the attitude of plunge of the β axis necessarily varies, as in sub-area 17, from horizontal in

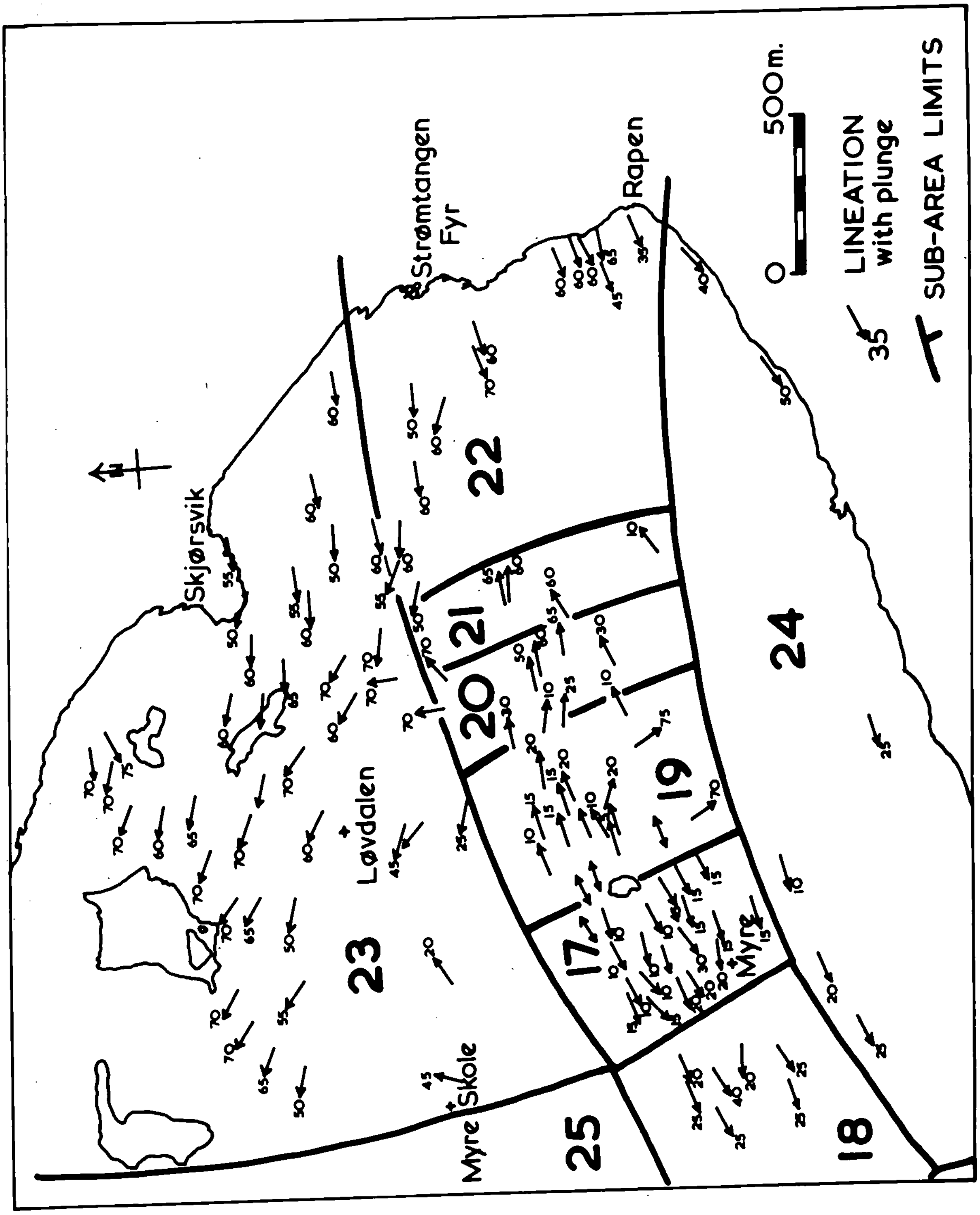
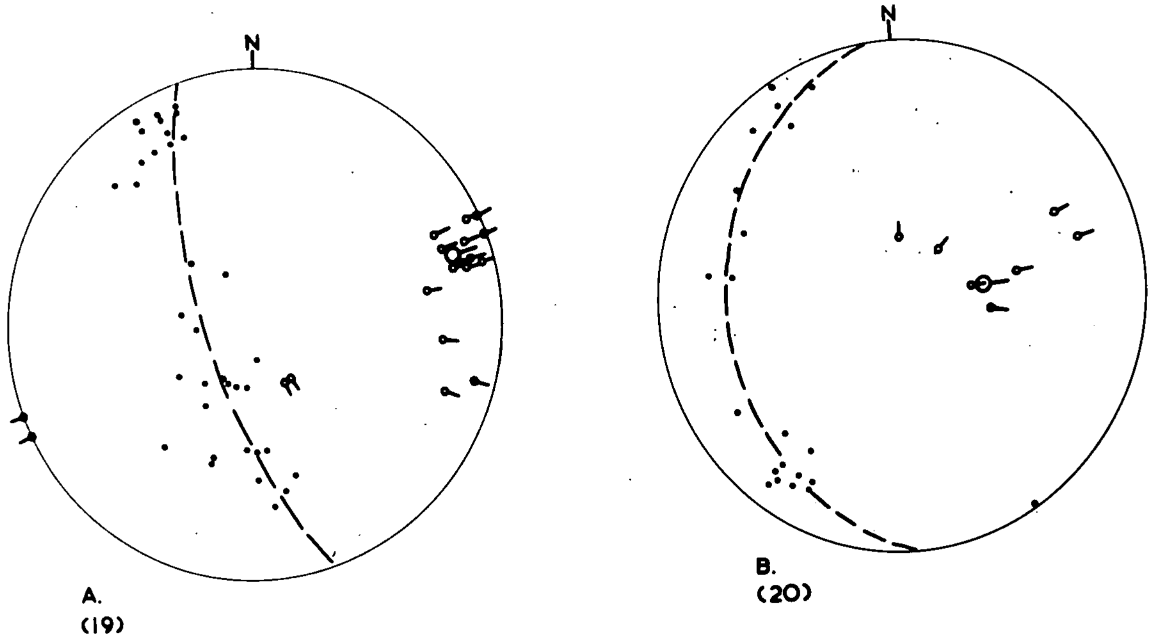

Skjørsvik
Strømtangen Fyr
Rapen
Løvdalen
Myre Skole
Myre
17
18
19
20
21
22
23
24
25
0
500m.
35
LINEATION with plunge
SUB-AREA LIMITS

FIG. 26



EASTERN MYRE DOME

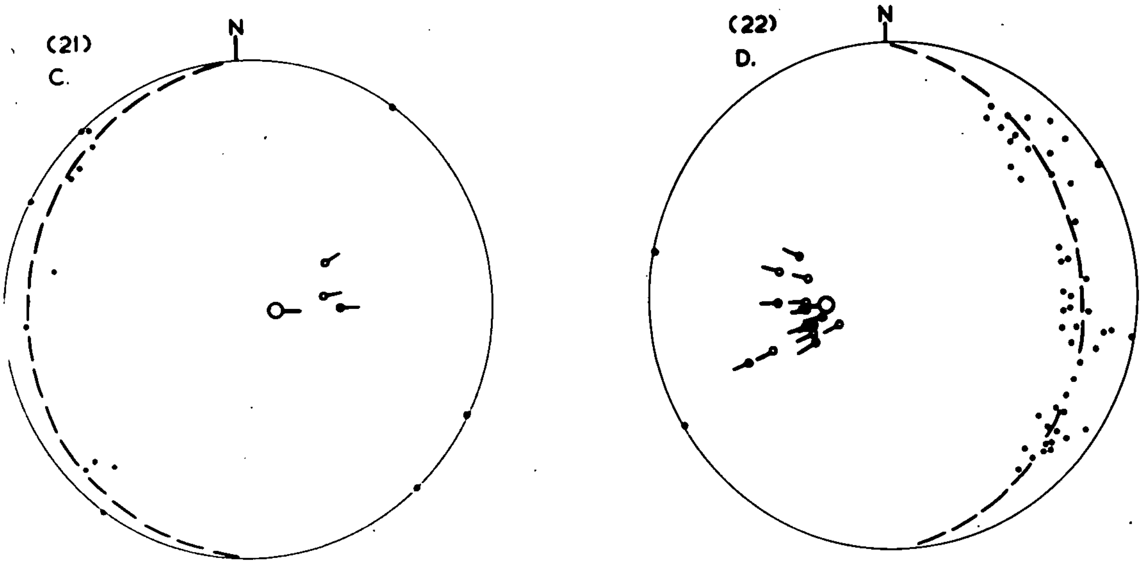


FIG. 27 πS DIAGRAMS

the west to about 40° in the east.

The 17 linear structures which have been plotted show an interesting distribution. 12 of these, with plunges varying from horizontal to 30°, are closely grouped around the computed axis. Two of these are plots of measurements made on tightly folded minor folds in the granite gneiss, of the type which has previously been met with in sub-area 15, and are interpreted as congruous parasitic minor folds. The remainder were mineralogical lineations, in both the basic and acidic gneisses. Three other lineations, with plunges of 10 to 25°, are displaced somewhat towards an easterly trend. The remainder two plots, the readings for which were taken in the granitic gneiss of the southern limb on minor folds of the low amplitude, open corrugation type, have very steep plunges of 70°, and trend 145° and 150°, respectively. These folds trend very nearly at right angles to the major fold axis, and may thus be plications in the limb of the fold in the 'a' direction. Alternatively, they could represent refolded B elements from an earlier deformation which involved shortening in a roughly north east to south west direction.

The fold form here is that of a markedly asymmetrical anticline, the axis of which trends 070°, with a plunge varying within the given sub-area from horizontal in the west to about 40° in the east.

<u>Sub-Area 20</u>.- Only granitic gneiss is exposed in this fairly small sub-area, the location and size being shown in fig. 26.

The acidic gneiss has a foliation which is not difficult to measure in the field, and does not contain any garnets.

The northern limb of the fold strikes 120 to 130°, with dips of up to 75°. The foliation swings rather abruptly over the hinge, to trend 060° in the southern limb, the maximum dip here being vertical. In the hinge zone, minimum dips of the order of 45 to 70° have been measured.

In the πS diagram, fig. 27B, 20 poles to the foliation have been plotted. There is a deficiency of plots from the axial region of the fold, but the poles nevertheless define very clearly a single girdle, the pole to which plunges 62°, bearing 085°. The πS diagram possesses monoclinic symmetry, and the fold is statistically cylindroidal within the given sub-area.

The pronounced scatter of the 7 linear structures which were measured can, in part, be explained by the fact that the β axis of the fold is in this region rapidly changing its trend and plunge, so that even within this relatively small sub-area, B lineations with attitudes widely different from that of the computed axis will be included. Note that the scatter is towards a shallower plunge in the more north easterly trending lineations, while in the last sub-area the structures which had a trend close to due east showed a tendency towards slightly steeper than average plunges. There is, however, one mineralogical lineation which trends exactly due north, with a plunge of 70°, in the northern limb, and this again is either a linear element in 'a' with reference to the major axis, or is a refolded B lineation.

The shortage of readings from the foliation planes in the hinge zone of the fold was due to the trend of the latter having been obscured by minor folding. These folds were only rarely amenable to measurement, since they were most commonly exposed in only two dimensions. Those which could be measured and plotted were interpreted as congruous minor folds.

The fold form in this area is that of a fairly open anticline, plunging from 50 to 70° in the general direction 085°. The fold is asymmetrical, the northern limb dipping less steeply than the southern.

Compared to the sub-area immediately to the west, the mean plunge of the axis has steepened 40 to 60°, and the trend has turned from 070 to 085°.

Sub-Area 21.- The location and size of this sub-area are shown in fig. 26. The eastern boundary has been drawn at the limit of eastwards dipping foliations in the granite gneiss, though it includes a few vertically dipping planes.

One unit of basic rock has been mapped in this area. It is a micaceous amphibolite lens, 250 m. long and with a maximum thickness of around 15 m. It was thought at first that this lens might be related to the amphibolitic sheet mentioned above, (p. 184), as terminating 300 m. to the west, near the eastern boundary of sub-area 19. It appears, however, from detailed mapping, that the basic unit in this sub-area is at a 'stratigraphic' horizon some 50 m. higher than the other sheet, and the two are probably not continuous in depth, although axial plane shearing, (for which no evidence has been found), during the formation of the 'dome', could have displaced the sub-area 21 sheet the requisite amount.

The granitic gneiss has a foliation which is fairly easily seen in the field, although again, particularly in the hinge zone, its trend with reference to the major structure is obscured by minor folding. No accessory garnets were noted in this sub-area.

