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THE GEOLOGY OF NORTH-EASTERN HEIMEFRONTFJELLA, DRONNING MAUD LAND

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L. M. JUCKES, B.Sc., Ph.D.

British Antarctic Survey
and
Department of Geology, University of Birmingham

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ABSTRACT

THE Basement Complex, which forms the majority of the exposures in north-east Heimefrontfjella, consists largely of *para*gneisses which have undergone almandine-amphibolite-facies regional metamorphism. The biotite-gneisses and amphibolites of Milorgfjella, which are intruded by a body of gneissic granite, may be older. Extensive shearing in Milorgfjella has caused widespread retrograde metamorphism and the formation of mylonitic rocks. Small acid and basic dykes were emplaced during the metamorphism and there are also post-metamorphic basic dykes.

Overlying the Basement Complex with an angular unconformity is a sequence of terrestrial sediments at least 160 m. thick with a locally developed basal conglomerate which may be of glacial or fluvioglacial origin. Thin coal seams are present and there are plant fossils indicative of a Lower Permian or possibly an uppermost Carboniferous age.

Faulting, tilting and erosion of these sediments appears to have occurred prior to the Jurassic, when a sequence of at least 300 m. of uniform basaltic lavas was extruded and the sediments were intruded by a dolerite sill. The geochemistry of these basic rocks confirms earlier suggestions that the Jurassic magma in this region differs from that of south Victoria Land, notably in its lower silica and potash contents. The compositional range of these rocks is restricted and it is possible that the magma has undergone very little modification since its generation.

The present distribution of massifs and glaciers does not seem to be a result of block-faulting. The degree of dissection of the different mountain blocks is believed to be controlled in part by the height of the pre-Permian erosion surface.

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I. INTRODUCTION

1. *Location*

Heimefrontfjella, the main mountain range in western Dronning Maud Land (Fig. 1), trends south-west to north-east for a distance of 150 km.; it is subdivided into four "blocks" named Tottanfjella, Sivorgfjella, XU-fjella and Milorgfjella.

The north-eastern part of Heimefrontfjella described here lies between lat. 74°40′S., long. 11°00′W. and lat. 74°15′S., long. 9°45′W., and it includes the north-eastern part of Sivorgfjella, XU-fjella and Milorgfjella (Fig. 2). An isolated nunatak (Sembberget), approximately 48 km. east of Bjørnnutane, was also examined but geographically it is not part of Heimefrontfjella.

2. *Previous investigations*

This study is based on the first field mapping of north-east Heimefrontfjella, although earlier workers have commented on the area. Milorgfjella could be the mountain range seen on flights during the Deutsche Antarktische Expedition and named "Kottas Berge" (Ritscher, 1942). Much of Heimefrontfjella was photographed from the air during the Norwegian-British-Swedish Antarctic Expedition, 1949–52. Two of the flight lines passed over Milorgfjella, and a photograph showing most of this block has been described in detail by Swithinbank (1959).

Worsfold (1967*a*), who worked immediately south-west of this area during 1963–64, included a brief description of XU-fjella and Milorgfjella in his observations on Tottanfjella and Sivorgfjella, commenting on the glacial geomorphology and the geology.

3. *Scope of the present study*

The field work was carried out between January 1964 and January 1966 from the British Antarctic Survey scientific station at Halley Bay (lat. 75°30′S., long. 26°42′W.).

In the summer of 1964–65 the writer mapped in north-east Heimefrontfjella and also in Mannefallknausane, a small nunatak group about 150 km. west of Milorgfjella (Juckes, 1968). Transport was by dog sledge and the field work was supported by depots laid by a tractor party. Milorgfjella was visited again in the early part of the following summer season but time was limited. During the remainder of the season, G. W. Lovegrove (the surveyor) and an assistant re-mapped Milorgfjella at 1 : 100,000, mapped Mannefallknausane at 1 : 50,000 and made a small collection of specimens which has been examined by the author.

II. PHYSIOGRAPHY AND GLACIAL GEOMORPHOLOGY

A. PHYSIOGRAPHY

THE mountain ranges parallel to the coast of Dronning Maud Land have been considered by earlier workers to be fault blocks (e.g. Roots, 1953; Gunn, 1963). Worsfold (1967*a*) has described Heimefrontfjella as a dissected range of block mountains, and a tectonic origin for this mountain range is supported by the fact that its trend approximates to the regional strike. The range could have been uplifted to its present elevation either as a horst or as a tilted fault block, but it is considered unlikely that the mountain blocks of north-east Heimefrontfjella are individual fault blocks (p. 30).

There is no direct evidence for geological events in north-east Heimefrontfjella during the period after the end of the Jurassic, and Heimefrontfjella may well have been uplifted before the glaciation of Antarctica and affected by erosion under whatever conditions prevailed. The mountain blocks were subsequently modified by the ice sheet when it was at a higher level (Roots, 1953; Juckes, 1968) and at the present time scarp retreat is the predominant form of erosion.

North-east Heimefrontfjella includes four distinct physiographic units: eastern Sivorgfjella, XU-fjella, the nunatak areas of Milorgfjella and the main massif of Milorgfjella. The physiography of each of these units is different. Much of this difference is considered to have originated when the area was covered by

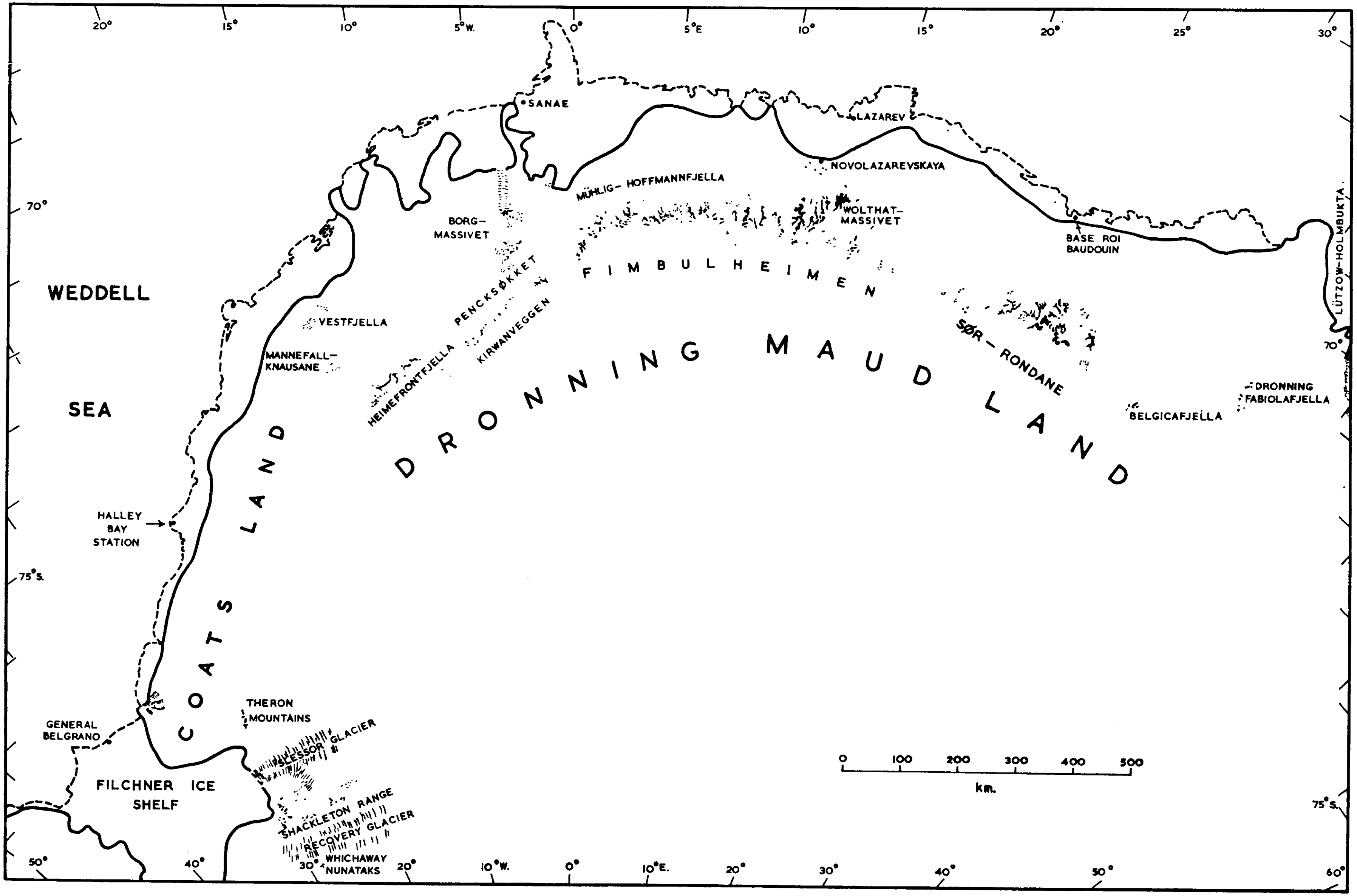

FIGURE 1

Sketch map of parts of Coats Land and Dronning Maud Land, showing Heimefrontfjella and its relationship to other mountain ranges in this region of Antarctica.