The rather small number of 11 poles to the foliation which have been plotted in the πS diagram, fig. 27C, all plot close to the primitive, but still define clearly a single girdle, the pole to which plunges 78°, in the direction 088°. The true range in the value of the axial plunge is from 70° in the east, to vertical in the west.

Three linear structures have been plotted. Two similar minor folds mapped in the northern limb plunge 60° and 65°, with trends of 090° and 080°, respectively. The other element was a mineralogical lineation in the granitic gneiss of the southern limb, plunging 60° in the direction 060°. All three are interpreted as B lineations, the minor folds being congruous drag folds.

The fold form here is that of a more-or-less symmetrical antiform, which plunges at very steep angles, up to and including the vertical, due east. Unlike the previous two sub-areas, the axial plane is here vertical and has the same trend as the β axis.

Sub-Area 22.- This is the largest of the sub-areas covering the axial region of the eastern part of the Myre Dome, and it has been drawn to include all those foliations which have a dip in a general westerly direction, as well as several vertically dipping planes in the eastern part of the area. The location and size of the sub-area are shown in fig. 26.

With the exception of the small included sections of the basic gneiss 'envelope', to the north of Strömtangen, (268 222), and south of Rapen, (271 213), granitic gneiss is the only metamorphic rock type exposed in this sub-area. Readings from the amphibolites, etc., of the 'envelope' have been included in the πS diagram. An unmetamorphosed, presumed Permian, dolerite dyke is well exposed in the shore section in the bay at Strömtangen, where it can be seen to cut obliquely the granite gneiss foliation.

The northern limb of the fold trends around 120° to 130°, with dips from vertical to 70° towards the south west. The granite gneiss foliation, which is readily measured in the field, swings gradually and evenly over the hinge to strike 045° to 055° in the southern limb, the general dip here being 70 to 80° towards the north west. The minimum dip measured in the axial zone was 60° at localities on the east coast, 300 m. north of Rapen.

A total of 50 poles to the foliation have been plotted in the πS diagram, fig. 27D. These were taken from localities evenly distributed over the whole of the structure and the diagram displays monoclinic symmetry. The poles define a single girdle, the pole to which plunges 65°, bearing 267°. As in previous areas, the attitude of plunge for the β axis varies from vertical in the west to 60° in the east.

Of the 14 linear structures plotted, 3 were readings made on minor folds in both the basic and acidic gneisses, and the remainder on mineralogical lineations in the granitic gneiss. The majority plunge from 60 to 70°, but a plunge as low as 35° was recorded on a lineation in the basic gneiss at Rapen. Trends lie within an arc from 250° to 295°. Most of these linear elements show a fair correlation with the computed axis, and are interpreted as B lineations.

Within this sub-area the fold from is that of a slightly asymmetrical <u>syncline</u>. The axial trend is very nearly due west, with a plunge which varies from a minimum of 60° in the east to vertical in the west. The southern limb of the syncline is steeper than the northern at equivalent horizons by from 5 to 10°.

As it is traced eastwards from the apex of the dome, the initially horizontal axis is seen to plunge towards the east at rapidly steepening angles, eventually attaining a vertical plunge in the region of the boundary between sub-areas 21 and 22, a distance of 1.2 km. from the central lake of Myren. Simultaneously, the trend of the fold axis turns through nearly 20°, from 070° in sub-area 19 to 088° in sub-area 21. Further east, in sub-area 22, the axis 'turns over' to plunge westwards at gradually shallower angles, the lowest being 60° measured in granitic gneiss on the extreme east coast of the peninsula.

In the synoptic diagram, fig. 28, the mean trend and plunge for the β axes within each of the six sub-areas covering the axial region of the dome (sub-areas 17 to 22, inclusive) have been plotted. The important sub-area 22 axis has been marked with a crossed symbol. It can be seen that the overall change in trend of the dome is almost 30°, from 242° (062°) in sub-area 18, to 088° in sub-areas 21 and 22.

Thus, in this single complex structural unit, termed here the Myre Dome, it can be demonstrated that the quaquaversally dipping foliations of the central region become 'over-turned' to form a synclinal fold in the eastern extremity of the structure. These observations are of considerable significance and will be further discussed below.

The relationship of this synclinal fold to the rest of the structure can be illustrated by tracing the attitude of a particular horizon from the hinge zone of the fold where it has a plunge of 60° towards the west. Followed north west, the westerly dip of the foliation plane steepens from 60 to 70° as the strike turns from due north to a bearing of 130°. An approximately 70° dip is maintained as far as Skjörsvik, but beyond this bay the foliation steepends to vertical before Bjelkevann (250 230) is reached. West of this lake, the foliation at this horizon is vertical or dips towards the north. Traced southwards from the hinge zone, the same horizon steepends to 75° at a strike of 045° in the vicinity of Rapen, and 1 km. further south west dips vertically at a strike of 065° to 070°. West of this point the foliation is vertical or, like that in the north, dips steeply 'off' the dome.

SYNOPTIC DIAGRAM

β FOLD AXES

SUB-AREAS 17, 18, 19, 20, 21 & 22

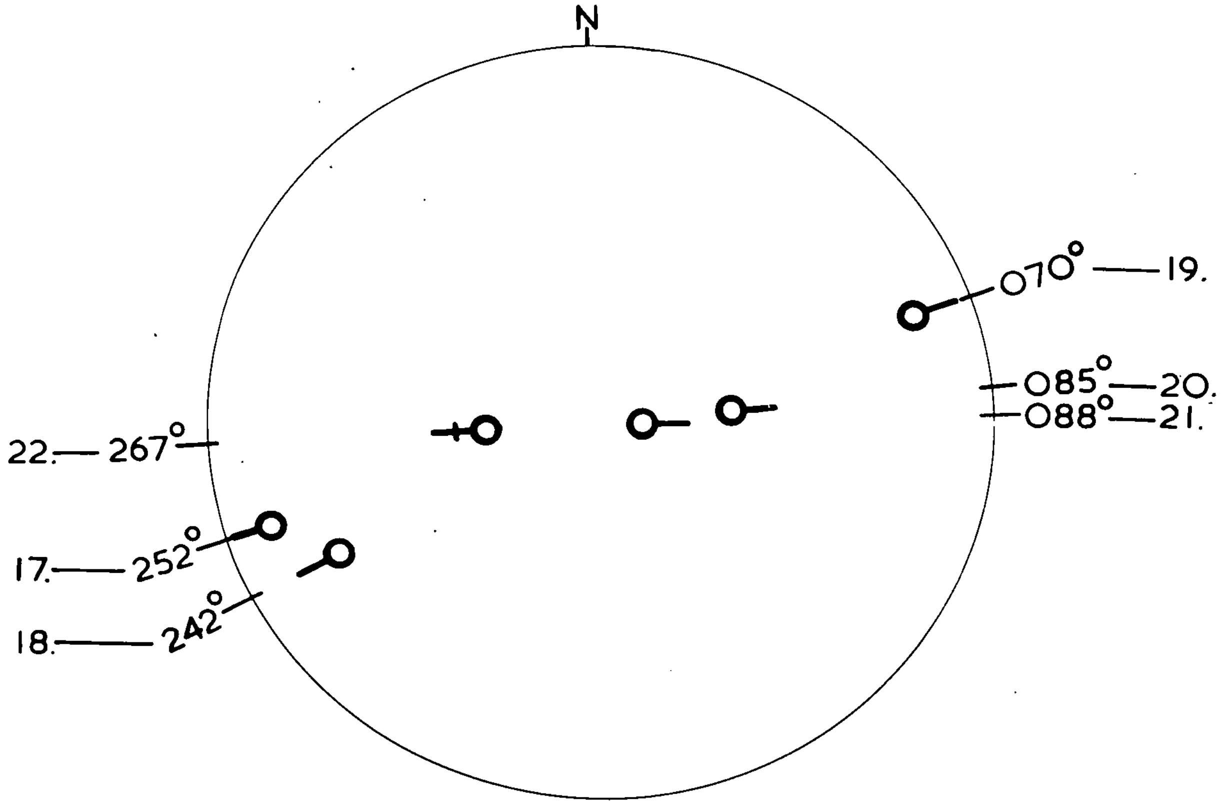


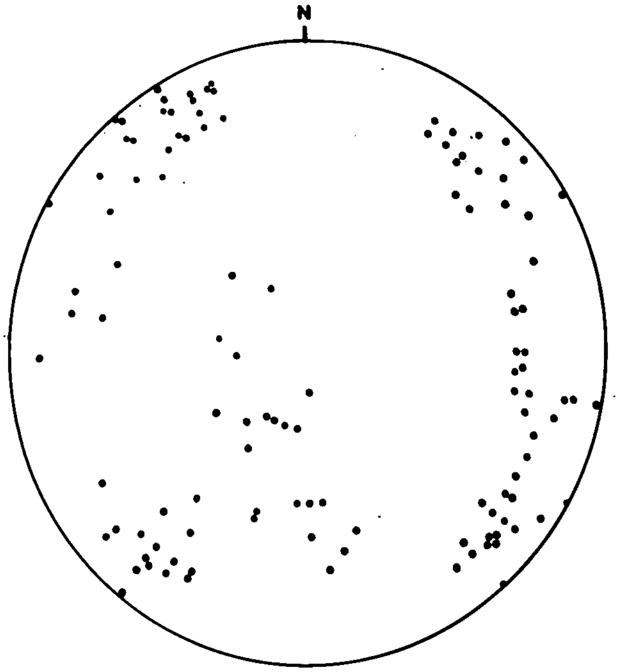
FIG. 28

The synoptic diagram, fig. 29A, which combines the stereographic plots of the foliations from the four eastern sub-areas, (19,20,21, and 22) is highly informative. The pattern produced by the plots is more or less that which would be obtained from an analysis in which readings had been taken from all parts of a true domal structure. The only shortcoming of the synoptic diagram in this respect is the absence of plots corresponding to foliations with a shallow dip towards the west. All the plots in the semi-isolated group in the right side of the diagram are from sub-area 22.

Similarly, in the synoptic diagram, fig. 29B, the lineations from these four sub-areas have been plotted and these also display a pattern which could have been produced by readings from a true dome. Again there is an exception, in this case the absence of plots for linear structures with a shallow to moderate dip towards the west, (corresponding, for example, with the plots for the β axes of sub-areas 17 and 18, as shown in fig. 25).

The next three sub-areas to be examined, two in the north and one in the south, cover the remainder of the Myre Dome outside the axial region.

Sub-Area 23.- This is a large sub-area covering the north and north east of the 'dome'. Its location and limits are shown in fig. 26. It includes a stretch of the boundary of the granite gneiss 2.5 km. long, from a point 250 m. north of Strömtangen



A. *FOLIATIONS*

SYNOPTIC DIAGRAMS – EAST MYRE DOME

B. *LINEATIONS*

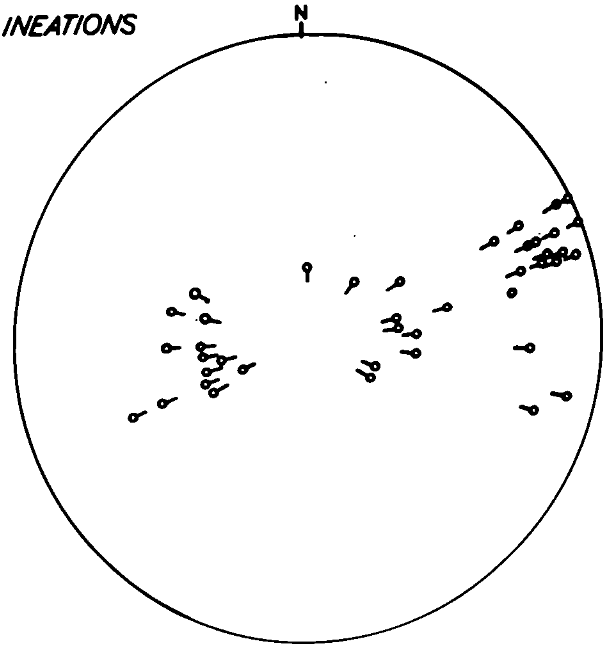
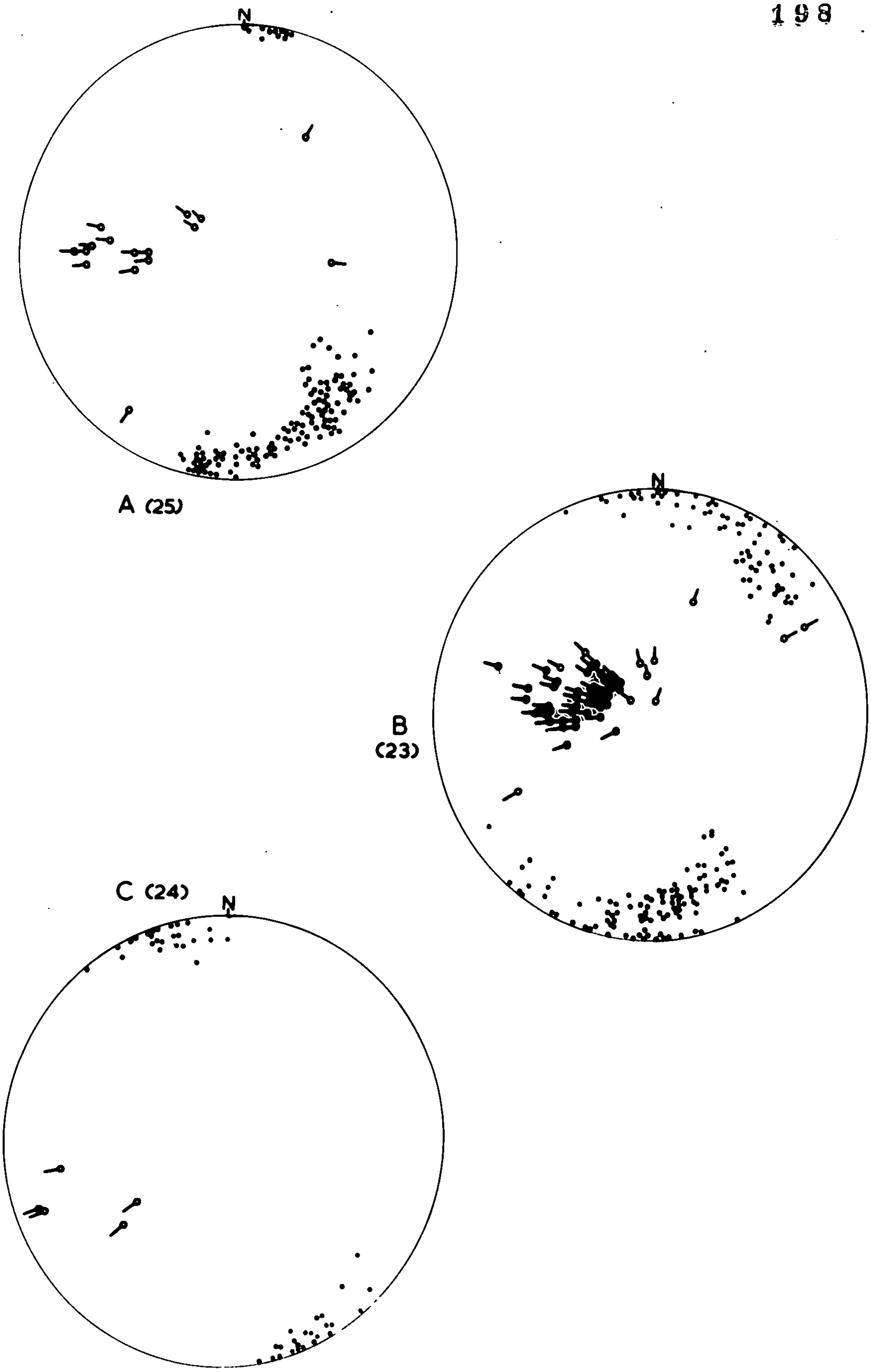


FIG. 29

almost as far as Stabbestad, and measurements made on the foliation in the gneisses on both sides of the contact are incorporated in the πS diagram.

Within the granitic gneiss basic rock units are very largely confined to the central and south western parts of the area, i.e. in the Lövdalen (253 224) to Myre Skole (245 221) region. Most of these are thoroughly micaceous amphibolites, occurring as conformable sheets of varying size, the largest being ca. 60 m. wide at the present level of exposure and 1 km. long. An amphibolite with only minor amounts of biotite was mapped in the extreme south west of the sub-area, and several of the mica-amphibolites have a 'core' of more amphibole rich rock. In the main these basic rocks are poorly exposed in low-lying ground between ridges of more resistant granite gneiss. Exposed in the new road cutting at Lövdalen farm (252 223) is a basic mass of 'hyperite'. The sheet like body is 450 m. long and attains a maximum width of 35 m. It has an arcuate trend, parallel to the strike of the foliation in the surrounding granite gneiss, from 120° at the south eastern end, near Lövdalen, to 090° at the western extremity.

In the πS diagram, 155 poles to the foliation have been plotted, together with a total of 56 linear elements (see fig. 30B). The πS plots are arranged in two distinct groupings. The larger concentration of plots is in the sector of the diagram between south east and south west, these representing foliation planes which have steep dips in a general northerly direction. These measurements were collected from foliations at localities in the central and south western parts of the sub-area, closest to the apex of the dome. In the north and north eastern part of the



A (25)

B (23)

C (24)

FIG. 30 πS DIAGRAMS

diagram is a second concentration of πS plots which represent foliations which dip steeply towards the south and south west, i.e. towards the centre of the dome. All of these readings are from localities in the coastal regions of the sub-area, i.e. in the north and north west. The plots from vertically dipping foliations are common to both groups.

Approximately 80% of the linear structures have a plunge of from 50 to 70° in a direction within an arc from 265° to 310°. The remainder either have steep plunges with a trend slightly due west of north, or plunge at variable attitudes in the general directions 060° and 250°.

It does not seem possible readily to draw a plane of symmetry through the poles as plotted in the πS diagram which would define a girdle the pole to which plunges in the expected direction, i.e. 340°. If, however, the foliation of the granite gneiss did not 'overturn' towards the boundary of the mass, and instead of dipping towards the south west the coastal foliations had a 'normal' dip towards the north east, the plots for such foliations would fall in the south and south west of the πS diagram, producing a grouping through which a plane (or planes) of symmetry could be drawn, and this would have a steeply plunging pole trending roughly due north.

Only a small group of three lineations, all measured in granitic gneiss, has an attitude corresponding to this direction. These lineations, mapped south of Mellomvann (244 231), plunge 70 to 75°, bearing 345° to 360°.

Sub-Area 24.- This is a fairly large sub-area situated to the south of the hinge zone of the Myre dome. It includes that part of the coastal section extending from just south of Rapen to a point 600 m. west of Myrstranden. (See figs. 23 and 26).

Apart from the basic banded gneisses exposed along the coastal section, which include amphibolites, garnet-amphibolites, mica-schists, pyroxene-garnet-schists, etc., very little basic material has been mapped within this sub-area. North and north east of Bekkeviken (252 224), several narrow conformable sheets of amphibolite are exposed within the granite gneiss, but none of these could be traced for more than a few tens of metres along the strike.

In the πS diagram, fig. 30C, 38 poles to the foliation have been plotted. With regard to the distribution of the poles in the diagram, much the same remarks apply as were made for those of the last sub-area. Instead of a single concentration of plots, there are two, one in the north western part of the diagram, the other in the south east. The latter is that for the foliations which are 'over-turned', from localities in the east of the sub-area. All foliations are steeply dipping, from 70° to vertical, and the swing in trend through the region is from 040° near Rapen to 090° north west of Myrstranden. This small variation in strike of the foliations of only 50° makes the drawing of a plane of symmetry through the πS plots impracticable, even when, as was done in sub-area 23, the direction of dip of the 'overturned' foliations is reversed so as to produce a single group of plots. No 'a' direction fold can, therefore, be defined in this sub-area.

A total of 5 linear structures has been plotted, 3 from granitic gneiss and 2 from banded gneisses. These plunge from 10 to 50° on bearings from 230° to 260°, and, as such, can probably be correlated most closely with the β fold axis. In contrast to the northern part of the Myre Dome, there do not appear to be any well developed linear structures in 'a' in this sub-area.

The two synoptic diagrams in fig. 31 combine all the foliations and lineations, respectively, from sub-areas 19 to 24 inclusive. As in fig. 28, which treats synoptically the data from the axial region only, the diagrams again serve to emphasize the abnormal distribution of πS plots and lineation poles for the eastern half of the structure, the result of the overturning of the fold axis in sub-area 22. Compared to the axial zone πS diagram, that for the whole of the eastern part of the structure shows plots for foliations with strikes at every compass bearing, with the greatest concentrations of plots now in the south eastern and northern parts of the diagram.

The most significant difference between the synoptic lineations diagram for sub-areas 19 to 24 and that for the axial region only is the heavy concentration of plots for linear structures plunging around due west and north west at moderate to steep angles. Also, the number of northwards trending 'a' lineations has increased slightly, while the complete absence in either diagram of any linear structures in the 'a' direction which have a southwards trend is noteworthy.

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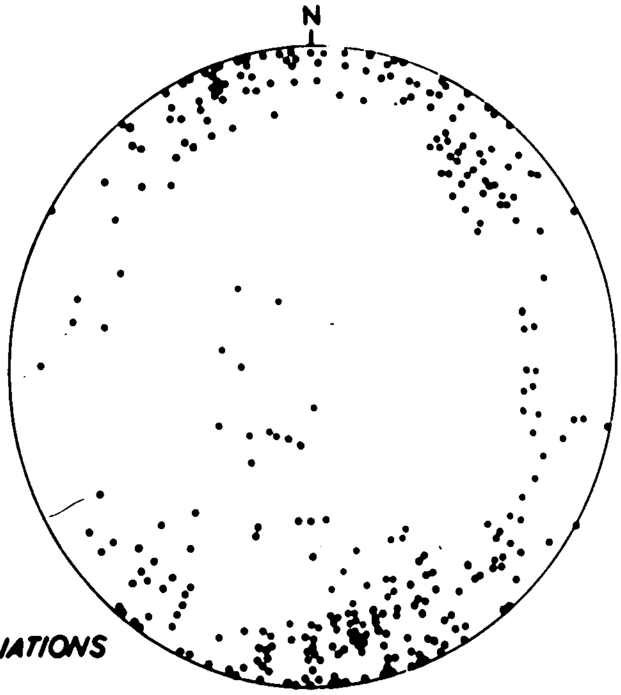
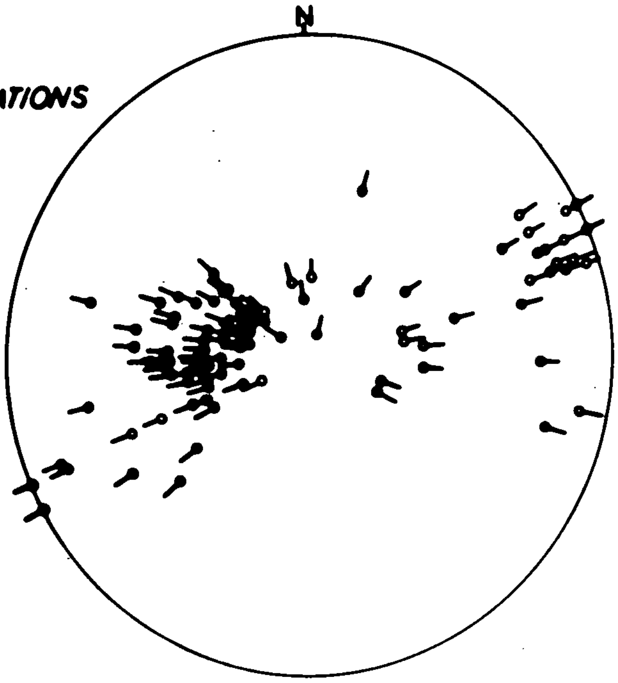


A *FOLIATIONS*

SYNOPTIC DIAGRAMS

SUB-AREAS 19, 20, 21, 22, 23, & 24.

MYRE DOME



B *LINEATIONS*

FIG. 31

Sub-Area 25.- This is a very large sub-area, the unusual shape of which is the result of its having to conform to the boundaries of other sub-areas, whose limits were determined so as to achieve the best possible coverage for important major structures, particularly in the Tonstöl and Myre districts. The exact location and size of sub-area 25 are shown in fig. 23.

Granitic gneiss is exposed over most of the sub-area, but a 2 km. long section of the contact in the region of Stabbestad is also covered, as well as a number of basic rock units within the granite gneiss mass. The banded gneisses near Stabbestad include quartzites and sillimanite gneiss, inter-layered with mica-schists and garnet-amphibolites. Conformable sheets of micaceous amphibolite are the commonest basic rock types within the granite gneiss, but biotite free amphibolites have also been mapped, together with a small lens of 'hyperite' exposed in the southern part of the area, about 1.1 km. east of Tonstöl.

With the exception of a small area south west of Stabbestad, where it is rather vague, the granite gneiss foliation is readily discernable in the field. This rock type is also markedly garnetiferous at several horizons, particularly west of Myre Skole (244 221), and north east of Tonstöl.