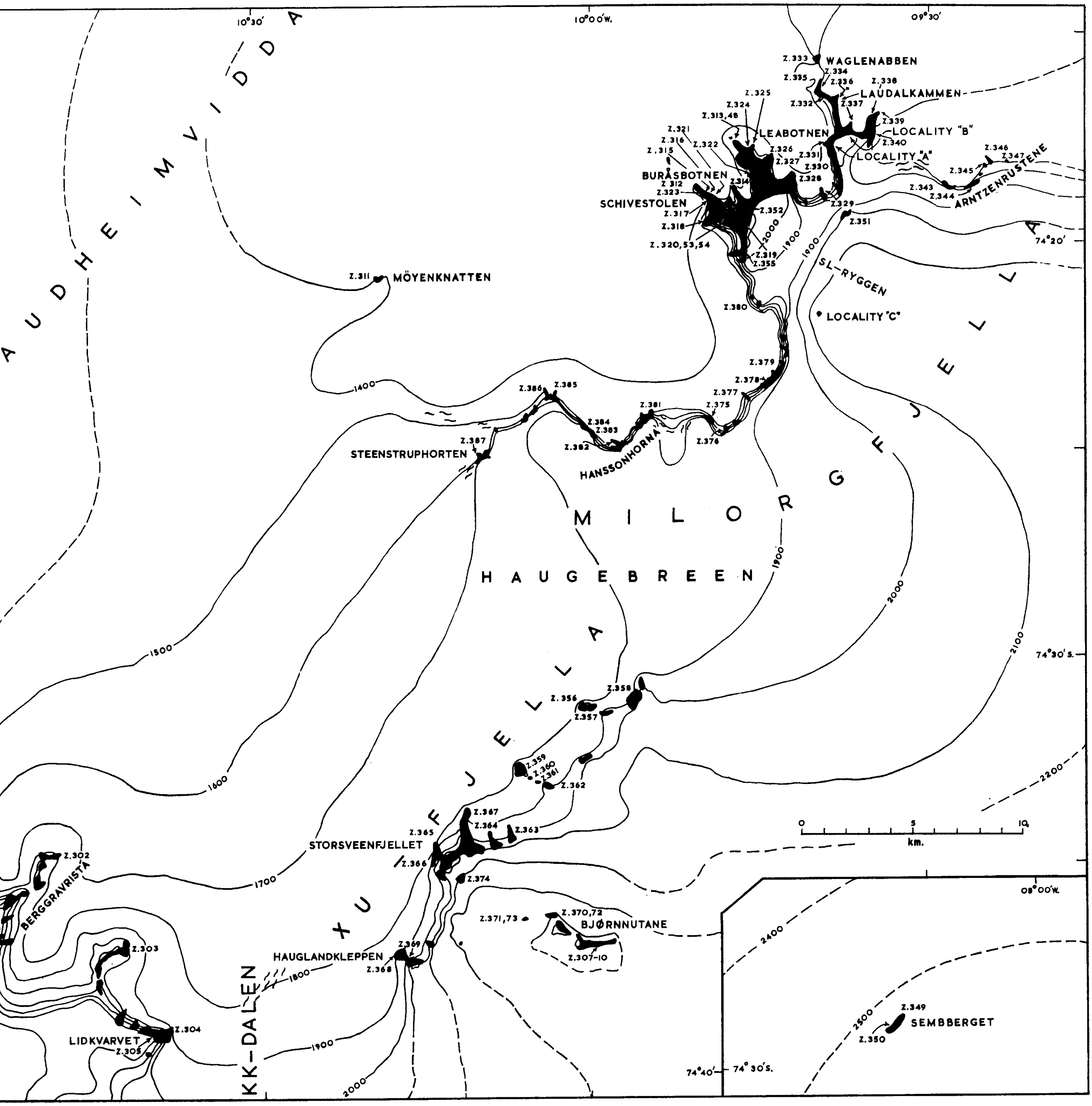

FIGURE 2

Topographical sketch map of north-east Heimefrontfjella, showing the place-names and the geological stations. The station numbers used at locality "A" are Z.342, 392, 393, 399A and 399B; at locality "B", Z.341 and 394; and at locality "C", Z.399C. The contour interval is 100 m.

the ice sheet and it is believed to be related to the depth of dissection by that ice sheet relative to the erosion surface on which the sub-horizontal sedimentary and volcanic rocks rest.

The erosion of a typical mountain block in Heimefrontfjella appears to follow a definite pattern. Originally the block would have been formed of Basement Complex rocks overlain by sediments and volcanic rocks. Erosion of the resistant basalt would proceed slowly but it would be sufficiently irregular for rugged nunataks to be preserved. When erosion exposed the softer sediments, it would accelerate, stripping away the strata until the more resistant Basement Complex rocks were encountered. Erosion of any remaining outcrops of sediments would have been more rapid than dissection of the re-exposed Basement Complex, and the pre-sedimentation surface would be exhumed. Naturally, dissection of the Basement Complex would be affected both by its lithology and structure.

The mountain blocks of north-east Heimefrontfjella are believed to represent various stages of this process. Worsfold (1967*a*) attributed the differences in degree of dissection between Tottanfjella and Sivorgfjella to differential elevation through block-faulting. His geological evidence supported the suggestion of a fault between these two blocks but there is no evidence as to the age of this faulting. In contrast, it is unlikely that any post-Permian faults separate the mountain blocks of north-east Heimefrontfjella.

1. *Eastern Sivorgfjella*

Although only the eastern end of Sivorgfjella was examined, its form is closely related to that of the block as a whole. The physiography of the larger part of Sivorgfjella has been described by Worsfold (1967*a*); it is a block of Basement Complex rocks with a sloping but almost planar upper surface which is covered by a thin ice cap. At its northern and western corners there are large spurs and rock outcrops, while the faces of the block itself are ice cliffs broken by rocky ridges (Plate Ia).

At the top of the north-east side (Lidkvarvet), which is the lowest part of the block, are the only known outcrops of the sedimentary sequence in Sivorgfjella. The height and the attitude of the erosion surface on which they rest are practically the same as those of the surface forming the top of the block elsewhere, and it appears that the latter is an exhumed erosion surface.

2. *XU-fjella*

The main feature of XU-fjella is a north-west-facing ice cliff, interrupted in the north-east by small ridges with offlying nunataks and in the south-west by larger more massive spurs such as Hauglandkleppen. South-east of and at a higher level than these spurs are Bjørnnutane, several steep-sided nunataks composed of basaltic flows protruding through the ice sheet. These rise about 200 m. above the surrounding snow level.

3. *Nunatak areas of Milorgfjella*

South-west of and, to a lesser extent, east of the main massif of Milorgfjella are ice cliffs punctuated by ridges. Here the sediments were probably removed at an early stage, and the dissection of the Basement Complex has continued to give a line of rugged peaks and ridges separated by ice cliffs and glaciers. Swithinbank (1959) thought that much of this dissection had occurred through frost action and scarp retreat since the lowering of the ice sheet.

4. *Main massif of Milorgfjella*

This massive block of resistant gneisses has scarps as high as 400 m. facing north-west. Three large spurs and one smaller one trend north-west from it, and they are separated by cirques occupied by stagnant glaciers.

The north-western ends of these ridges are steep and narrow, and they have an irregular profile, the continuation of which below snow level is shown by crevasses and offlying nunataks (e.g. Waglenabben off Laudalkammen). The formation of these nunataks has been discussed by Swithinbank (1959), who attributed them to uneven scarp retreat on the ridges separating the cirques. This could cause two scarps to meet, breaching the ridge some distance from its end. Further erosion would result in an offlying nunatak beyond the new end of the ridge (Plate Ib).

The sides of these ridges are usually steep or sheer but some are mantled by scree slopes. These attain their greatest development just south of Buråsbotnen.

B. Glacial Geomorphology

1. *Glaciers*

The main ice flow in this area is from the polar plateau in the south-east towards Maudheimvidda. This flow is diverted by the main blocks of Heimefrontfjella and the ice is channelled between them, while much smaller quantities flow through gaps in the individual blocks (Worsfold, 1967*a*).

The largest glacier in this area is Haugebreen which is 25 km. wide between Berggravrista and Steenstruphorten. From XU-fjella, this glacier descends from 1,900 to 1,400 m. over a distance of 25 km. KK-dalen, between Sivorgfjella and XU-fjella, is a major tributary of Haugebreen. Small glaciers flow between the nunataks of Milorgfjella but the main massif is only breached at one locality. At the head of Leabotnen, ice falls descend from the ice cap to merge with the stagnant ice within the cirque.

The almost stagnant glaciers in Buråsbotnen, Leabotnen and the cirque between Laudalkammen and Lütkennupen are in part floored with blue ice similar to that found by Worsfold (1967*a*) in other parts of Heimefrontfjella. Van Autenboer (1964) considered that similar occurrences of blue ice in the Sør-Rondane resulted from ablation. The largest expanses of blue ice in north-east Heimefrontfjella surround Schivestolen, where they are in places covered by moraines.

2. *Moraines*

The best development of moraines in north-east Heimefrontfjella is on the blue-ice areas surrounding Schivestolen and in Sömmemorenen, where lines of moraine as long as 8 km. extend from the massif to where they vanish beneath the snow cover (Plate Ic).

Sediments intruded by dolerite cap the south-eastern part of this ridge, below which the direction of the ice flow is to the north-west. In the moraines directly below these outcrops there are abundant boulders of dolerite and sandstone, but farther to the north-west such boulders are rare. While this is possibly in part due to frost-shattering, it is believed to indicate a more rapid rate of accumulation compared with the rate of transport.

The surfaces of the thicker moraines are often irregular, and there are transverse ridges (Plate Id), ice-cored mounds and circular or elliptical ice-filled depressions (Plate Ic).

In some of the moraines on blue ice there are occasional elongated slabs of rock standing on end (Plate IIa). One possible explanation is that this was their original orientation within the ice and that they have been exposed by ablation *in situ*.

Below the north-west face of Sembberget there is an ice-cored terrace (Plate IIb) with a concentration of rock debris along the ridge at its outer edge. This locality was visited in late summer, when the surface snow was soft, and rocks whose "bounce marks" showed that they had fallen since the last high wind had all come to rest in the lowest part of the terrace, near the figure in the photograph. Freeze-thaw action is probably most effective in early summer when a harder surface might cause falling rocks to reach the edge. Below the terrace (off the photograph in Plate IIb) is a wide expanse of blue ice strewn with boulders.

3. *Patterned ground and encrustations*

The only occurrence of patterned ground in the area mapped is at locality "A" (Plate IIc) where sorted circles (Washburn, 1956) were recorded. These circles occur only in an area about 100 m. long and 20 m. wide, where beds of fissile shale and sandstone crop out on a relatively level surface. Besides the circles, less regular features were noted where lines of shale flakes were packed on edge. The loose cover above the shale *in situ* is sometimes only a few centimetres thick, and such lines may occur when the edge of a thin outcropping shale band is turned up.

The absence of patterned ground at other localities is difficult to explain, although the combination of fissile strata and a horizontal outcrop is rare. Most of the other shale outcrops are on steeper slopes or under overhangs, so that fragments are either removed by wind or gravity, or they are covered by coarser debris. The absence of patterned ground on outcrops of other rock types could possibly be a result of the scarcity of felsenmeers and soil or rubble deposits on level surfaces (excluding moraines on blue ice) or it could be a characteristic of the climatic conditions prevalent in Heimefrontfjella.

Calcite encrustations, either in the form of small white knobs 1 cm. or less in diameter or more frequently thin buff, grey or white coatings, are found on some weathered surfaces. The first type usually forms on calcite-bearing rocks, such as calcite-cemented sediments, whereas the coatings appear to occur on any rock type.

A white mass about 10 cm. in diameter was found on the summit of Sembberget. This consists of thaumasite with a little gypsum, and the field relations indicated that the mass was an encrustation derived from minerals in a vug in the underlying basalt. This is not the normal paragenesis of thaumasite (Vogt, 1938) and this unusual assemblage and its possible origin are discussed in more detail on p. 33.

III. STRATIGRAPHY

The stratigraphy of north-east Heimefrontfjella is summarized in Table I, and Figs. 2 and 3 show the stations visited and the geology of this area. This area is unique in western Dronning Maud Land in the amount of information which it has yielded concerning the post-metamorphic stratigraphy of the whole region. Unfortunately, the stratigraphy of the Basement Complex is less clear and the scarcity of index minerals has hampered the interpretation of the metamorphic history.

Geological mapping of the eastern flank of Sivorgfjella, XU-fjella and Milorgfjella has revealed that the Basement Complex, which forms most of the exposures, is unconformably overlain by terrestrial sediments and basic lavas. Several small basic dykes represent different periods of intrusion and it is possible that the more widespread pegmatitic dykes are of two generations. Granitic dykes are rare and localized.