The strike of foliations at particular horizons does not vary greatly as they are traced through the sub-area, but whereas in the northern part of the area the trend is east-west, further south there is a gradual swing to a foliation trending 040° to 050° as the Myre dome is approached. Simultaneously, there is a shallowing of the dip of the planes from vertical in the

Stabbestad-Viborgtjern region, to a dip of 50 to 60° towards the north west near Myre.

In the πS diagram, fig. 30A, some 117 poles to the foliation have been plotted. There is a small grouping of poles in the northern part of the diagram, these representing vertically dipping, east-west trending foliations, while the remainder form a heavy concentration in the south eastern quadrant. In the analysis of this πS diagram, due allowance must be made for the fact that the pattern is only pseudo-monoclinic. This is because the sub-area lies on the flanks of the Myre dome, so that the complete girdle of plots for a monoclinic diagram would only be produced by a synoptic treatment of poles from this sub-area together with a number from the axial region of the westwards plunging part of the fold and from the southern flank, in the Grønsvik to Myrstranden region.

A further complication in this analysis is the fact that running into the south western boundary of sub-area 25 are the extensions of two isoclinal folds described above, viz. parts of the Heligesvann antiform and of the Kapel Basin synform.

The eastern part of the Kapel Basin synform has been interpreted as tightening, in the Tonstöl region, into an isoclinal synform about a sub-horizontal axis, and this fold, presumably, extends further north eastwards from sub-area 8 into this sub-area. Similarly, the Heligesvann antiform has an axial trend sub-parallel to that in the Tonstöl region, and there is no direct evidence to suggest that the isoclinal antiform of sub-area 6 does not extend north eastwards into sub-area 25. The hinges of these isoclinal folds have not been found, and it is possible that the postulated extensions of these folds may be refolded about the 'a' tectonic axis of the northern flank of the Myre dome.

A total of 16 linear structures has been plotted. The majority of these were measured on lineations and open corrugations in the banded gneisses of the Stabbestad coastal region, where the foliation is vertical or dips very steeply towards north. With one exception, these coastal linear structures trend between 260° and 280°, at plunges of from 25 to 55°, while the other plunges 55° due east.

Within the granite gneiss, two lineations measured in the south west of the sub-area trend roughly parallel to the fold axis for the Tonstöl synform, and the remainder plunge steeply on bearings close to 300°.

With the exception of the lineations which seem to be related to the Tonstöl fold, these linear structures are difficult to relate to any of the known major folds, either as lineations in B' or 'a'. However, it should be noted that lineations with moderate to steep plunges in a general westerly direction seem to be more-or-less universal in the banded gneisses outside the main mass of the Levang granite gneiss. The Portör rocks, for example, all show lineations plunging from 25 to 45° on a general bearing of 240°.

The foliation in this sub-area forms part of the north western flank of the major domal structure centred near Myre. The isoclinal folds of Heligesvann and Tonstöl may extend into it, though no direct evidence to support this proposal has been found.

Sub-Area 26.- This sub-area, lying south of Kapelen, covers parts of the southern flanks of the Mörk Vann and Grönsvik antiforms. Its location and limits are shown in fig. 32.

In the extreme south of the sub-area, near Hovet (215 188), a 200 m. section of the granite gneiss boundary has been included, but otherwise, non-garnetiferous granitic gneiss is exposed over the whole area, with only a few small units of basic material.

In the eastern part of the sub-area, in the Stölestranden district, the granite gneiss foliation strikes 090° with dips of around 60° towards the south. As it is traced further west, the strike of the foliation swings round to 050° to 060° as the dip decreases to minimum values of from 10° to 40°, depending on the distance of the particular horizon from the horizontal foliation in the adjacent structural 'col' at Stavsengen farm (212 198), close to the north west corner of the area. Further south, the strike turns further to 030 to 040°, and the dip steepens to a maximum of 70 to 80° towards the south east, in the vicinity of Hovet farm.

The maximum variation in trend of the foliation is thus only 50°, so that the πS diagram, fig. 33A, in which 38 poles to the foliation have been plotted, is difficult to analyse. The plots form a single concentration in the north west quadrant of the diagram.

One possible analysis on the basis of the orthorhombic symmetry of the πS diagram is as follows. Firstly, there is a vertical plane of symmetry, P, passing through the centre of

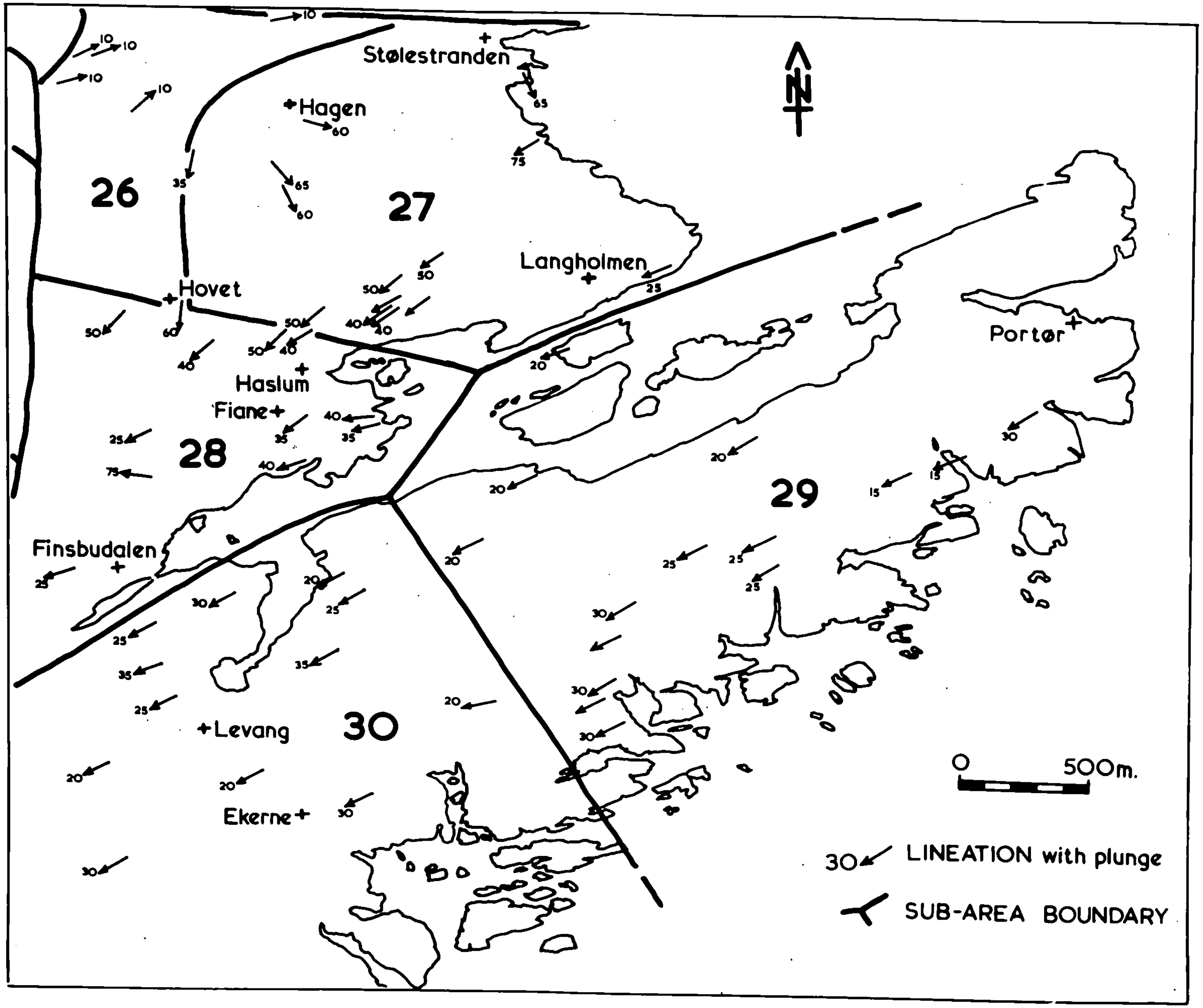
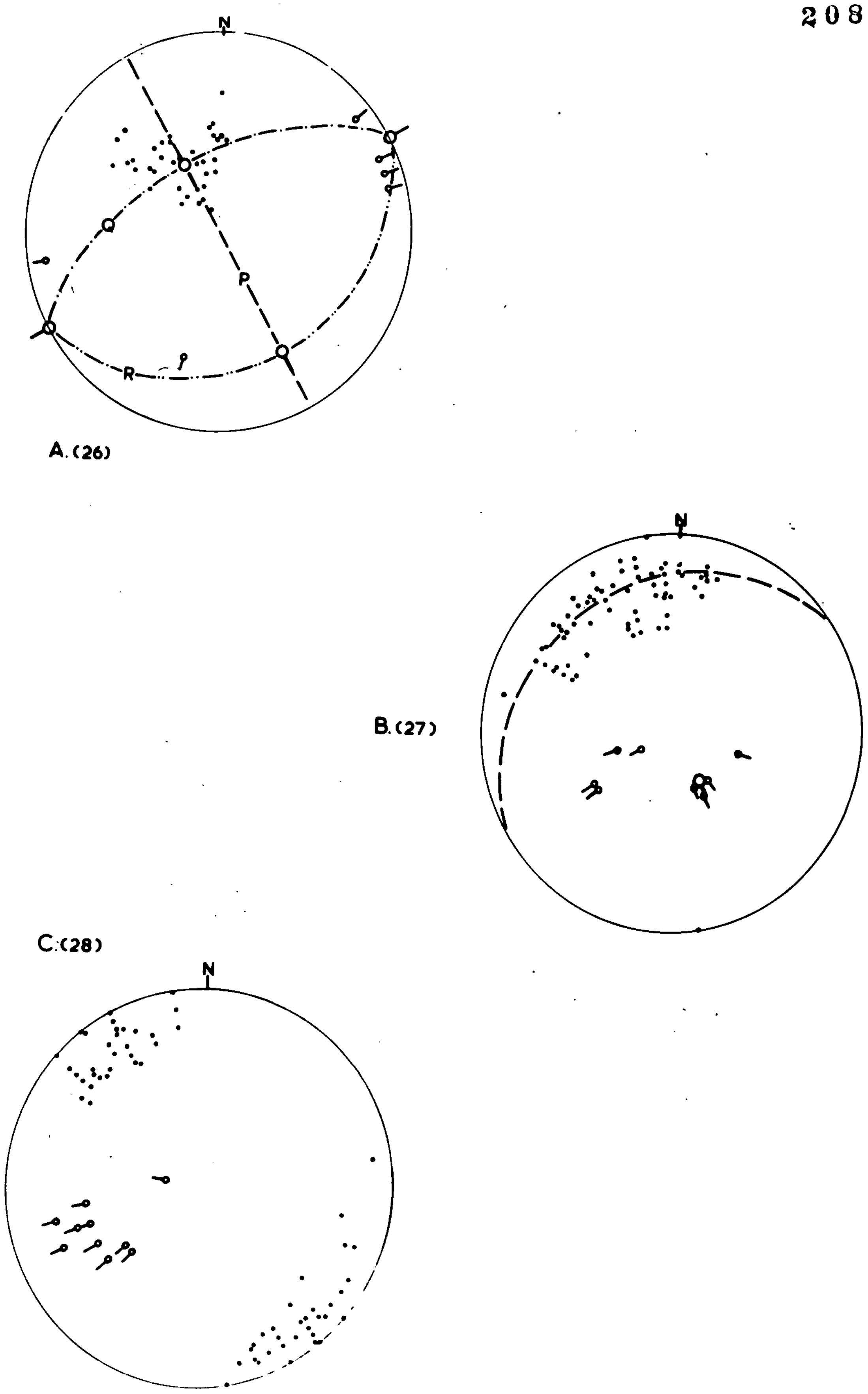

N
Stølestranden
Hagen
Hovet
Langholmen
Haslum
Fiane
Finsbudalen
Portør
Levang
Ekerne
26
27
28
29
30
0
500m.
30 LINEATION with plunge
SUB-AREA BOUNDARY

FIG. 32



A. (26)

B. (27)

C. (28)

FIG. 33 πS DIAGRAMS

the group of plots on a strike of 150°. The pole to this plane would have a bearing of 060° and be horizontal. A second plane, Q, could be drawn, the stereographic trace of which also passes through the group of plots, having a strike of 060° and a dip of approximately 60 to 65°, towards the north west. The pole to this plane plunges 25 to 30°, on a bearing of 150°. The third plane of symmetry, R, which is mutually perpendicular to these two, strikes 060° and dips about 30° towards the south east, its pole plunging 60° on a bearing of 330°.

The latter pole can not represent an axis of rotation for a fold with the observed distribution of foliation poles. The horizontal axis trending 060° can be correlated with a small group of linear structures, all of which have plunges of 10°. This axis forms an approximate representation of the anticlinal fold axes to the north and west. It is only approximate because the trends and plunges of these axes change rapidly away from the Stavsengen area, more especially in the Mörk Vann fold. The pole plunging 25 to 30° in the direction 150° represents, in fact, the 'a' tectonic direction, with reference to the major anticlinal folds, and is a mean for axes with plunges of variable attitude, according to their level in the structure, from 10° near the 'col' to 40° at the boundary of the sub-area north west of Hagen (221 196).

Thus, while the analysis of this sub-area would appear to indicate the presence of an open synclinal fold plunging at moderate angles towards the south east, reference to the structure within adjacent sub-areas reveals that the β axes for the major folds in this region trend roughly north east - south west, and the 'syncline' in sub-area 26 merely defines the 'a' direction for these folds.

THE GEOMETRY OF S IN THE BANDED GNEISSES

Sub-Area 27.- Extending from Stölestranden in the north almost to Haslum in the south, this sub-area covers the major part of the Langholmen peninsula. Its limits have been drawn so as to include a long section of the granite gneiss contact, together with a broad strip of granitic rocks within the boundary, as a further demonstration of the continuity of structure on each side of the 'contact'. The limits of the sub-area are shown in fig. 32.

A detailed account of part of this sub-area, viz. a section of the granite gneiss contact at Stölestranden, has already been given, (see p. 56). The banded gneisses are extremely varied, the only major group common to Levang which is not represented being the quartz-diotitic type of the Portör peninsula. A thick unit of quartzite, in part sillimanite bearing, extends from the extremity of the peninsula to Haslum and is traceable for several kilometres in sub-area 28.

In the eastern part of the area, the foliation strikes 090° to 100°, with dips to the south of around 60 to 75°. Further west, the foliation is seen to swing in a broad arc parallel to the granite gneiss contact, so that it trends 030° to 040° east of Hovet. Here the dip is again about 70°, towards the south east. In the southern part of the area, at the level of the quartzite, the foliation turns through only 30°, from a strike of 090° in the east to 060° near Haslum.

The 67 poles to the foliation which have been plotted in the πS diagram, (see fig. 33B), define a pattern which is monoclinically symmetrical. A single girdle has been drawn through the plots which has a pole plunging 65° on a bearing of 145°.

A small group of linear structures, all measured in the central part of the sub-area, correlate closely with the computed axis.

There is a further group of linear structures which have moderate to steep plunges in a general direction roughly at right angles to the axial direction, i.e. a bearing of ca. 240°. These measurements were made on lineations in amphibolitic horizons in the folded quartzites north east of Haslum, (222 186).

The proposed interpretation is that the computed 'axis' is an 'a' direction with reference to the folds of Mörk Vann and Grönsvik, the structure in this sub-area being a development of that seen in the last area. The linear structures which trend roughly south east are thus 'a' lineations, and the remaining linear elements are B lineations, with reference to the major folds to the north and to isoclinal folds believed to be developed in the banded gneisses to the south.

Sub-Area 28.- This sub-area extends from Haslum in the north east to the limit of the mapped ground, some few hundred metres south west of Nybu farm, (204 173). It covers the remainder of the southern boundary of the granite gneiss. Gedrite anthophyllite rock has not been found in this sub-area, but otherwise the rock types are similar to those of the last sub-area. It is here that the unusual rock type, the nodular silliminite gneiss is best exposed.

The gneiss foliation is steeply dipping throughout this area. As the attitude of the foliation is traced along the main road from near Hovet in the north to Finsbudalen in the south west, the initial south easterly dip of 70° steepens and, close to Fiane (220 183), at the level of the northern contact of the quartzite with the amphibolite, the foliation is vertical. Further south west, the foliation turns over and the dip shallows to a minimum of 60° towards the north west. In the Nybu district, the dip of the foliation is constant at 50 to 60° towards the north west, with a strike of 060°.

60 poles to the foliation have been plotted in the πS diagram, fig. 33C. These are distributed in two distinct groupings, and do not define a single girdle.

A total of 10 linear structures, the majority measured in the banded gneisses, all trend between 225° and 260°, at plunges varying from 25° to 50°. Fig. 13B illustrates the fold in quartzite from which one of the readings was taken. The lineation in the nodular sillimanite gneiss is particularly well marked, the longest axis of the nodules invariably being aligned parallel to the mineralogical lineations in the rock.

In the analysis below of the two sub-areas, 29 and 30, which cover the Portör Peninsula, the proposal is made that the rocks of that region are folded isoclinally about axes which plunge at fairly shallow angles towards the south west. While the trends and plunges of the linear structures in this area (sub-area 28), are very similar to those for Portör, the more variable strike of the foliation results in a much greater spread of πS plots in the πS diagram compared to the Portör diagrams. A similar structural interpretation here is thus a tentative one, but it is possible that isoclinal folding is also developed in sub-area 28, especially in the Finsbudalen district.

Sub-Area 29.- This sub-area covers the major part of the Portör peninsula, together with several small islands in the bay to the north called Haslumkilen. The western boundary has been arbitrarily drawn 1 km. east of Ekerne farm (220 168), and the sub-area extends to the tip of the peninsula. The exact size and location are shown in fig. 32.

The degree of exposure throughout the peninsula is very high, probably of the order of 90%, and all the rocks are strongly foliated. The series of rock types exposed is dominated by banded gneiss of the type which comprises alternating bands, of variable thickness, of quartz-dioritic and amphibolitic composition.

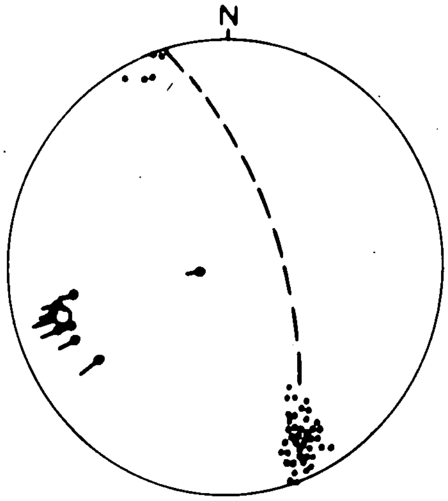
Throughout the peninsula, the strike of the gneissic foliation is remarkably constant, a fact which is borne out by the pattern of plots in the πS diagram. 065 to 070° is the general trend of the foliation, which is vertical or dips steeply towards the south east, except in the north west of the sub-area and in the islands, where a steep dip towards the north west is found.

In the πS diagram, fig. 34B, 48 poles to the foliation have been plotted. These are concentrated into two groups and do not define a single girdle.

The linear structures, of which 11 have been plotted, are also remarkably constant in trend and plunge and are similarly tightly grouped together. They trend from 235° to 250°, and their plunges vary from 15 to 30°. The measurements were made, for the most part, on a very strongly developed lineation and 'mullion' structure in the basic gneisses. Pl. 41 illustrates this structure as it is seen in an amphibolite exposed on the road from Levang to Portör, 1 km. east of Ekerne.

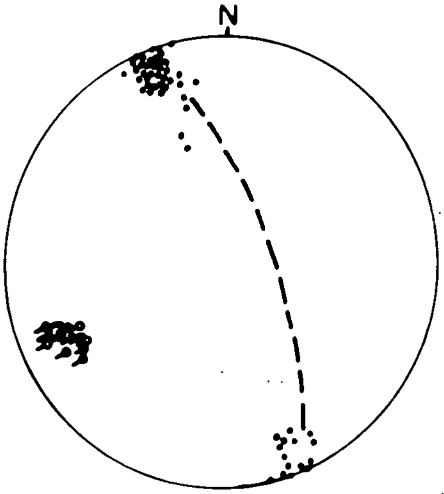
The type of analysis most appropriate here is the same as that first used in the account of the structure in the Tonstöl Lakes area, sub-area 8. This assumes a broadly orthorhombic symmetry for the πS diagram pattern, and, following the same reasoning as that employed for Tonstöl, of the three possible planes of symmetry, that drawn in fig. 34B is the one considered to most nearly define the probable fold pattern. The pole to this great circle plunges between 20 and 25° on a bearing of 245°. The strong concentration of linear structures in this part of the diagram was a deciding factor in the selection of the given plane, the assumption having been made that these were B lineations.

The structure in this sub-area is thought to be that of very tight isoclinal folding about β axes plunging at relatively



A. (30)

PORTØR PENINSULA.



B. (29)

FIG. 34

shallow angles on a bearing of approximately 245°. The axial planes of these folds dip steeply towards the south east throughout the greater part of the area. The hinges of the folds are not seen at the present level of exposure.

Sub-Area 30.- This sub-area covers the remainder of the Portör peninsula and extends to the limit of mapped ground in the region of Trollvann, (210 163), south west of Levang pension, (216 172). The northern boundary has been drawn parallel to the strike of the gneisses, along the line of the scarp face which forms the southern side of the valley of Finsbudalen, thus coinciding with a suspected major fault. Fig. 32 shows the size and limits of the sub-area.

The rock types exposed are broadly similar to those of the last sub-area, the differences lying in their relative proportions. Granitic gneisses are more-or-less restricted to a horizon approximately 200 m. thick, just north of Levang, where in good fresh exposures on the main road, they are seen to be intercalated with basic amphibolites. A number of Permian dolerite dykes, of variable thickness and attitude, are exposed around Levang and further to the west.

As in sub-area 29, the strike of the gneiss foliation is remarkably constant, although the general trend is slightly closer to due north east, at 060 to 065°. In contrast to the Portör end of the peninsula, the dip of the foliation is towards the north west throughout the major part of this area, the angle of dip being again high, with minimum dips of 50°, and the majority 70 to 80°. The small number of readings from foliations dipping towards the south east were taken from localities near the coast.

In the πS diagram, fig. 34A, 46 poles to the foliation have been plotted. Over 90% of these are concentrated in a single group in the south eastern part of the diagram.

There is again little variation in the trend and plunge of the linear structures, and, with one exception, the lineations plotted trend between 235° and 260°, and have plunges of from 20 to 30°. The strong lineations and 'mullion' structures noted in sub-area 29 are also well developed in the amphibolites of this area, especially in the region of Ekerne farm.

The analysis of the πS diagram and the conclusions regarding the structure of the area are the same as those for the last sub-area. In fig. 34A, the plane of symmetry which has been drawn defines approximately an isoclinal fold (or folds) the β axis of which plunges at around 25°, on a bearing of 250°, coinciding with the group of observed linear structures. The axial plane dips steeply towards the north west.

THE LINEAR STRUCTURES

Introduction

A study of the different types and orientations of linear structures is of prime importance in the elucidation of the structural evolution of an area of deformed rocks. On Levang the commonest linear structures are caused by preferentially oriented minerals and minor fold axes; striations, crenulations, mullion structures, and boudinaged layers are also found. A linear structure produced by the intersection of planar surfaces of varying inclination, for example, the intersection of a foliation with a secondary axial plane foliation, is rare.