TABLE I

STRATIGRAPHICAL, STRUCTURAL AND METAMORPHIC HISTORY OF NORTH-EAST HEIMEFRONTFJELLA

Age	*Metamorphic activity*	*Structural activity*	*Rock types*
Recent		Erosion	
Jurassic			Basaltic lavas, dolerite
?		Tilting, faulting, erosion	
Lower Permian		Thrusting	Sedimentary sequence
	Retrograde metamorphism to greenschist facies	Faulting, uplift, erosion	Altered dolerites Narrow zones of mylonite Actinolitic amphibolites
			Amphibolites of station Z.375
Lower Palaeozoic or Precambrian	Metamorphism attaining almandine-amphibolite facies	Faulting and shearing ? ↑ Folding	Pegmatitic and granitic veins Mylonitic rocks and sheared gneisses Gneissic granite
			*Para*gneisses and amphibolites of Sivorgfjella and XU-fjella Possibly massive biotite-gneisses and amphibolites of Milorgfjella

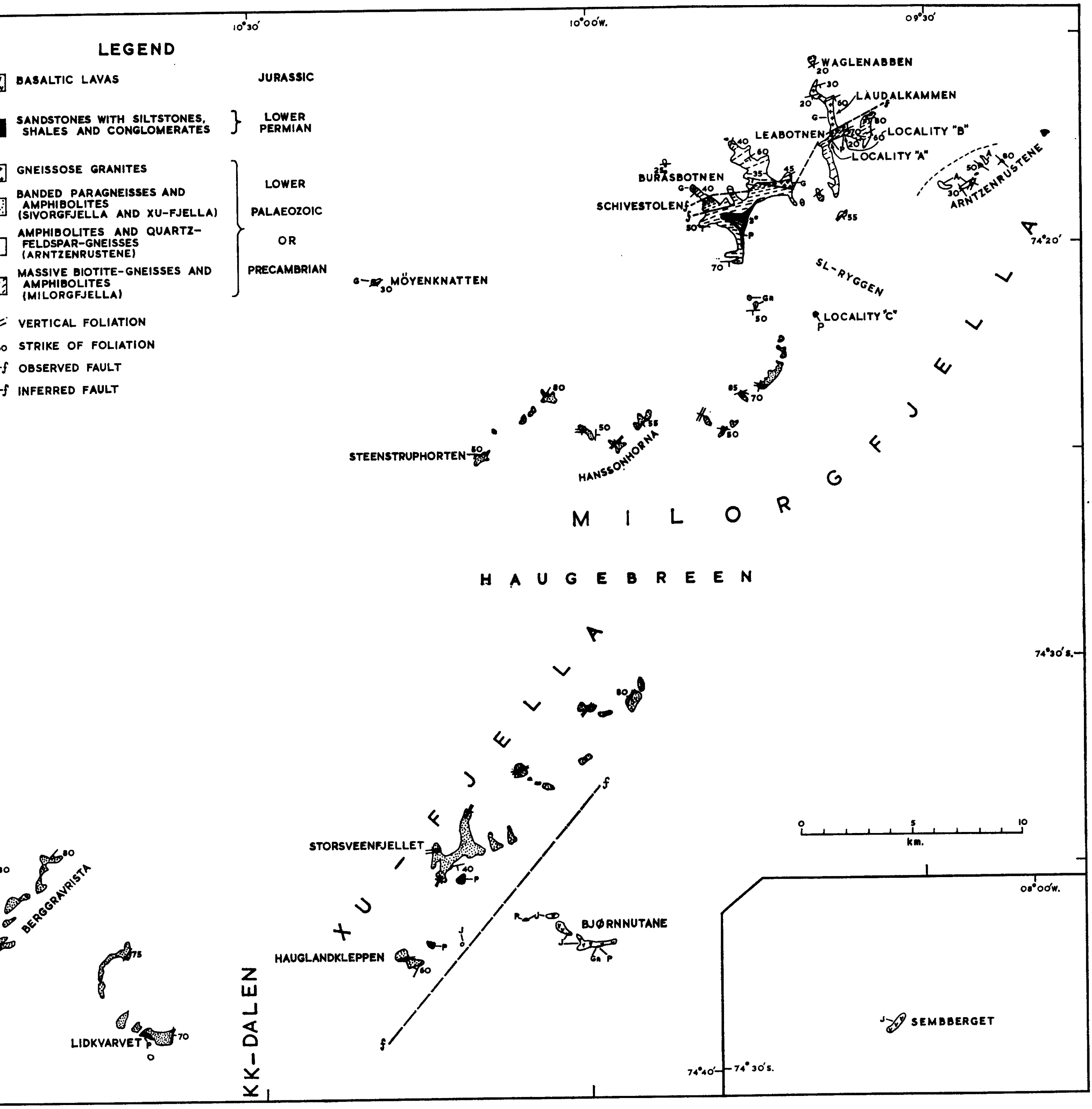

FIGURE 3

Geological sketch map of north-east Heimefrontfjella, showing the distribution of the main rock types, the main foliation trends in the Basement Complex and the positions of observed and inferred faults.

*Para*gneisses are predominant in the Basement Complex and they may be the oldest rocks exposed. These are mainly quartzo-feldspathic biotite-gneisses which have undergone almandine-amphibolite facies metamorphism. Considerable retrograde metamorphism has occurred, mainly in the vicinity of a wide shear zone. The probable presence of concealed folding and faulting has prevented any accurate estimate of the thickness of the original sedimentary sequence.

The majority of amphibolite bands that occur within the *para*gneisses are concordant and have gradational contacts, suggesting that they were originally semi-calcareous sediments. In contrast, other amphibolite bodies are markedly transgressive and some of them appear to be younger than the main phase of deformation. These are interpreted as altered basic dykes, a conclusion which in some cases is supported by the presence of relict igneous textures.

In Milorgfjella, a large mass of gneissic granite appears to have intruded the *para*gneisses at an early stage but the relationships have been obscured by subsequent tectonism and most of the exposed contact is faulted.

The ubiquitous small pegmatitic veins are thought to represent at least two periods of intrusion, because some of them appear to have been affected by widespread shearing associated with the major fault zone in north-east Milorgfjella, while others intrude the mylonitic rocks in the fault zone. The localized granitic veins are thought to be related to the earlier group of pegmatitic veins.

After the cessation of the metamorphism, small basic dykes with chilled margins were emplaced, and some of them occupy fault planes and have been sheared.

Considerable uplift and erosion, probably during the late Palaeozoic, must have preceded the formation of the erosion surface beneath the sediments.

The age of the sedimentary sequence resting on the Basement Complex has been established by Dr. E. P. Plumstead, University of the Witwatersrand, as early Permian on the basis of the *Glossopteris* flora, and this sequence has been divided into three lithological units. The basal unit is conglomeratic, the middle one includes fine sandstones and siltstones of deltaic or fluviatile origin, and the upper one contains sandstones alternating with finer horizons which sometimes include thin coal seams. The total thickness of this sequence is greater than 160 m. and it could be nearly 500 m. if faulting is absent between Schivestolen and locality "C".

Overlying the sediments, either disconformably or with a slight angular unconformity, is a sequence of basaltic flows at least 300 m. thick; their age has been determined by the K-Ar method as 174 ± 7 m. yr. (personal communication from Dr. J. C. Briden). A thin dolerite sill which intrudes the sediments is probably contemporaneous with the basalts.

Correlation of these rock units with those described from other parts of Antarctica is difficult in view of the great distances between the areas described so far but certain comparisons can be made.

Worsfold (1967*b*) has described the geology of Tottanfjella and Sivorgfjella, where he found that the Basement Complex consists of schists, *para*gneisses and *ortho*gneisses. He believed that the massive gneisses of Sivorgfjella had formed at a greater depth than the schistose rocks of Tottanfjella. The metamorphic rocks of XU-fjella and Milorgfjella appear to have formed under similar conditions to those of Tottanfjella or at an even higher level in the crust.

In the metamorphic complex south and east of Jutulstraumen (Roots, 1953), the grade of metamorphism shows greater variation than in north-east Heimefrontfjella but this is consistent with the larger area mapped by Roots. The unusual distribution of garnet discussed by Roots (1953, p. 22) is also applicable to Heimefrontfjella as a whole, where garnet may be absent over wide areas despite the great variety of rock types.

The occurrence of marble at Hauglandkleppen is unique in Heimefrontfjella, although similar rocks are included in the Shackleton Metamorphics of the Shackleton Range (Stephenson, 1966).

The Basement Complex of Mannefallknausane appears to have undergone a grade of metamorphism considerably higher than in north-east Heimefrontfjella (Juckes, 1968). This may be due to the lower altitude of Mannefallknausane, which would result in the exposure of rocks from deeper levels, although Voronov (1964, p. 694) has noted the occurrence of granulite-facies rocks near the coast in other parts of eastern Antarctica, and he attributed this to intense uplift along the continental margin.

Terrestrial sediments of Permian to Jurassic age are widely distributed in eastern Antarctica. Grindley and Warren (1964) have suggested the name Beacon Group for these, although Harrington (1958) had recommended the term "Beacon System" and Mirsky (1964) has put forward a case for the abandonment of the name "Beacon" in all formal descriptions. However, the term "Beacon Supergroup" is now generally accepted as being the most satisfactory stratigraphical description for this succession of sediments (Barrett and others, 1971). Preliminary palaeobotanical evidence has shown that the Heimefrontfjella sediments are early Permian in age and thus they can be broadly correlated with part of the Beacon Supergroup.

Jurassic dolerite intrusions have approximately the same distribution as the sediments of the Beacon Supergroup, as the latter nearly always form the country rock. The intrusions of Victoria Land have been described by several authors (e.g. Hamilton, 1964; Gunn, 1966) but descriptions from other parts of eastern Antarctica are less common. Stephenson (1966) has described four chilled dolerites from two localities in the Theron Mountains and Whichaway Nunataks, but of those described from western Dronning Maud Land (von Brunn, 1964; Brown, 1967; Worsfold, 1967*b*; Juckes, 1968) only in one case is the age definitely known (Rex, 1967).*

Unaltered basic lavas are uncommon in eastern Antarctica and those previously described occur near Beardmore Glacier, more than 2,000 km. from Heimefrontfjella (Grindley, 1963; Grindley and others, 1964). Whether the original extent of these lavas was as great as that of the underlying Beacon Supergroup is a matter for conjecture, but it should be noted that the invariable association of basic sills with the Beacon Supergroup sediments testifies to the widespread nature of the Jurassic magmatic activity.

Altered basic and intermediate lavas have been recorded from other parts of Dronning Maud Land (Roots, 1953; Juckes, 1968), but in no case is the age definitely known. von Brunn (1964) suggested a Jurassic age for the altered lavas exposed north of Jutulstraumen but Klimov and others (1964) favoured a late Precambrian to Lower Palaeozoic age.

IV. BASEMENT COMPLEX

SIVORGFJELLA, XU-fjella and Milorgfjella, which are formed largely of *para*gneisses of the Basement Complex, are separated by glaciers 8–25 km. in width. Worsfold (1967*b*) concluded that Sivorgfjella and Tottanfjella are fault blocks and that this faulting accounts for the marked differences in the geology of these two massifs. It is believed that in north-east Heimefrontfjella the variations in the geology are largely gradational and that they are the result of a general decrease in the grade of regional metamorphism towards the east. This is modified by the effects of a granitic body and a wide shear zone in north-east Milorgfjella.