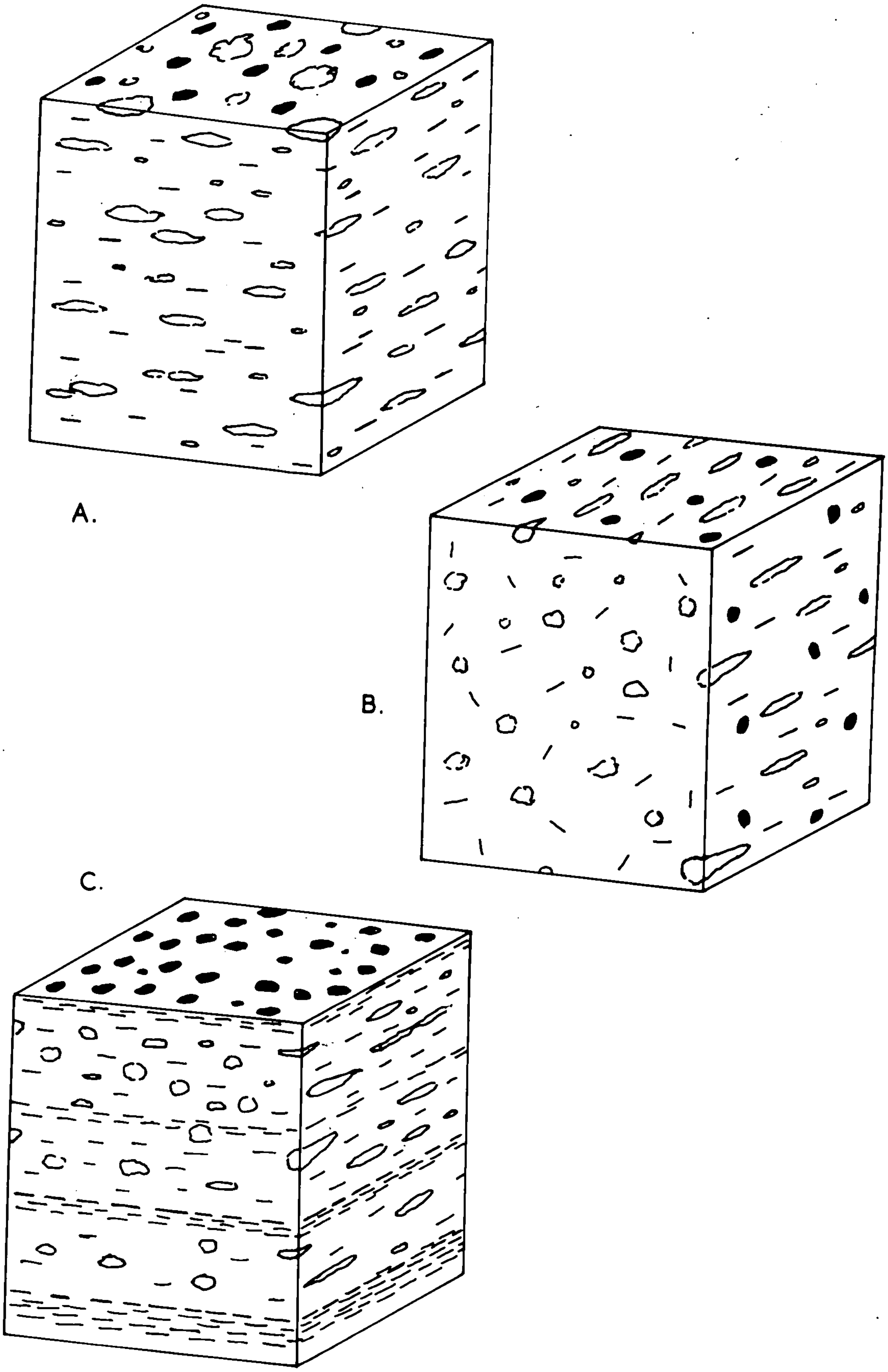
Mineral Orientation.- Preferred orientation of inequant mineral grains is perhaps the most widespread linear structure in the area. Those amphibolites with a low content of felsic minerals not infrequently show a strong lineation produced by the nematoblastically oriented amphiboles, while foliation may be very weak or absent. In the granitoid gneisses preferred orientation of biotite mica and amphibole is usually the most prominent contribution to a linear structure, but feldspars, particularly microline, generally show fairly strong dimensional orientation and 'augen' of granulated feldspar are found in several areas. Quartz may occasionally be stretched parallel to the lineation. In the nodular sillimanite gneisses the long axes of the nodules have a common trend which is always parallel to the lineation in the rock as a whole. Pl. 42 illustrates the marked striation sometimes developed in the foliation planes of the micaceous amphibolites. This striation, which resembles slickensides, parallels the mineral orientation. Pl. 41 shows the very strong fluting seen particularly well developed in basic gneisses on the Portör peninsula, this example being exposed close to Ørsvik farm (224 171). These structures resemble mullions (Wilson, 1953)

Fig. 35 Structures in the Granite Gneiss.

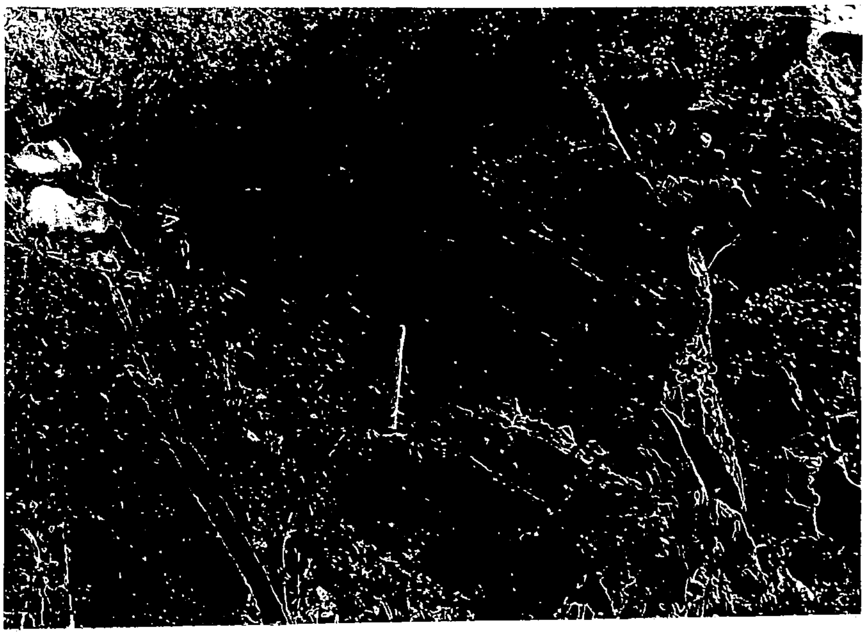
A. Foliation, no lineation.

B. Lineation, no foliation.

C. Banding, foliation, and lineation.


A.
B.
C.

Pl. 41. 'Mullion' structure in basic gneisses exposed on the road close to Ørsvik farm. The hammer is 35 cm. long.

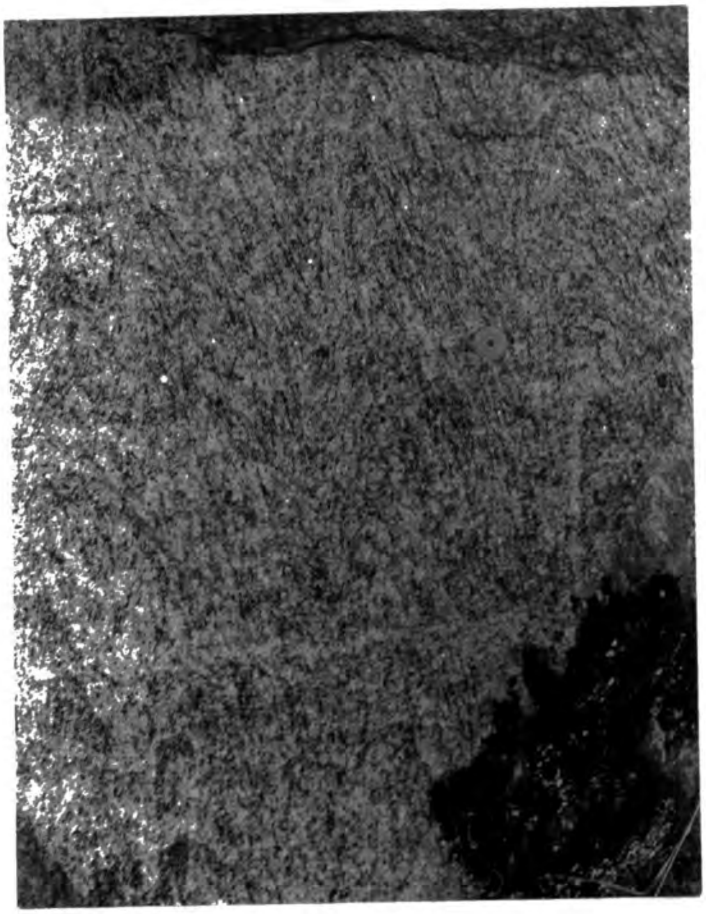


Pl. 42. Striations on the plane of foliation in micaceous amphibolites. The exposure is on the east side of the road, 150 m. south of Varpesund.

and are found to plunge consistently towards the south west at around 25°, paralleling the other linear structures on this peninsula.

Minor Fold Axes.- Minor folds vary in style from broad open corrugations to very tightly appressed isoclinal folds in which shearing may obscure the hinge zones. Pl. 43 shows such tight folding of the foliation of the granite gneiss in the Hellermyren (196 180) region of the Mörk Vann antiform. With only a small amount of further tightening and shearing in this type of fold the folding virtually ceases to be discernable in all but the very cleanest exposure.

Many of the minor folds observed may with reasonable certainty be related to the β axis of the major structure within which they are found, and can thus be classified as congruous drag folds in B. However, in some cases these folds are found to be equally common, or even more common, in the hinge zones than on the flanks of major folds. The term drag fold implies that the fold has been produced by concentric displacement along foliations or bedding planes. In as far as slip on the foliations falls to zero on the crest of the fold, minor folds found in the hinge zone cannot be drag folds. The term parasitic folds has been proposed (de Sitter, 1958) for those minor folds previously termed drag folds, (i.e. parasitic folds are taken to include minor folds found on the flanks as well as the crests of major folds), and the mechanism responsible for their formation is a flattening process of stress cleavage. de Sitter (ibid.)



Pl. 43. Tightly appressed and sheared minor folds in granite gneiss from the Hellermyren district in the Mörk Vann antiform. The coin is 2.5 cm. across.

Pl. 44. Ptygmatic folds in micaceous amphibolite, Fiane, showing the coincidence of the trend and plunge of the fold axes with the lineation in the host rock.

has also suggested that parasitic folds may be more typical of cleavage (shear) superimposed on concentric folds.

In the majority of the πS diagrams the minor fold axes parallel the computed β axis. Exceptions exist, however, notably in the Myre Dome and the Mörk Vann fold, and in these cases the minor folds may or may not be relatable to the 'a' tectonic direction.

Flow Folds.- Extremely complex folds with highly variable axial attitudes are found in zones of extensive migmatization particularly in the Portör region. These folds appear to be rootless, and in as far as signs of cataclasis are lacking they must have been formed in an essentially plastic environment, i.e. they may be classified as flow folds. The recrystallization and homogenization which accompanied the granitization in migmatite zones has frequently tended to obscure the flow folds, so that they become very nebulous in character.

Ptygmatic Folds.- Ptygmatic folds appear to be most common in the felsic gneisses of the Portör peninsula, (this is also the area of highest exposure), but are also seen in the amphibolitic and quartzitic gneisses surrounding the granite. Within the main mass of granite gneiss they appear to be comparatively rare. The ptygmas, in which the grain size is frequently seen to vary directly as the thickness of the vein, are composed essentially of quartz and feldspar. They are almost always very complexly folded and determination of their structural elements is difficult since exposures seldom afford information as to the attitude of the veins in the third dimension. In several cases, however, it was found that where they were amenable to measurement the fold axes of the ptygmas coincided with the dominant linear elements of the host rock. Pl. 44 illustrates a ptygmatic vein in micaceous amphibolite exposed near Fiane (220 183) where the axes of the ptygma plunge 30° bearing 250°, parallel to the lineation in the amphibolite. At Portör several examples were noted of ptygmas which appeared to be offshoots of essentially concordant felsic pegmatitic sheets and lenses, the highly contorted ptygma not infrequently interconnecting several parallel sheets. The formation of the ptygmas was clearly one of the later stages in the evolution of the area since they are seen to cut all the 'K' and 'L' Pre-Cambrian amphibolite dykes.

Discussion

The orientation of β as deduced from the separate πS diagrams indicates that, with the possible exception of the Mörk Vann fold, the major folds in the area have north east - south west, or east north east - west south west trending axes. The plunge of these axes is variable, but is generally low to moderate. In the eastern Myre Dome a vertically plunging and overturned β axis has been demonstrated. The gneisses south of the main granite mass show the greatest geometrical homogeneity, S being tautozonal over practically the whole area. The linear structures in the Portör peninsula have been related to the B direction within isoclinal folds, the β axes of which plunge between 20 and 30° on a bearing of approximately 260°. Strongly appressed isoclinal minor folds have been found in the Portör peninsula. The major fold crests have not been recognised, perhaps indicating that shearing out of the hinge zones has occurred.

Within the main granite mass examples can be found of β fold axes which plunge towards the north east, while other major folds plunge towards the south west. Outside the granite virtually all the linear structures measured plunge at fairly shallow angles towards the south west. Elders (1963) states that in the region of the Herefoss granite in south east Aust-Agder, (south west of Levang and within the Bamble Formation), there exists a complex of major, almost isoclinal, folds, with sub-vertical axial planes, the β axes of which, with one exception, plunge south south west at angles up to 45°. Apart from the general trends of the folds being further towards the east, it would appear that the fold pattern in the Levang peninsula outside the granite mass is broadly consistent with that found by Elders (op. cit.).

In the area as a whole, examples of both concentric (flexural slip) folds and similar (slip) folds are found. Not uncommonly a single fold may show features characteristic of both mechanisms. It is probable that the dominant mechanism involved an initiation of folding through flexural slip, with the subsequent development of slip folds as deformation proceded.

No evidence whatever has been found from a study of the geometry of the planar and linear structures in the banded gneisses to suggest that the disposition of these structures has been influenced in any way by a possible intrusion or diapiric rise of the Levang granite.

The form of the Heligesvann antiform is such as to suggest that the rigid block of the Heibö hyperite may have been of some influence in the (presumed) isoclinal tightening of the eastwards extension of this structure. The relationship of this structure, and of the similar isoclinal extension eastwards of the Kapel Basin synform, to the Myre Dome is obscure. The hinges of both folds appear to have been sheared out, or alternatively, the present distribution of the fabric elements may be indicative of disharmonic folding.

The major problem concerns the interpretation of the proven overfolding in the Myre dome, and of the much more obscure structure which has been termed the Mörk Vann antiform.

<u>The Mörk Vann Antiform</u>.- On the aerial photograph (pl. 37) it can be seen that there is an apparently complex relationship between the simple east north east plunging anticlinal fold at Stavsengen (212 198) and the fold system south of Mörk Vann, in the region of Hellermyren farm (196 180). It must be emphasized that the following proposals concerning this structure are tentative in the extreme, since it was only from the apparent trace of the foliation on the aerial photographs (pl. 37) that the

proposed fold form was deduced. In the field extremely complex parasitic shear folds completely obscure the overall strike and dip of the granite gneiss foliation, and it was on the basis of the assumption that those minor folds measured were linear structures in B that the attitudes of β in the major structure were arrived at.

In the synoptic πS diagram, fig. 21, the tentative β axes for sub-area 15 plunge 70° on a bearing of 330°. The β axes for all four sub-areas thus appear to show a steady trend towards a steepening of the axial plunge from 10° at Stavsengen to 70° at Hellermyren, while the bearing swings from 070°, through 063° and 040° to 330°.

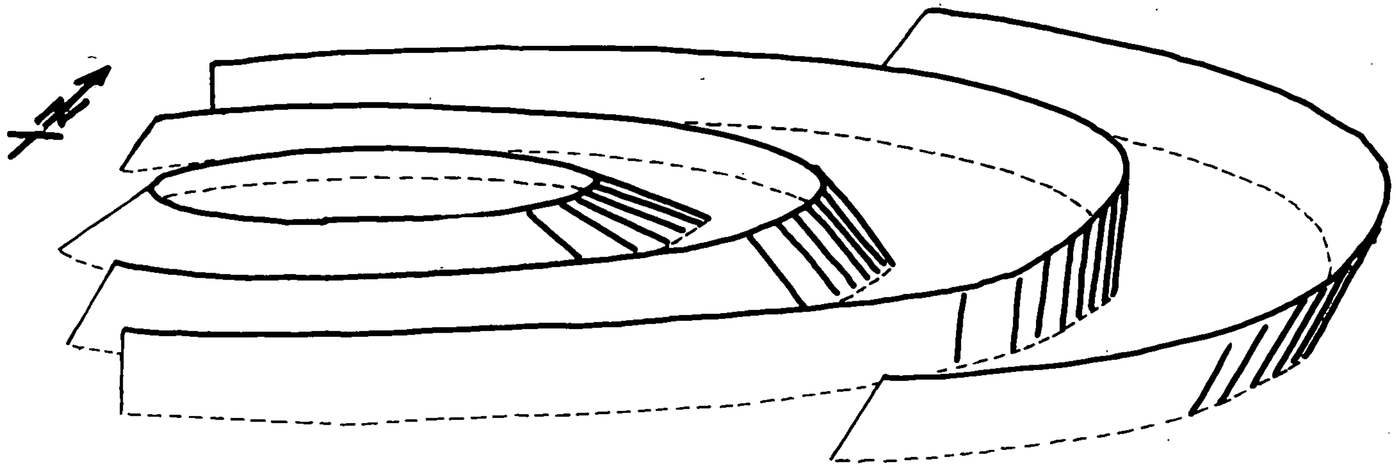
The three dimensional sketch, fig. 21 Q, is an attempt at representing schematically the form of the structure as a whole, and shows a foliation plane traced through the north eastwards trending part of the fold (in the region of Mörk Vann itself) over the anticlinal hinge at Stavsengen, and then further south westwards into the ?north westwards plunging 'chevron' fold at Hellermyren. The overlay on pl. 37 indicates the trace on the ground of the foliation plane in fig. 21 Q. The line is solid where the attitude of the foliation as seen in the photograph was confirmed in the field and broken where it was not.

A tentative interpretation is as follows. A first phase of deformation gave rise to a fairly tight anticlinal fold with a north west to south east trending axis and axial plane. The axis probably had a steep plunge towards the south east. This fold is represented in fig. 21 P. Later shortening, presumably about a north west - south east direction, as a second phase of the same, or of a different, orogenic period, resulted in refolding of the first structure about a north east - south west trending axis. The 'nose' of the earlier fold forms the 'middle' and southern limbs of the chevron fold, while an anticlinal fold with variable axial plunge and trend has been formed from the limbs of first fold. The parasitic shear folds described from the Hellermyren region are related to the second phase of deformation. The chevron fold dies out north eastwards as it is traced along the re-folded axial plane, shown in fig. 21 Q, of the first antiform. Original closure of the foliation through this plane is no longer discernable within what is now the northern limb of the Hellermyren fold because here the second phase folding has been tightly isoclinal.

Irrespective of the possible implications of the geometry of the planar fabrics in the Mörk Vann fold, the distribution of the linear structures in a partial girdle in the synoptic diagram, fig. 21, is strongly suggestive of superposed folding.

The Myre Dome.- The eastern part of the Levang peninsula has been shown to be an elongate domal structure in which there is overturning of β towards the east. Fig. 36 represents diagrammatically the attitude of the foliation at several different levels within this structure.

In a brachyanticlinal dome there are, trending roughly perpendicular to the tighter major folds in the B direction, more open folds in 'a'. The 'a' fold axes have a somewhat steeper plunge than the β axes at equivalent horizons within a



A DIAGRAMMATIC REPRESENTATION OF THE ATTITUDE OF THE FOLIATION IN THE MYRE DOME.

FIG. 36

normal brachyanticline. The β direction in the Myre Dome has a general bearing of 070° and the 'a' fold in the northern part of the dome should trend at about 340°. The linear structures observed south of Mellomvann (243 232) trending 340 to 360° may thus simply be interpreted as 'a' lineations for a single phase of folding. However, the overall geometry of the structure is triclinic, and the trends of many of the observed linear structures lie between 265° and 310°. These lineations are not readily relatable to B or 'a'. This lack of correlation is almost certainly due to the complex overturning of the foliations in the nose of the fold and in the north eastern part of the structure, since it is only on vertical or south westwards dipping foliation planes that the aberrant lineations have been measured.

The effect on the trend of a lineation which lies within the plane of a foliation when the latter is rotated in space is considerable. For example, a foliation plane mapped 400 m. south of Skjörsvik, (i.e. in the northern limb of the fold, roughly half way between the traces of the B and 'a' directions on the ground), strikes 305° and dips 65° towards the south west and within it a lineation plunges 50° on a bearing of 270°. If this plane is rotated into a vertical position the trend of the lineation will correspond to the strike of the plane, i.e. its plunge will have increased to 58° on a bearing of 305°. If the plane is then further rotated until it is dipping 65° towards the north east (i.e. a normal quaquaversal dip for the Myre Dome) the lineation then plunges 50° at a trend of 340°. This is parallel to the 'a' direction, as shown by the analysis. The extreme case as regards the change in trend on rotation would be where a foliation in which the lineation had a plunge equal to the true dip were overturned; the trend of the lineation would be completely reversed through 180°. This complete reversal would only take place exactly on the hinge of the fold, where overturning of the foliation plane with its B lineation reverses the direction of plunge of the lineation though the trend remains parallel to that of the fold axis. Consequently, the effect of the overturning of a fold is to produce the most widely diverging lineation trends on the flanks of the folds and the closest correlation in the axial zone.

The aberrant lineations in the overturned foliations in the Skjörsvik region do not appear to be B lineations with reference to the major fold axis trending 070°. In as far as linear structures in 'a' are generally less well developed than those in B, it is possible that these linear structures belong to an earlier phase of deformation than that responsible for β, i.e. that they may be refolded B lineations.

The synoptic diagrams for the eastern Myre Dome, figs. 31A and 31B, demonstrate clearly the triclinic symmetry of the structure as a whole, while the πS diagrams for the individual sub-areas indicate that subdivision does not eliminate the triclinic symmetry. In fig. 31A, πS develops a complete girdle around the primitive, and one weaker girdle. In fig. 31B, the linear elements likewise define a girdle. The triclinic geometry is further confirmed by the attitude of β, which not only varies from horizontal to vertical, but is also completely overturned.

The girdle development of the fabric elements and the overturning of the fold axis indicates double folding.

While the evidence produced by the present study is not conclusive, the writer would prefer to account for the formation of the observed fold pattern in the Levang peninsula through two periods of deformation. The deformation need not necessarily have taken place in two separate orogenies, but may have been two phases in a single complex orogeny. The tectonic direction of transport for the earlier deformation is uncertain, but the shortening involved in the later deformation probably took place in a roughly north west - south east direction.

CHAPTER 5

CONCLUSIONS

Three main possibilities present themselves regarding the mode of origin of the Levang granite; it could have formed through intrusion of a magma, metasomatic granitization, or isochemical metamorphism of a series of supra-crustal rocks of suitable composition. The granite will now be examined with the aim of establishing which of these hypotheses accords best with the known facts.

The origin of the foliation in the granite is of vital importance in the elucidation of its history. The foliation may have originated by:

1. Fluid flow in an intrusive igneous body.
2. Deformation of an originally structureless granite.
3. Solid flow in a crystalline mass.
4. Inheritance from a pre-existing foliated rock.

In all known massifs the strike and dip of the nearest contact plane determine the orientation of the flow layers (Balk, 1937). In as far as the foliation in the Levang granite always parallels the contact, this could support a primary flow origin for the foliation. However, in steep walled massifs flow structures do not seem to develop into a true dome, but are more often steeply dipping throughout, and in a flow layered body the foliation is always much more distinct near the margins, becoming weaker, or even disappearing, towards the centre

(Balk, ibid.) In the Levang granite the foliation is equally strongly developed throughout the mass, and it defines a perfect dome.

Deformation of an originally massive granite would produce an axial plane foliation which would probably be sub-vertical throughout the body, and have a broadly constant strike. This means that irrespective of the direction in which the shortening involved in the deformation took place, such an axial plane foliation would, at some point, intersect at right angles the boundary of the granite. The foliation in the Levang granite is everywhere conformable to the contacts.

Solid flow in a crystalline mass (which could have originated through magmatic or metasomatic processes) would produce a foliation which might be equally well defined throughout the rock, but it would also very probably be everywhere sub-vertical.

None of the first three possibilities can account for the observed size, form, and disposition of the amphibolitic inclusions, all of which are completely conformable sheet-like horizons frequently traceable for several kilometres along the strike.

The foliation in the Levang granite has been inherited from a pre-existing series of foliated supra-crustal rocks.

Nowhere around the contacts of the granite have agmatites or intrusion breccias been observed. There is no contact metamorphic aureole, and neither is there a finer grained marginal facies to the granite. Those inclusions which have been mapped in the region of the contact, although petrologically identical to the wall rocks and thus possibly derived from them, are always sheet-like, never fragmentary, and show no signs of rotation or displacement.

The contact parallels the foliation of the banded gneisses in strike and dip, and discordance, in the few places where it is observed, is on a very minor scale. No apophyses, other than granitic pegmatites, are seen to penetrate the gneiss envelope. On the other hand, the granite contacts are always sharp, though in places 'interfingered', and gradational contacts, generally held to be typical of metasomatic granites, are not found.

None of the granitic or basic contact rocks show any evidence of shearing, brecciation, or mylonitization, features which might be expected had forcible intrusion and/or diapiric (Wegmann, 1930) uprise of the granite occurred.

The fold pattern within the granite, as defined by the foliation, is in complete structural conformity with the banded gneisses, and the analysis has not revealed any evidence to suggest that the structural geometry of the gneissic envelope has been modified through intrusion or diapirism of the granite.

The textures of the granite are metamorphic, granitic textures have not been observed. The nature and distribution of the heavy accessory minerals in several granite specimens may be indicative of original sedimentological segregation. The composition of the plagioclase may show a range of values in a single hand specimen, and zoned plagioclases, typical of igneous crystallization, have not been found.

The virtually universal occurrence in the granite of irregularly developed film and flame perthites in adjacent microcline grains, inclusions of sericitised plagioclase in fresh microcline, myrmekite, etc., certainly demonstrates a complex evolution for these rocks, and may well be indicative of microcline porphyroblastesis through the (metasomatic) introduction of potash. The textural features of the granite are, however, ambiguous, since it could be argued that the observed relationships are due to metamorphism of an original igneous granitic texture, or to deuteric effects post dating magmatic crystallization.