A. SIVORGFJELLA

In the course of the field work only the north-east scarp of Sivorgfjella was examined and the few rock exposures there are all on strike ridges.

The rocks exposed in this area are mainly *para*gneisses with a small proportion of schists and more quartzitic bands. The strike of the banding and the foliation is generally north-east to south-west with a steep south-easterly dip, which increases locally to vertical or is rarely inverted to give a steep north-westerly dip. Small intrafolial folds were observed at some localities but there is insufficient evidence

* Since this report was prepared age determinations on some of the specimens have become available (Rex, 1971). As some of these ages yield significant new information about the geological history of this area, they and some inferred age limits for associated events are summarized below.

Specimen Z.313.4 (452 ± 15 and 458 ± 15 m. yr.) gives a minimum age for the regional metamorphism of Milorgfjella. This dyke, which has chilled margins, follows one of a well-developed set of joints which is younger than granitic veins and the extensive shearing. The dyke has been displaced by a later thrust fault.

The ages of the dolerite specimen Z.353.7 (179 ± 7 m. yr.) and the basalts Z.308.4 (172 ± 7 m. yr.), Z.349.1 (162 ± 6 m. yr.) and Z.371.7 (173 ± 7 m. yr.) agree with the field relations, although they are slightly older than the average for the Victoria Land dolerites (McDougall, 1963). Although the three ages for the basalts overlap, it is worth noting that specimen Z.349.1 is from well up in the succession, whereas the other two are from near the base.

Two specimens from Mannefallknausane, Z.338.1 (259 ± 10 and 256 ± 10 m. yr.) and Z.391.1 (547 ± 100 and 580 ± 100 m. yr.) had previously been tentatively correlated with the Jurassic suite (Juckes, 1968). Specimen Z.391.1, collected from a sill with chilled margins which follows the prominent sub-horizontal joints in the massive gneiss, shows that there has been little metamorphic or tectonic activity in this area since its intrusion. If the joints are release joints, similar to those followed by the Basement Sill below the Kukri Peneplain in Victoria Land (Hamilton, 1964), considerable Cambrian or Precambrian erosion would have been necessary to bring close to the surface the originally deep-seated rock types now exposed.

In north-east Heimefrontfjella several generations of minor basic intrusions emplaced during the waning stages of the main phase of metamorphism can be distinguished by their differing degrees of alteration. Although post-metamorphic intrusions cannot easily be differentiated in the field or by their petrology, the scatter of ages in Heimefrontfjella, Mannefallknausane and the Shackleton Range (Rex, 1971) suggests that there may have been many more post-metamorphic episodes of intrusion than was previously thought.

for any attempt at an interpretation of the structure of the area. No major structural features were observed in the field, probably because the ice which conceals an overwhelming proportion of the section exposed across the strike would tend to follow any lines of structural weakness.

1. *Paragneisses*

The gneisses of Sivorgfjella consist of well-crystallized quartz, feldspar, biotite and smaller amounts of other minerals, and in strong contrast to many of the gneisses of Milorgfjella there is no indication of retrograde metamorphism.

Typical of the majority of the *para*gneisses is specimen Z.301.3, a biotite-gneiss. It has a granular groundmass of quartz, untwinned potash feldspar and andesine ($Ab_{60}An_{40}$) showing albite twinning. The quartz is rarely strained and there are no signs of post-crystallization deformation. Parallel flakes of biotite, arranged in discontinuous streaks, are sometimes intergrown with muscovite. Also associated with the biotite are small crystals of an unidentified yellow mineral around which pleochroic haloes have developed in the biotite. Small quantities of garnet, apatite, allanite and zircon are distributed throughout the specimen. In some cases the untwinned potash feldspar is embayed by myrmekite.

Other specimens (such as Z.303.2) contain porphyroblastic crystals of orthoclase which is twinned on the Carlsbad law. They are 5 mm. or more in length and are orientated parallel to the foliation. These porphyroblasts, which contain inclusions of the other minerals composing the rock, have patches of myrmekite around their margins, but they are not perthitic as is some of the potash feldspar in the groundmass.

At Lidkvarvet there are quartzo-feldspathic gneisses with randomly distributed but well-orientated flakes of biotite and also hornblende. The hornblende has a pleochroism scheme α = yellow-green, β = olive-green, γ = dark green or blue-green.

2. *Amphibolites*

Several discordant bands of amphibolite, usually less than 2 m. wide, are present at stations Z.301 and 302. Because of their field relations and their mineralogy, they are interpreted as metamorphosed basic dykes.

Some of these intrusions have resulted in plagioclase-amphibolites such as specimen Z.301.2. About 50 per cent of this rock consists of hornblende with a pleochroism scheme α = yellow-green, β = olive-green, γ = dark green. The hornblende has crystallized as well-orientated prisms considerably coarser than the groundmass and there is a small amount of diopside which sometimes forms roughly equidimensional crystals. Andesine crystals ($Ab_{58}An_{42}$) forming the groundmass are often twinned on the albite law and they may show slight zoning. The accessory minerals are quartz, iron ore, sphene, muscovite and chlorite.

Some of the specimens retain traces of their igneous origin and specimen Z.302.4 contains cloudy crystals of andesine ($Ab_{55}An_{45}$) 2–5 mm. long. These are twinned on the Carlsbad and albite laws, and they are considered to be primary in origin. They are set in a streaky matrix of fine recrystallized plagioclase and green hornblende. Fine aggregates of hornblende and quartz have probably formed by the breakdown of individual primary clinopyroxene crystals. Biotite, which is often partly altered to chlorite, is usually associated with iron ore. There are ragged garnet crystals sometimes riddled with inclusions. Crystals of apatite up to 1 mm. in diameter are present and there are a few small crystals of zircon.

B. XU-FJELLA

The most abundant rock group in XU-fjella is a succession of banded *para*gneisses and amphibolites. These grade from quartz-feldspar-gneisses with traces of biotite through biotite-gneisses containing amphibole into amphibolites. This assemblage is a regionally metamorphosed sedimentary sequence of predominantly impure arenaceous rocks with some argillaceous and semi-calcareous strata. Minor intercalations of limestone have recrystallized to form the marble exposed at Hauglandkleppen. At most localities the gneisses are cut by pegmatitic veins often containing calcite.

The foliation at all localities is steep to vertical with the strike approximately north-east to south-west. No evidence was found suggesting faults or folds within this area other than the contortions in the marble bands at Hauglandkleppen (Plate Va). Isoclinal folding may be present but it must be borne in mind that the marble bands, which are the only distinctive marker horizon in the Basement Complex of Heimefrontfjella, are not repeated in other outcrops.

1. *Paragneisses*

The predominant rock type is a quartz-feldspar-biotite-gneiss often containing some amphibole, while other bands consist of rocks composed of the same minerals in different proportions.

The groundmass of these gneisses is a granoblastic mosaic of quartz, andesine ($Ab_{68}An_{32}$ in specimen Z.363.1), microcline and myrmekite. Red-brown biotite is characteristic of these gneisses and it is sometimes accompanied by hornblende (α = yellowish, β = olive-green, γ = dark green). Sphene, apatite, magnetite, allanite and garnet are occasional accessories.

In some of the gneisses, hornblende becomes the predominant mineral, forming porphyroblasts as long as 3 mm. (Z.366.1) which are sometimes penetrated by flakes of biotite. The groundmass of the amphibolites differs from that of the biotite-gneisses only in the presence of labradorite instead of andesine.

2. *Marble and associated lime-rich rocks*

Several bands of marble 2–4 m. thick are exposed at Hauglandkleppen, where the intense flowage localized in them increases the difficulty of estimating their thickness or even their number (Plate Va). When fresh the marble is white but the weathered surfaces are stained yellow and orange. Exposed surfaces are friable to a depth of at least 5 cm. as a result of weathering.

The calcite in specimen Z.369.1 has a grain-size of 2–5 mm. and it is always twinned. Other minerals are scarce but in addition to the graphite which is visible in the hand specimens there are scattered grains of quartz, feldspar, muscovite and yellow-brown tourmaline.

The gneisses immediately adjacent to the marble were either derived from marly sediments or they may have been enriched in lime derived from the marble. They are now coarse quartz-feldspar-diopside-gneisses, the diopside forming large crystals often 1 cm. long.

Specimen Z.369.3 consists largely of strained quartz with some microcline, myrmekite and a little plagioclase. Within the diopside there are small patches of an amphibole (α = yellowish, β = olive-green, γ = dark green) whose shapes appear to be influenced by the cleavage of the diopside. The patches in each diopside crystal have similar optical orientations, suggesting that there is a fixed crystallographic relationship between the two minerals. Euhedral sphene forms lozenge-shaped crystals up to 5 mm. in diameter and pale pink garnet is rare.

3. *Pegmatitic veins*

At several localities pegmatitic veins cut the gneisses and the largest exposure is a vein 0·6 m. wide trending north–south for 1·5 km. along a ridge below Storsveenfjellet. The veins consist of coarse cream-coloured or pink feldspar, quartz and calcite with either clean-cut flakes of muscovite or more ragged biotite. The veins at Hauglandkleppen contain tourmaline, which has also been introduced into some of the adjacent biotite-gneisses.

In a vein at Hauglandkleppen (Z.368.1) the muscovite has crystallized both as trains of large flakes and as smaller crystals scattered throughout the groundmass of plagioclase, quartz and untwinned potash feldspar. Calcite forms irregular grains replacing plagioclase and perhaps to a lesser extent the other minerals. There is a little schorlite which is blue-green in thin section.

C. Milorgfjella

1. *Western nunataks*

The rock outcrops punctuating the arcuate ice cliff between Steenstruphorten and Schivestolen differ geologically from the main massif of Milorgfjella. They are banded gneisses, similar in appearance to the *para*gneisses of XU-fjella, and they are believed to have originated under comparable conditions. The dip of the foliation is usually steep and it is often vertical.

About five metamorphosed basic dykes, ranging in thickness from 0·6 to 30 m., intrude the gneisses at station Z.375. Although they are largely concordant, in closer detail the contacts are slightly transgressive and typically intrusive (Plate Vb); they appear to have been intruded subsequent to the folding of the gneisses. Some shearing of the dykes has occurred but it is largely confined to the northern part of the widest dyke.

a. *Paragneisses*. Apart from thin bands rich in biotite or hornblende within the more typical quartz-feldspar-gneiss, the *para*gneisses do not show much variation in composition. The groundmass consists of severely strained or recrystallized quartz together with plagioclase and potash feldspar, and these minerals are sometimes segregated into rough bands. The plagioclase is usually cloudy and where it is twinned (as in specimen Z.376.1) it is oligoclase ($Ab_{71}An_{29}$). The potash feldspar in the groundmass is usually microcline but when it occurs as porphyroblasts it is untwinned and perthitic.

Crystals of hornblende or biotite, or both, are randomly scattered throughout the rock or concentrated in discontinuous streaks. In some thin partings within specimens either mineral may predominate. Chlorite, probably replacing biotite, is less common. Muscovite, sphene, magnetite, apatite, zircon and allanite occur in small amounts.

b. *Amphibolites*. Apart from the minor amphibole-rich bands within the *para*gneisses, there are larger occurrences of amphibolite of clearly intrusive origin. The largest of these dykes, which is 30 m. wide, is highly sheared at its northern margin. The central part is less sheared, and near the southern margin shearing has been negligible and the original igneous texture is preserved. The modal compositions of a specimen from a 0·6 m. wide dyke and specimens from different parts of the large dyke are given in Table II.

TABLE II

MODAL ANALYSES OF SOME AMPHIBOLITES AND ALTERED DOLERITES FROM MILORGFJELLA

	Z.323.1	Z.375.3	Z.375.4	Z.375.5	Z.375.6
Plagioclase	—	42·4*	38·4	33·4	12·6†
Clinopyroxene	—	—	2·2	11·5	7·9†
Hornblende	—	53·8	53·2	46·7	—
Tremolite	30·5	—	—	—	—
Biotite	—	—	—	0·7	—
Garnet	—	—	3·2	3·2	0·5
Opaque minerals	tr	—	3·0	4·5	—
Sphene	5·6	3·8‡	—	—	—
Epidote	1·6	—	—	—	—
Groundmass	62·3§	—	—	—	79·0‖
Plagioclase composition	—+	—+	An_{46}	An_{48}	An_{68}+

tr Trace.
*Includes a little quartz.
†Phenocrysts.
‡Includes a little rutile.
§Composed of fine plagioclase, quartz, amphibole, clinozoisite, epidote, biotite and chlorite.
‖Apparently fine hornblende, plagioclase and iron ore.
+Few twinned crystals present.

Z.323.1 Margin of an irregular transgressive amphibolite, 5–15 m. wide.
Z.375.3 Amphibolite from the north-western margin of a sheared basic dyke 30 m. wide.
Z.375.4 Garnet-amphibolite with slight palimpsest igneous texture; 1 m. from north-western margin of the same dyke.
Z.375.5 ? Uralitized dolerite containing some garnet; from the south-eastern margin of the same dyke.
Z.375.6 Altered chilled dolerite from a thin dyke (0·5 m.) a few metres south-east of the dyke described above.

In specimen Z.375.6, collected from the small dyke, the phenocrysts have escaped alteration. The fine groundmass consists of an aggregate of green hornblende, feldspar and/or quartz and magnetite. Small aggregates of fine garnet including grains of iron ore are present in the groundmass and they show a tendency towards coalescence into single crystals. The distribution of these clusters is completely random and they do not appear to be replacing any specific original mineral. Phenocrysts of labradorite ($Ab_{32}An_{68}$), twinned on the albite and Carlsbad laws and sometimes 0·5 mm. long, are arranged sub-parallel to the margin of the dyke. Phenocrysts of augite are present but less frequent and they are rarely twinned.

The unsheared rock of the larger dyke has a similar mineralogical composition (Z.375.5) but it is much coarser (Plate IXa). Original andesine and some schillerized augite, either mantled or completely replaced by green hornblende, are common. Well-crystallized garnet and smaller amounts of biotite and magnetite are also present.

Near the northern margin of the dyke, where shearing has deformed the fabric of the rock (Z.375.4), the texture is more streaky and much of the feldspar is recrystallized to fine untwinned grains. Relics twinned on the albite and Carlsbad laws have survived but they are rare. The pyroxene has been replaced by a fine granoblastic aggregate of hornblende and quartz which is rimmed by hornblende alone. Garnet and iron ore are still present.

The most sheared specimen (Z.375.3) is a plagioclase-hornblende-schist with streaks of parallel hornblende prisms and fine untwinned plagioclase. The pleochroism scheme of the hornblende is α = yellow-green, β = green, γ = dark green. Garnet is absent and iron ore has been replaced by sphene and a little rutile, and the original texture of the rock has been completely obliterated (Plate IXb).

2. *Main massif*

In the main massif of Milorgfjella there are excellent exposures which can be examined from a distance (Plate IId) but accessibility is often restricted by the steepness of the rock and ice.

Excluding numerous small dykes of several generations, four major rock units are distinguished. With some modification by faulting, the zones in which they occur trend parallel to the regional strike, and they are partly the result of intense shearing during the final stages of the main metamorphic event. From north-west to south-east the four units are: biotite-gneisses and amphibolites, coarse gneissic granites, mylonitic rocks and sheared gneisses.

The contact between the granite and the sheared gneisses at Laudalkammen is tectonic and the mylonitic rocks have developed along the major dislocation separating them. The gneisses on either side of the mylonitized zone have been affected by the shear stress but in different ways. The granite and some of the biotite-gneisses behaved as a rigid block and deformation is only obvious in thin section, where the individual mineral grains are seen to be shattered. The gneisses south-east of the mylonitic zone grade into it, and some of the specimens collected 1 km. away from it have a sheared appearance both in the hand specimen and in thin section.

From the field evidence it is believed that the granite intruded the gneisses to the south-west and that the present tectonic contact closely followed the original contact.

Small granitic and pegmatitic dykes are abundant, intruding all of the other rock types except the basic dykes. Their distribution is widespread but they are concentrated at station Z.348 (Plate IIIa).

a. *Biotite-gneisses and amphibolites*. These two rock types form the north-westerly outcrops of the main massif. Coarse foliated biotite-gneiss is the commonest rock type (Plate IIIa) at station Z.348 but the relationships are not so simple at Waglenabben, where the biotite-gneiss has in places undergone plastic flow and the more competent bands of amphibolite have been fractured (Plate Vc). In general, these amphibolites are more coarsely crystalline and less sheared than the amphibolites from other parts of the range. These observations show that in this part of the range shearing stress was subordinate to temperature during the last effective metamorphism. Similar conditions may well have prevailed throughout the main massif, resulting in the formation of similar rocks before localized shearing caused deformation and retrograde metamorphism.

The biotite-gneiss has been deformed to some extent; quartz is usually strained and the feldspar is often fractured. The main constituent of specimen Z.348.2 is oligoclase, which is usually cloudy and often twinned. Some crystals are slightly fractured and they may contain patches of secondary calcite and sericite. Quartz, in streaky patches, is strained and often recrystallized to a fine aggregate. Biotite flakes, aligned in rough bands, may be bent or kinked and they are sometimes replaced marginally by chlorite. Crystals of green hornblende are present but not common and there is some accessory apatite. Specimen Z.324.1 is similar but it also contains some microcline whereas hornblende is absent.

The amphibolites consist mainly of hornblende and cloudy plagioclase. Sometimes (as in specimen Z.312.6) the plagioclase is highly saussuritized. Twinning on the albite law is common and the composition is andesine ($Ab_{68}An_{32}$). The hornblende (α = yellow-green, β = greenish, γ = dark green) forms crystals up to 2 mm. long and these are sometimes grouped together in large clusters. There are often poeciloblastic inclusions of quartz, apatite and other minerals, and biotite flakes often penetrate the hornblende crystals. Sphene forms large crystals, enclosing biotite, chlorite and apatite, but in specimen Z.334.1 ilmenite is the dominant titaniferous mineral. Strained quartz, chlorite replacing biotite, and rare rims of actinolite replacing hornblende complete the mineral assemblage.

At Waglenabben the biotite-gneisses apparently became sufficiently plastic to flow and in so doing they fractured and brecciated earlier basic dykes (Plate Vc). The reason for this is not clear but it is possible that heat and perhaps water from the adjacent granite may have been responsible for increasing the plasticity locally. Van Autenboer and others (1964) have described from the Sør-Rondane similar rocks which they regarded as having a tonalite matrix. The occurrence at Waglenabben, however, has a heterogenous matrix which is interpreted as mobilized gneiss of unknown origin.

Specimen Z.333.2 is a coarse biotite-gneiss with an inclusion of amphibolite. The biotite-gneiss consists largely of cloudy andesine ($Ab_{62}An_{38}$), possibly some untwinned potash feldspar, and strained and granulated quartz. Red-brown biotite, occasionally altered to chlorite, is abundant and there is a little muscovite. Sphene is present together with small amounts of epidote and allanite.

The amphibolite inclusion is composed of well-formed prisms of hornblende (α = neutral, β = green, γ = green-brown) and cloudy andesine ($Ab_{65}An_{35}$) which is occasionally twinned on the albite law. The small inclusions in the hornblende appear to be a clinopyroxene, probably diopside. Scattered flakes of chlorite may be pseudomorphs after biotite. Sphene and apatite are present as accessories.

It is possible that mobilization also occurred at station Z.327, where nebulitic patches of granite-gneiss cut a porphyroblastic biotite-gneiss. This granite-gneiss consists largely of microcline together with some cloudy untwinned plagioclase (Z.327.2). Quartz, in irregular bands, is strained and sometimes recrystallized. Biotite forms rough discontinuous bands and it often contains regularly orientated inclusions of rutile. There is a little epidote, which may have been derived from the alteration of plagioclase, and some myrmekite.

b. *Sheared gneisses*. South-east of the mylonitic zone are gneisses and schists which have undergone varying degrees of shearing, and which in places grade into mylonitic rocks. In some cases the shearing appears to have been concentrated in the more basic bands.

The sheared gneisses differ in general from those to the north-west in having suffered more thorough shearing and even occasionally granulation, which was succeeded by recrystallization of certain minerals after the shear stress had waned considerably. The groundmass is an aggregate of granulated quartz with streaks of biotite, muscovite or chlorite (Z.328.3). Larger crystals of feldspar, probably porphyroclasts, are often fractured and welded by younger quartz-muscovite or quartz-calcite veins. Cloudy or saussuritized andesine ($Ab_{66}An_{34}$), polysynthetically twinned, is ubiquitous and microcline is present in some specimens.

Near the mylonite zone, bands of a finer rock which is darker and more highly sheared alternate with the gneisses (Plate IIIb). These rocks are biotite-epidote-schists with quartzose streaks (Z.328.2), and the "eyes" of completely saussuritized plagioclase within them may have grown porphyroblastically.

c. *Mylonitic rocks*. The gneisses in the south-east become more highly sheared as the mylonitic zone is approached and there is a gradual transition from one to the other. Specimen Z.339.2 is intermediate between the two types; despite the intense granulation of the quartz-rich streaks (Plate IXc) and fracturing of the porphyroclasts, the rock is still recognizable as an extreme form of the sheared gneisses with porphyroclasts as large as 1 cm. surviving.

The final product of the intense granulation of the gneisses is a fine-grained, partly recrystallized mylonitic rock such as specimen Z.337.1. There is less distinction between the groundmass and porphyroclasts, and the only crystals larger than 1 mm. are porphyroblasts which formed subsequently. The quartz is granulated and sheared into elongated streaks (Plate IXd) which form a groundmass. There are coarser crystals of perthitic microcline and highly saussuritized plagioclase. Ragged flakes of biotite containing rutile inclusions are sometimes bent but the absence of any degree of deformation implies that this mineral may have crystallized after mylonitization.

Potash feldspar, together with myrmekite, appears to be of even later formation. Small undeformed crystals are often present among the porphyroclasts and these may have formed at a late stage. The microcline porphyroblasts in specimen Z.337.2 are as long as 2 cm. and they contain orientated inclusions of saussuritized plagioclase with clear albitic rims.

d. *Gneissic granites*. The largest exposure of the gneissic granite is at Laudalkammen where its outcrop extends for approximately 2 km. across the strike. It is usually a coarse red rock but there are variations which are either finer or contain more dark minerals as streaks between the coarse feldspar crystals.