The fact that all the microclines from the granite were found to be more or less fully ordered maximum microcline does not preclude the possibility that inversion from high temperature forms has occurred. Donnay, et. al. (1960) have proposed that high obliquity values are indicative of a relatively high volatile content.

According to Bowen (1928), basic inclusions should react with a magma to produce a mineral assemblage with which the magma is in equilibrium. In the case of an amphibolite, this should be transformed into an aggregate of biotite and more sodic plagioclase. While such a biotite-plagioclase assemblage may be produced at an intermediate stage, the final result seems always to be transformation of the inclusions into a rock type identical mineralogically to the granite itself.

The fact that the granite approximates to the minimum melting composition for the granite system would appear to be important evidence in favour of a magmatic origin for the granite. The Flå granite also approximates closely to the minimum melting composition, and within it numerous basic inclusions are seen to be transformed to this composition (Smithson, 1963). Smithson (ibid.) points out that, assuming an anatectic magma initially of minimum melt composition was involved in these reactions, in effecting the transformation of the inclusions the magma must have lost a considerable amount of potash. In order that the granite should return to the (now observable) minimum melt composition, more potash must be introduced, possibly by metasomatic introduction through the medium of residual solutions which have somehow become enriched in potash. The result is that the final minimum melting composition is caused by a process other than crystal-liquid equilibrium. On the basis of this argument, (which may equally well be applied to the Levang granite), a minimum melting composition loses much of its significance as a criterion for a magmatic origin of the rocks concerned.

The high quartz content of the gneisses in the core of the Heligesvann antiform is suggestive of metasedimentary origin. A 'ghost' stratigraphy, comprising a regular sequence of fairly sharply delimited granitoid gneisses of variable composition interlayered with a thick unbroken amphibolite, has been demonstrated in this structure. This is very strong evidence against a magmatic origin for the Levang granite.

In the opinion of the author, the overwhelming weight of evidence is against a magmatic origin for the Levang granite. The magmatic theory creates many more problems than it solves. There remain to be evaluated the alternatives of isochemical metamorphism and metasomatism.

Isochemical metamorphism would explain the sharp contacts. The minimum thickness of the granitic gneisses exposed in the core of the dome is of the order of one kilometre. While such a thickness of sediments of suitable composition, i.e. shales, greywackes, or arkoses, is not wholly unreasonable, it would be expected that such a considerable thickness of granitic rocks would commonly have been mapped elsewhere in the adjacent Bamble Formation rocks. With the exception of a small body of granitic gneisses (also occupying the core of a domal structure) exposed due west of Kragerö, and the Portör rocks, granitic gneisses are not common in this part of the Bamble Formation. Isochemical metamorphism is possible, but not probable.

The transformation of basic inclusions to rocks of granitic composition, and the widespread sericitisation of plagioclase implies the removal of Mg, Fe, and Ca, while the perthitic microclines indicate prophyroblastesis involving the introduction of potash. Although the source of the potash and the destination of the cafemic materials are unknown, it is nevertheless evident that the system was an open one.

Recent experimental work (Tuttle and Bowen, 1958, Orville, 1962) has demonstrated diffusion of potash in solution down thermal gradients under pressure-temperature conditions about equivalent to those of the amphibolite facies of regional metamorphism.

Metasomatic introduction of potash, if it occurred, was probably effected by pore solutions, since the maximum pressure-temperature conditions do not appear to have been higher than amphibolite facies. The position of the granite in the core of a dome is probably highly significant. Metasomatic fluids may have migrated into the dome which would form a potential area of low pressure and temperature. During deformation componential movements in the granite gneiss took place essentially parallel to the foliation; had they not done so, the foliation would not have been preserved. The solutions which transported, or allowed the diffusion of potash, probably migrated along shear zones paralleling the gneissic foliation. The sharp contacts of the granite with the amphibolites may simply demonstrate the efficacy of the basic rocks as a physical and chemical barrier to the metasomatic solutions. The localisation and concentration of granite pegmatites at the level of the amphibolite may be further testimony of this property. The amphibolites might represent a basic front, (Reynolds, 1946), but the field and petrographic evidence appear to indicate that the mineralogy of these rocks was determined by the compositions of the original supra-crustal rocks from which they were derived. The metasomatic hypothesis thus demands an introduction of potash from below and the removal of cafemic materials downwards.

The tectonic environment of the Levang granite is such that it bears a superficial resemblance to an intrusive pluton. If the major part of its investigation were to be based on chemical studies, and only a cursory field examination undertaken, it might readily be mistaken for an intrusive igneous granite. Detailed mapping has shown that the granite forms part of a metamorphosed fold structure which is in complete conformity with the regional pattern.

A magmatic origin for the granite has been discounted. Although unable to offer experimental confirmation of the exact mechanisms involved, the author believes the Levang granite to have formed synkinematically through the transformation of a pre-existing series of supra-crustal rocks by processes of metasomatic granitization.

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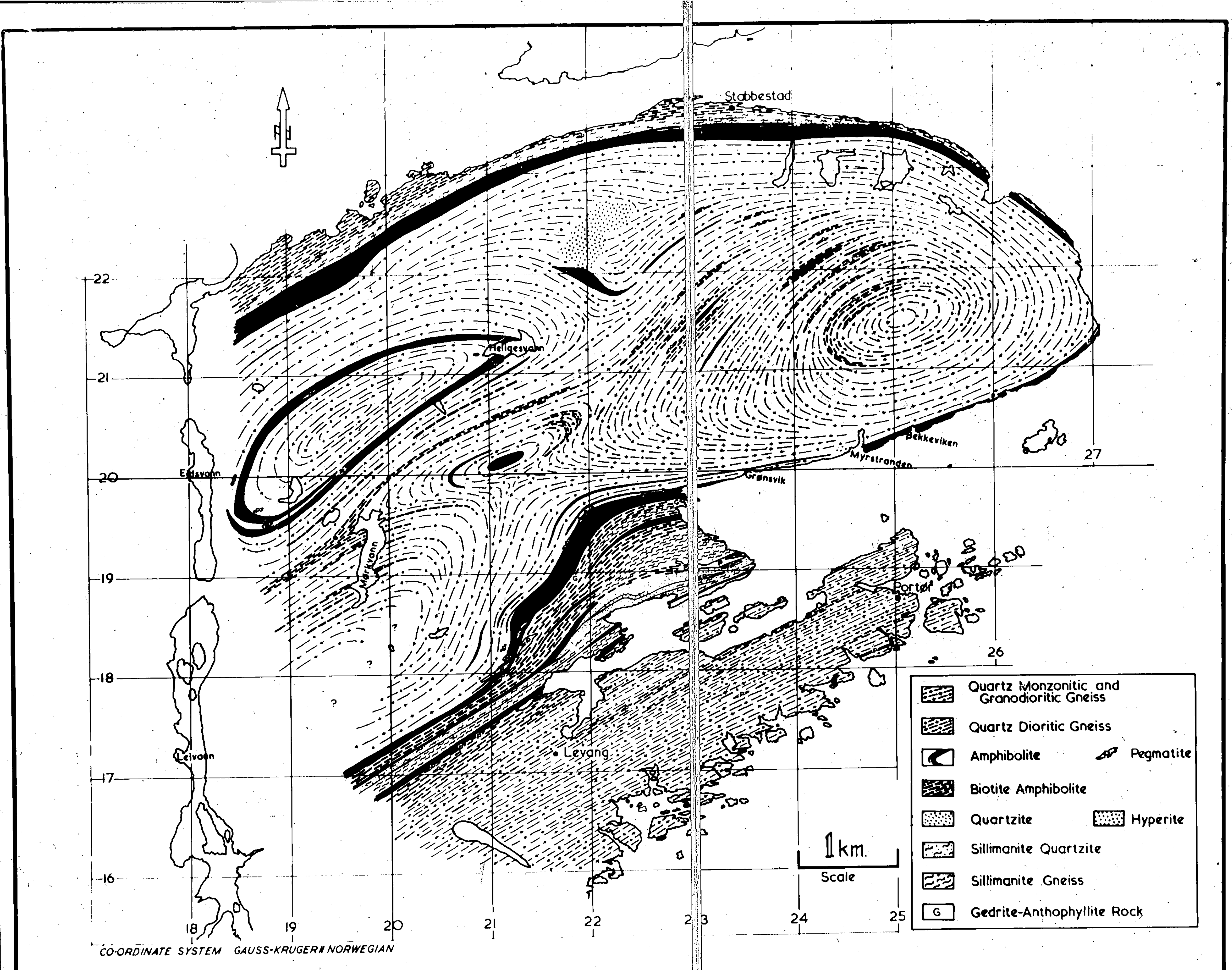
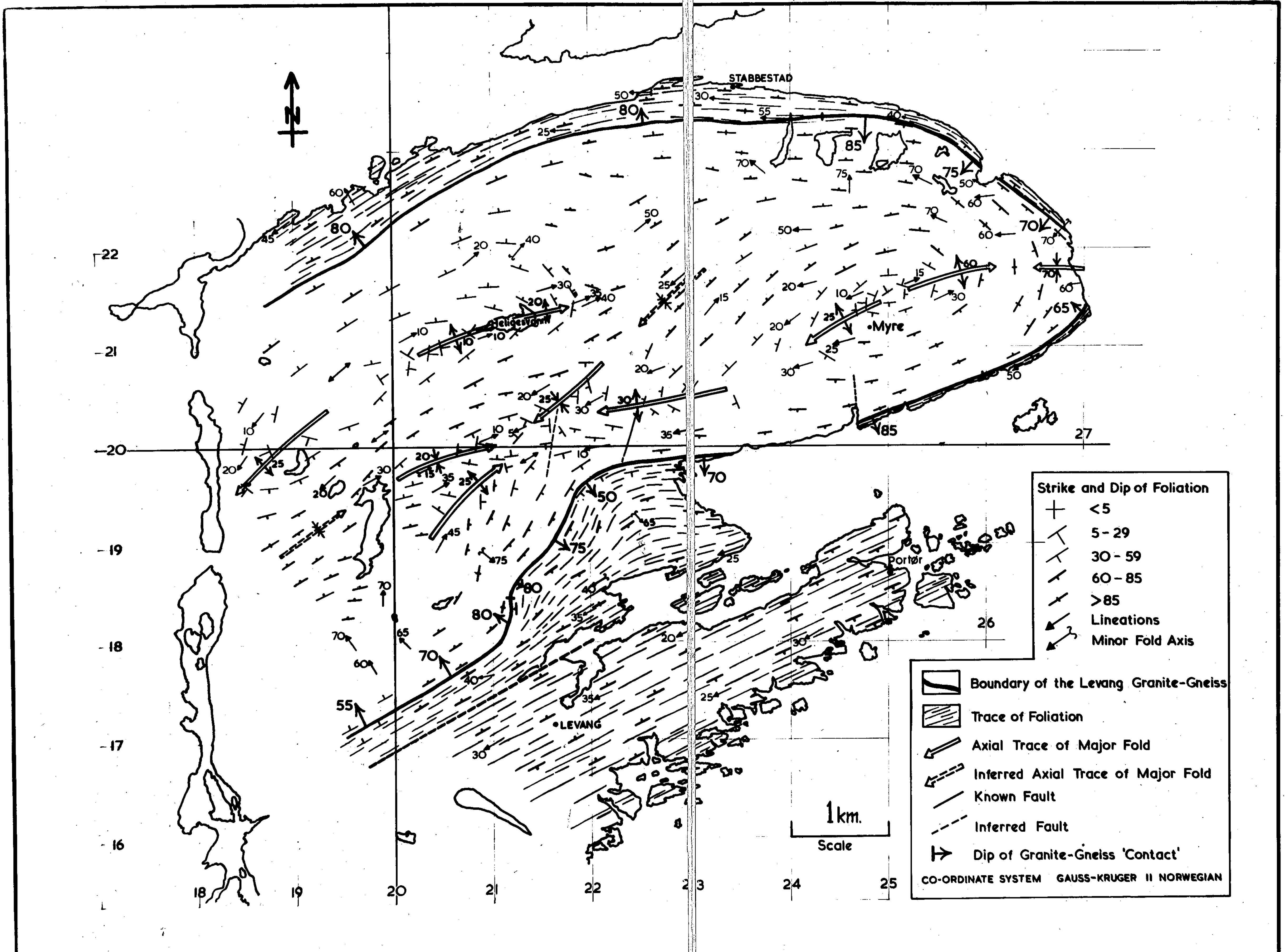


GEOLOGICAL MAP OF THE LEVANG PENINSULA NORWAY

T.G.E.
1964



STRUCTURAL MAP OF THE LEVANG PENINSULA, NORWAY

T.G.E. 1964

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