At this locality the contact is faulted but at some of the smaller outcrops near the fault minor exposures of *para*gneiss are present with the apparently intrusive granite. The relationship is clearer at station Z.312, where a similar granite intrudes a porphyroblastic biotite-gneiss (Plate IVa).

Thin-section examination shows that the minerals comprising the granite have undergone considerable fracturing at all localities (Plate IXe). The constituents are quartz, potash feldspar, plagioclase, chlorite and epidote (Z.332.1). The quartz is highly strained or granulated and some of it may be secondary. The potash feldspar is usually microcline but sometimes it is untwinned. Crystals of potash feldspar are usually shattered and perthitic, but in this specimen porphyroblastic microcline appears to have formed since the deformation. Myrmekite is associated with potash feldspars of both generations, and the andesine, cloudy with incipient alteration, is commonly twinned and the crystals are fractured and bent.

Aggregates of chlorite and epidote occur between the larger quartz and feldspar crystals, and epidote forms granular clusters which appear to pseudomorph large prisms of an earlier mineral. Some crystals of allanite are probably younger than the main cataclastic event and allanite often forms overgrowths on epidote crystals. Sphene is present in some specimens.

About 15 km. west of the main massif is Möyenknatten, an isolated outcrop of red gneissic granite cut by small quartz-chlorite-epidote veins. Because of the similarity of this granite to that of the main massif, and the fact that the two occurrences are approximately on the same line of strike, it is possible that they are related to each other.

Microcline is the main constituent of the red gneissic granite (Z.311.1) from this locality and it also contains streaks of strained quartz. Clusters of epidote crystals, similar to those in the granite of the main massif, are present together with small flakes of chlorite and biotite. Polysynthetically twinned albite is less abundant and there are occasional small zircon crystals.

e. *Pegmatitic and granitic veins*. Small pegmatitic veins 5 cm. to 10 m. wide occur at many localities where they intrude the gneisses and mylonitic rocks of the Basement Complex. At station Z.348 they are more abundant (Plates IIIa and IVb) and the typical coarse biotite-pegmatites (Plate IVc) are associated with finer pink granitic veins containing muscovite. Where veins of the two types intersect one another, they merge with no discernible contact. One granitic vein at station Z.312 has a coarse pegmatitic margin, resembling those interpreted by Roots (1953, p. 24) as granitic veins intruded along median lines of weakness in older pegmatites.

The intrusion of these veins into the sheared gneiss and mylonitic rocks demonstrates that they were emplaced after the major deformation of these rocks. The absence of chilled margins and the deformation observed in thin section are indications that the country rock was warm and that tectonism had not yet ceased. Thus the intrusion of the pegmatitic veins may have been a late event during the main metamorphism. It is also possible that there are two (or more) generations of similar pegmatitic rocks, one of which was intruded before the deformation and the other during a later period.

Specimen Z.348.4 is a typical biotite-pegmatite composed of coarse grey feldspar and ragged books of partly chloritized biotite up to 10 cm. in size. Examination in thin section shows that quartz, plagioclase and potash feldspar are the main constituents. The quartz is strained while the plagioclase crystals are bent and fractured. The plagioclase is cloudy oligoclase, which often has overgrowths of clear oligoclase of an almost identical composition. The potash feldspar is either microcline or untwinned feldspar and both forms are perthitic. In some cases the microcline appears to replace plagioclase. Traces of epidote, chlorite and calcite are present but for such a coarse-grained rock thin sections do not give a true indication of the composition.

In thin section, the granitic veins resemble the finer parts of the pegmatitic rocks described above, but because of the finer grain-size the section gives a truer reflection of the whole rock. Muscovite, chlorite, biotite, apatite, zircon and magnetite are present in addition to the strained quartz and feldspar, and in specimen Z.334.2 there are chlorite-epidote aggregates.

f. *Amphibolites*. Most of the transgressive amphibolites, which are believed to be basic intrusive rocks that have undergone varying degrees of metamorphism, are sheared. Shearing apparently occurred during two distinct periods, giving rise to two different types of amphibolite. Some are mylonitic but much fine well-orientated tremolite has crystallized in others.

Specimen Z.316.6 is a sheared rock with a granular groundmass composed of quartz or feldspar besides chlorite and epidote. The rock contains porphyroclasts of hornblende which are 0·5–1·0 mm. long and sometimes have clear overgrowths around the cloudy cores. Smaller porphyroclasts of plagioclase rarely attain 0·2 mm. in diameter.

This rock is intermediate between the types described by Sutton and Watson (1959) as mylonites and "rocks without cataclastic structure". The streaky texture of a mylonite is present but the groundmass has recrystallized to some extent and some of the porphyroclasts have overgrowths. These properties could be the result of stress while the rock was at an elevated temperature.

Other amphibolites have recrystallized more thoroughly under the influence of stress. They now consist of streaks of fine tremolite and chlorite with cloudy patches which appear to be relics of saussuritized plagioclase. Some hornblende crystals have survived the shearing and recrystallization, and these often possess tremolite or actinolite overgrowths. In specimen Z.316.1 this hornblende occurs as fractured brown prisms (α = light brown, β = brown, γ = dark brown) mantled by actinolite. While the brown colour of hornblende is strongly influenced by its titanium content (Deer, 1938), the usual setting of brown hornblende is either in igneous rocks or in those of the higher grades of regional metamorphism. The ragged prismatic form of the crystals described above favours an igneous origin.

This amphibolite forms one of several dykes occupying a fault zone (Plate IIIc) and, although the rock has been sheared, it is considered that they were emplaced after the main displacement had occurred. The coarse gneisses surrounding and separating these amphibolites have a greenish colour and thin-section examination reveals much fine acicular amphibole sometimes penetrating the quartz and feldspar crystals (Z.316.2). Some joint surfaces have a fine veneer of a green slip-fibre asbestiform mineral and a specimen collected from the scree below these dykes contains a band of coarse, diagonal-fibre green asbestos 1·5 cm. wide (Z.316.7). The X-ray diffraction pattern of this mineral suggests that it is riebeckite.

A small amphibolitized dyke at station Z.316 has retained its original texture and the feldspar phenocrysts are only slightly altered (Z.316.4). It resembles the dykes at station Z.375 (p. 14), and the pyroxenes have been replaced by an aggregate of tremolite rimmed by green hornblende and brown-green biotite. The labradorite phenocrysts ($Ab_{32}An_{68}$) are saussuritized around their margins and along fractures where small epidote granules and some sericite have also formed.

A transgressive amphibolite at station Z.323 has an irregular shape and its thickness varies from 5 to 15 m. Specimen Z.323.1 consists of cloudy twinned crystals of tremolite set in a fine groundmass of quartz, feldspar, amphibole, biotite, chlorite and minerals of the epidote group (Table II). The irregular sphene crystals usually have opaque cores. There are rare small crystals of green-brown hornblende which may represent relics from the original rock which have survived the shearing that resulted in the recrystallization of the present low-grade assemblage. The chemical composition of this rock (Table III) shows that, despite some similarities to other basic intrusions (e.g. Table III, Z.375.5), it is relatively rich in potash. This could be explained by the acquisition of potash from the surrounding gneisses during metamorphism but the rather high titania and low silica values suggest that the original intrusion may have had lamprophyric affinities.

The occurrence of amphibolite dykes showing such differences in degree and type of alteration could be the result of more than one period of intrusion. However, it is possible that these differences were caused by shearing. It is conceivable that shearing was localized in dykes with a certain orientation while other dykes remained relatively unaffected.

g. *Altered dolerites*. A group of about six dolerite dykes intrudes the biotite-gneisses at station Z.348 (Plate IIIa), following a prominent set of joints which dip steeply to the north-west. The two largest dykes are 3 m. in width and the others are all 1 m. wide or less. The dolerite is porphyritic and at the dyke margins it is chilled. Columnar jointing, usually normal to the margins, is present in the larger dykes.

No appreciable displacement was seen on either side of the dykes but some, especially the smaller ones, are slightly sheared and traversed by calcite veins. A thrust fault approximately parallel to the foliation of the gneisses truncates the dykes and displaces them by about 400 m.

TABLE III

CHEMICAL ANALYSES OF AMPHIBOLITES AND ALTERED DOLERITES FROM MILORGFJELLA

	Z.323.1	Z.375.3	Z.375.4	Z.375.5	Z.375.6
SiO_2	48·50	50·60	50·55	50·62	50·90
TiO_2	2·42	1·63	1·48	1·52	2·18
Al_2O_3	13·21	14·23	14·09	14·09	13·41
Fe_2O_3	4·07	2·00	0·93	1·35	2·82
FeO	9·67	9·84	12·89	12·19	10·83
MnO	0·25	0·21	0·23	0·23	0·22
MgO	5·58	6·45	5·10	5·63	5·35
CaO	10·51	10·27	9·58	9·81	9·97
Na_2O	1·45	2·72	2·48	2·49	2·54
K_2O	1·62	0·57	0·65	0·66	0·66
H_2O+	2·04	1·37	1·21	0·89	0·65
H_2O-	0·31	0·11	0·11	0·14	0·13
P_2O_5	0·28	0·17	0·29	0·32	0·36
CO_2	0·13	0·07	0·15	0·01	0·17
TOTAL	100·04	100·24	99·74	99·95	100·19
	ANALYSES LESS TOTAL WATER (Recalculated to 100)				
SiO_2	49·65	51·24	51·36	51·17	51·20
TiO_2	2·48	1·65	1·51	1·54	2·19
Al_2O_3	13·52	14·41	14·32	14·24	13·49
Fe_2O_3	4·17	2·03	0·95	1·37	2·84
FeO	9·90	9·96	13·10	12·33	10·90
MnO	0·25	0·21	0·23	0·23	0·22
MgO	5·71	6·53	5·18	5·69	5·38
CaO	10·76	10·40	9·73	9·92	10·03
Na_2O	1·48	2·75	2·52	2·51	2·56
K_2O	1·66	0·58	0·66	0·67	0·66
P_2O_5	0·29	0·17	0·29	0·32	0·36
CO_2	0·13	0·07	0·15	0·01	0·17
	NORMS				
Q	4·68	0·51	1·42	0·98	4·15
or	9·80	3·41	3·90	3·94	3·92
ab	12·56	23·30	21·32	21·29	21·61
an	25·33	25·25	25·80	25·59	23·37
di	20·78	20·40	16·49	17·91	19·02
hy	15·13	20·49	25·81	24·59	18·40
mt	6·04	2·94	1·37	1·98	4·11
il	4·70	3·13	2·86	2·92	4·16
ap	0·68	0·41	0·70	0·77	0·86
cc	0·30	0·16	0·35	0·02	0·39
	ELEMENT PERCENTAGES				
Si^{+4}	23·21	23·95	24·01	23·92	23·94
Al^{+3}	7·15	7·63	7·58	7·54	7·14
Fe^{+3}	2·92	1·42	0·66	0·96	1·99
Mg^{+2}	3·44	3·94	3·12	3·43	3·25
Fe^{+2}	7·70	7·74	10·18	9·58	8·47
Na^{+1}	1·10	2·04	1·87	1·86	1·90
Ca^{+2}	7·69	7·43	6·95	7·09	7·17
K^{+1}	1·38	0·48	0·55	0·56	0·55
Ti^{+4}	1·49	0·99	0·91	0·92	1·31
Mn^{+2}	0·19	0·16	0·18	0·18	0·17
P^{+5}	0·13	0·07	0·13	0·14	0·16
C^{+4}	0·04	0·02	0·04	—	0·05
O^{-2}	43·56	44·13	43·82	43·82	43·90

	TRACE ELEMENTS (p.p.m.)				
Cr	110	175	140	134	121
Ni	42	65	59	44	48
Cu	128	118	274	76	139
Zn	96	96	103	101	100
Ga	17	17	17	17	16
Rb	43	13	14	14	13
Sr	268	227	200	199	202
Y	31	22	33	33	33
Zr	176	122	185	188	194
Nb	10	8	13	12	11
Ba	367	227	263	298	309
La	10	7	21	9	9
Ce	33	17	44	40	48
Pb	10	13	7	4	11
Th	2	*	2	2	3
Position [($\frac{1}{3}$Si+K)−(Ca+Mg)]	—2·01	—2·91	—1·52	—1·99	—1·89
Fe	75·5	69·9	77·7	75·4	76·3
Mg	24·5	30·1	22·3	24·6	23·7
Fe	64·2	58·7	66·2	64·3	64·7
Mg	20·8	25·2	19·0	20·9	20·1
Alk	15·0	16·1	14·8	14·8	15·2
Ca	75·6	74·7	74·2	74·6	74·5
Na	10·8	20·5	20·0	19·5	19·8
K	13·6	4·8	5·8	5·9	5·7

*Below limit of sensitivity.

Z.323.1 Margin of an irregular transgressive amphibolite 5–15 m. wide.
Z.375.3 Amphibolite from the north-western margin of a sheared basic dyke 30 m. wide.
Z.375.4 Garnet-amphibolite with a slight palimpsest igneous texture, 1 m. from the north-western margin of the same dyke.
Z.375.5 (?) Uralitized dolerite containing some garnet, from the south-eastern margin of the same dyke.
Z.375.6 Altered chilled dolerite from a thin dyke (0·5 m.) a few metres south-east of the dyke described above.
(All analyses by L. M. Juckes.)

The age of the dykes is not known but, because of their degree of alteration and the fact that they are older than the thrusting, it is considered they are older than the dolerite which intrudes the sediments.

There has been extensive silicification of the dykes, affecting both the groundmass and certain phenocrysts. The groundmass now consists of quartz with a little plagioclase, sericite, actinolite and iron ore.

In the coarser specimens (Z.313.4) from the larger dykes, pink augite is abundant both as euhedral or subhedral phenocrysts, and as subhedral or anhedral crystals in the groundmass. The phenocrysts, some of which are twinned parallel to {100}, may attain a size of 3 mm. and they are often glomeroporphyritic. A fine fringe of actinolite surrounds the augite crystals but otherwise they are unaltered. Some of the plagioclase phenocrysts have been altered extensively to sericite, tremolite and epidote, and others have been replaced by quartz. Any plagioclase which may have been present in the groundmass has been obliterated by alteration.

Regularly shaped aggregates of quartz with some chlorite and actinolite, some as large as 2 mm. by 1 mm., are believed to pseudomorph original phenocrysts. In a specimen from a chilled margin (Z.313.7) the shape of these aggregates is better shown. This rock has a fine dark groundmass with a prominent flow structure, and the phenocrysts have been replaced mainly by quartz, but calcite and epidote are also present. Some of the phenocrysts are lath-shaped and occasional relics within them confirm that they were originally plagioclase; others have more complex shapes (Plate IXf) and these resemble the skeletal olivine crystals described by Drever and Johnston (1957, text-fig. 7). Replacement of olivine by secondary quartz and calcite has been described previously by Smith (1936, p. 89) but it appears to be a comparatively rare phenomenon.

3. *Eastern nunataks*

A steeply dipping assemblage of amphibolites and quartz-feldspar-gneisses is exposed in the nunataks south-east of Laudalkammen. The strike direction varies considerably from one outcrop to another, possibly as a result of plunging folds. Small contortions of the banding are numerous but no major structures are exposed.

a. *Amphibolites.* Two generations of amphibole are distinguishable in the amphibolites. Well-crystallized brown hornblende (α = light brown, β = brown, γ = dark brown) is the most abundant amphibole, forming much of specimen Z.344.1. Actinolite of later origin is present as overgrowths and it sometimes replaces the hornblende. Dark brown biotite occurs in varying proportions in different specimens and it usually contains regularly orientated needles. These lie parallel to three directions which intersect one another at angles of 60°, an orientation presumably controlled by the crystal structure of the biotite. Similar inclusions in biotite have been identified in rocks from Tottanfjella by Worsfold (1967*b*) as rutile and by Thomson (1969) as sphene. Plagioclase forming the groundmass is andesine ($Ab_{64}An_{36}$) and it is often saussuritized. Accessory minerals include sphene with opaque cores and occasional zircon crystals.

Rosenzweig and Watson (1954) have confirmed the suggestion by Deer (1938) that the brown colour of some varieties of hornblende is related to the ratio of titanium to ferrous iron. The occurrence of brown hornblende in the granulite-facies rocks of regionally metamorphosed areas has been noted by Leake (1965), who correlated this with the high temperature of formation of brown hornblende.

b. *Quartz-feldspar-gneisses.* These gneisses rarely grade into the amphibolites and they are believed to have originated either as intrusive veins or as anatectic segregations.

In thin section, signs of deformation are visible as in specimen Z.345.1. Quartz forms either elongated strained crystals or is granulated, and microcline crystals are shattered and recrystallized along localized fractures. Cloudy plagioclase, sometimes showing the effects of strain, has a composition of $Ab_{92}An_{8}$. Biotite and muscovite are sparsely distributed throughout the rock and there is some chlorite replacing biotite. Calcite, probably secondary, is the only other mineral recorded.

D. Discussion

1. *Structure*

There is no direct evidence for faults separating the major mountain blocks of north-east Heimefrontfjella, although within the main massif of Milorgfjella faults of three ages can be distinguished.

The oldest fault recognized in the field trends from south-west to north-east across this massif and, if the intrafolial folds near it (Plate IIIb) are correctly interpreted as drag folds, the south-eastern side has been downthrown. The recrystallization of the mylonitic rocks demonstrates that the faulting occurred during the declining stages of the main period of regional metamorphism or during a later but less intense recurrence of such conditions.

Steeply dipping or even vertical faulting occurred at several localities after the cessation of the metamorphism and some of these faults are now occupied by sheared and silicified dykes. At station Z.334 one such dyke is truncated by a shallow-dipping fault or thrust, and the sheared dykes at this locality are probably the equivalent of the unsheared basic dykes at station Z.348 which are truncated by a low-angle thrust with a displacement of about 400 m. (Plate IIIa).

The occasional presence of intrafolial folds in Sivorgfjella and XU-fjella, and the contortions in some of the amphibolites in the eastern nunataks of Milorgfjella, suggest the presence of major folds. None was seen in the field and it is possible that lines of structural weakness such as the axial planes of major folds would be more rapidly eroded and thus obscured by the snow cover. Insufficient data are available for a structural analysis of these areas but it should be noted that the marble bands exposed at Hauglandkleppen are not repeated anywhere else.

The variations in the strike of the foliation at different localities in the western nunataks of Milorgfjella are indicative of plunging folds; small folds are rarely exposed (Plate IVd). 20 measurements of the strike and dip of the foliation in these nunataks and the axes of two small folds have been plotted on an equal area net (Fig. 4). Although there are insufficient points for definite conclusions to be drawn, the points

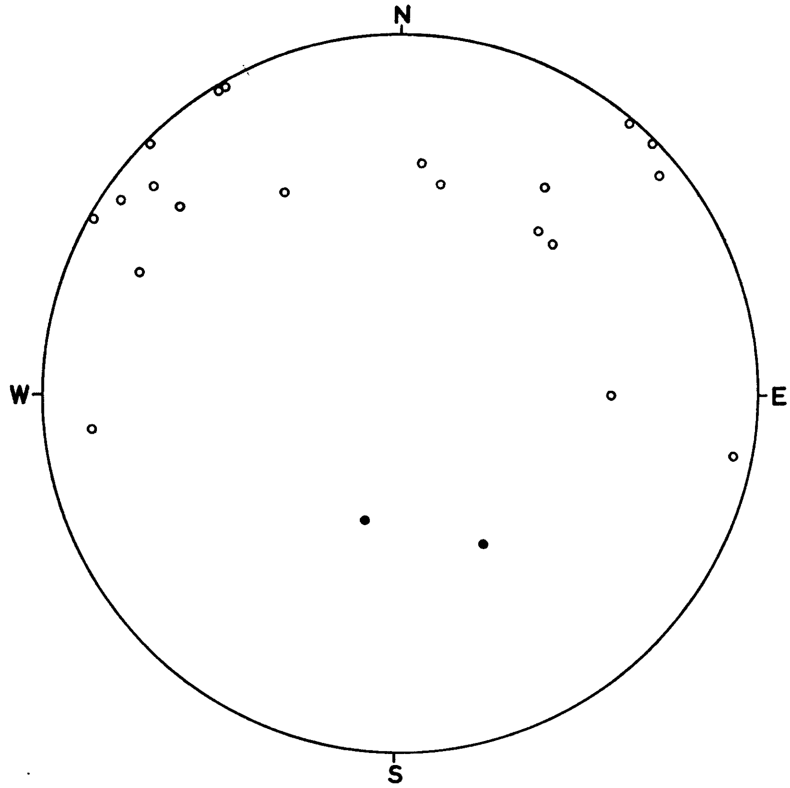

FIGURE 4

Lower-hemisphere projection on an equal-area net of poles to planes of foliation (o) and two observed fold axes (•) for stations in the western nunataks of Milorgfjella.

appear to form a great circle 90° away from the observed fold axes with two possible maxima separated by about 90°. This implies that in this area there is a set of large plunging folds (usually too large to be seen in a single exposure) with a similar attitude to the smaller folds exposed at station Z.377.

Apart from the distortion adjacent to the major fault in the main massif of Milorgfjella, the foliation there has a shallow dip to the south-east at most localities. Roots (1953) ascribed a similar structure in the Basement Complex of other areas of western Dronning Maud Land to moderate deformation; in contrast, Van Autenboer and others (1964) interpreted such features in the Sør-Rondane as the result of intense orogenic activity with the formation of recumbent folds. If the biotite-gneisses in the main massif of Milorgfjella had been derived from the same sediments which now constitute the *para*gneisses of the western nunataks, the first possibility is the more likely; however, if they are older, either explanation is possible.

The difference between the structural setting of the western nunataks and the main massif of Milorgfjella is marked; in the former, the rocks were in a relatively rigid state during the deformation (Plate IVd), whereas in the latter the response to deformation has been more plastic (Plate IIIa). This greater plasticity could be the result of higher temperatures in the vicinity of the granite, possibly enhanced in some cases (such as Waglenabben) by a locally high volatile content. Alternatively, the gneisses of the main massif could be part of an original Basement Complex on which were deposited the sediments that now form the *para*gneisses of the western nunataks.

2. *Metamorphism*

The determination of the grade of regional metamorphism to which a rock has been subjected depends on the presence or absence of certain index minerals, and the minerals most commonly used are rare in quartzo-feldspathic and potash-rich rocks. To some extent, it is probably for this reason that the more diagnostic index materials are absent in parts of north-east Heimefrontfjella. In such cases the grade of metamorphism must be ascertained by reference to minor occurrences of rocks of a different chemical composition, particularly amphibolites.

The gneisses of Sivorgfjella and XU-fjella have undergone almandine-amphibolite-facies regional metamorphism, as is shown by the assemblages containing garnet, hornblende, biotite and andesine. This is confirmed by the rare occurrences of diopside (Z.301.2 and 369.3).

In the western nunataks of Milorgfjella, few rocks contain diagnostic minerals but the biotite-hornblende-oligoclase assemblage also appears to represent the almandine-amphibolite facies. The absence of garnet from the *para*gneisses is probably a result of their quartzo-feldspathic composition, although it is surprising that there were no intercalations with a composition suitable for the formation of garnet. It is conceivable that garnet did in fact form but that it has since been made over to other minerals by retrograde metamorphism. Scattered aggregates of biotite which occur in some specimens (e.g. Z.383.2) could perhaps have formed by the break-down of garnet crystals but there are no relics to confirm this.

In this context, the presence of garnet in the basic dykes at station Z.375 assumes considerable significance. The textural and mineralogical relationships in specimens from these dykes demonstrate that two stages of metamorphism have affected the dykes. In the first, which may have been contemporaneous with the crystallization of the magma, the margins of the clinopyroxene crystals were altered to amphibole and garnet was formed (Z.375.5). Later shearing caused granulation and recrystallization of both plagioclase and clinopyroxene (Z.375.4), and where the rock has been completely recrystallized the resultant assemblage of plagioclase, hornblende, quartz and sphene (Z.375.3) does not contain garnet.

The chemical compositions of the specimens from these dykes (Table III) show that the shearing has not caused any major chemical re-organization and thus another explanation is necessary for the absence of garnet from specimen Z.375.3.

Altered basic dykes, sometimes containing garnet, occur in the north-west Highlands of Scotland and the Hebrides. These have been interpreted both as dykes intruded into deeply buried rocks which were still hot and as dykes intruded near the surface and subsequently metamorphosed. Reviewing these possibilities, Tarney (1963) concluded that both the mineral assemblages and the fact that, in several groups of dykes, the degree of alteration increased with age were consistent with intrusion at depth into hot country rocks.

If the dykes at station Z.375 had formed under similar conditions, the garnet probably crystallized at an early stage, possibly while the dyke was still hotter than the surrounding rocks. During later retrograde metamorphism shearing was localized along the north-western margin of the dyke, and this may have relieved the shear stress in its immediate vicinity with the result that other parts of the dyke escaped the widespread recrystallization.

Neither garnetiferous rocks nor any containing possible pseudomorphs after garnet were found in the main massif of Milorgfjella, although the biotite-hornblende-oligoclase assemblage (Z.348.2) is indicative of almandine-amphibolite-facies regional metamorphism.

The absence of garnet over wide areas in Basement Complex rocks of western Dronning Maud Land, despite the wide variety of rock types exposed, was first noted by Roots (1953) who offered no explanation for this. Worsfold (1967*b*) proposed a chemical explanation for the unusual distribution of garnet in Tottanfjella and Sivorgfjella, where he found that garnet did not form in acid gneisses if the total FeO : MgO ratio was less than unity. The chemical analyses of three biotite-gneisses (Table IV) (one garnetiferous biotite-gneiss from Sivorgfjella and two garnet-free biotite-gneisses from the main massif of Milorgfjella) demonstrate that the gneisses from both areas have a total FeO : MgO ratio considerably greater than unity. In certain granulite-facies rocks, Howie and Subramaniam (1957) found that garnet tended to form in those richer in Al_2O_3+(FeO+MgO). In this respect, specimen Z.301.3 which contains garnet is intermediate between specimens Z.324.1 and 348.2.

Thus, if there is a chemical explanation for the absence of garnet from these rocks, it is probably a complex one which would require a large number of chemical analyses to define it. Alternatively, there could be a physical explanation and the body of gneissic granite in Milorgfjella may be significant.

Apart from the problem of the absence of garnet, it seems that the gneisses of this massif have been metamorphosed at a higher temperature, with a possible resultant reduction in shear stress, compared with the gneisses of the western nunataks. The gneisses of this massif are generally coarser-grained and more massive in appearance, and the occurrence of green-brown hornblende at Waglenabben is further evidence that the temperature there was high (Leake, 1965).

TABLE IV

CHEMICAL ANALYSES OF BIOTITE-GNEISSES FROM NORTH-EAST HEIMEFRONTFJELLA

	Z.301.3	Z.324.1	Z.348.2
SiO_2	68·48	73·11	64·45
TiO_2	0·66	0·26	0·57
Al_2O_3	14·31	15·01	16·34
Fe_2O_3	1·16	0·66	1·52
FeO	3·28	1·17	3·46
MnO	0·08	0·05	0·08
MgO	0·92	0·25	2·36
CaO	2·58	1·61	3·85
Na_2O	2·54	3·50	4·24
K_2O	4·06	3·94	1·73
H_2O+	0·99	0·55	0·74
H_2O-	0·29	0·22	0·21
P_2O_5	0·17	0·10	0·17
CO_2	0·10	0·01	0·41
TOTAL	99·62	100·44	100·13

Z.301.3 Schistose quartz-feldspar-biotite-gneiss containing some garnet; northern Sivorgfjella.
Z.324.1 Quartz-feldspar-biotite-gneiss containing no garnet; main massif of Milorgfjella.
Z.348.2 Quartz-feldspar-biotite-hornblende-gneiss containing no garnet; main massif of Milorgfjella.

Retrograde metamorphism accompanied the widespread shearing which affected the south-eastern part of this massif and greenschist-facies mineral assemblages resulted.

Both the rock types and the apparent grade of metamorphism of the rocks of the eastern nunataks of Milorgfjella are so different from those of the main massif that any comparison would not be justified. The only diagnostic mineral which occurs there is brown hornblende, which, in regionally metamorphosed rocks, is usually characteristic of the granulite facies (Engel and Engel, 1962; Leake, 1965). This could signify either an increase in the grade of metamorphism east of the main massif or a fault separating this area from the main massif.

3. *Correlation*

The gneisses of Sivorgfjella, XU-fjella and the western nunataks of Milorgfjella appear to be metasediments with a dominantly quartzo-feldspathic composition and it seems likely that they were originally part of a single sedimentary succession. The origin of the gneisses of the main massif of Milorgfjella has been obscured by the effects of a granitic intrusion, extensive shearing and possibly one or more earlier phases of metamorphism. It is not clear whether the rocks of the main massif are part of the same metasedimentary succession, which has been intruded by the granite, or whether they were metamorphosed prior to the deposition of the sediments.

Correlation with the rock types described by Worsfold (1967*b*) is difficult because of the considerable variation within individual rock units in each area, but there is reasonable agreement in Sivorgfjella where the two areas are adjacent. The *para*gneisses of north-eastern Sivorgfjella could be expected, from extrapolation along the strike, to be exposed in the southernmost part of Sivorgfjella. The rocks exposed there have been described by Worsfold (1967*b*) as massive banded gneisses, which he interpreted as *para*-gneisses, and the two rock units appear to be similar despite the distance (25 km.) separating them. Extension of the strike from the northern part of Sivorgfjella reveals a striking similarity between the *para*gnesses described by Worsfold which are intruded by steeply dipping amphibolitized basic dykes and the *para*gneisses of the western nunataks of Milorgfjella which are intruded by similar dykes at station Z.375 and other localities.

V. LOWER PERMIAN SEDIMENTS

A. Distribution and Field Relations

Most of the outcrops of the sedimentary sequence are small outliers capping the much larger exposures of Basement Complex rocks. Because of their friable nature and their susceptibility to erosion by frost action in particular, large snow-free exposures are rare. In the largest outcrop, that capping Schivestolen, the alternation of beds of different hardness has given the outcrop a step-like appearance with 5–10 m. high cliffs alternating with wide ledges strewn with blocks from the higher beds.

Other outcrops, such as those at Lidkvarvet, Storsveenfjellet and south of Laudalkammen, are thin residual cappings on an otherwise exhumed erosion surface. Where the bedrock is still covered by a thin ice cap, small inaccessible windows of sedimentary rock are exposed in the ice cliffs such as that south-west of Berggravrista.

The thickest continuous section of the sedimentary sequence is on Schivestolen, where a total thickness of about 160 m. is exposed. About 6 km. south-east of this outcrop, at locality "C" (personal communication from G. W. Lovegrove), there is a small exposure of sediments and, if there are no faults between these two outcrops, an extrapolation of the dip of the underlying erosion surface suggests that the thickness could be nearly 500 m.

Incomplete sections are exposed elsewhere and only at Bjørnnutane are the underlying and overlying formations exposed in the same outcrop (Plate VIIIa). Here, only 2 m. of sediments separate the overlying basalts from the Basement Complex, and this may be the result of faulting and erosion prior to extrusion of the basalts.

The sedimentary sequence overlies the Basement Complex with an angular unconformity (Plate IId). From a distance the erosion surface appears to be planar at this outcrop but closer examination reveals certain irregularities. The beds at locality "A" were deposited on a gently undulating surface (Plate IIId), and about 1·5 km. away at locality "B" the sediments were deposited in a small valley incised in the Basement Complex. This valley appears to be controlled in part by structure, as one side approximates to the outcrop of a more resistant band of gneiss. The regional dip is 3–4° south-eastwards, although at some localities this is obscured by the local effects of bedrock topography.

Basalt flows overlie the sediments and the contact is exposed at two localities. In neither of these is the relationship clear, since the outcrops are small and both rock units are sub-horizontal, but the difference in age between the sediments and the basalt flows shows that they were separated by a considerable hiatus during which faulting and erosion could have occurred.

A dolerite sill, probably related to the basalt flows, is the only other exposed rock unit which is clearly younger than the sediments.

B. Lithology

Most of the exposures reveal only a small part of the succession, usually the lowermost 10 m. or less. The most complete section is the one at Schivestolen where a total thickness of about 160 m. is present. Changes in lithology are mostly gradual but three sub-divisions are recognizable (Fig. 5) and these are compared with sequences at other exposures.

1. *Schivestolen*

a. *Basal unit.* The erosion surface on which the sediments were deposited appears to be planar when viewed from a distance (Plate IId). However, at station Z.320, a channel about 5 m. deep and 30 m. wide has been incised in the rocks of the Basement Complex below the level of the main erosion surface. This channel is now filled with a coarse tightly packed conglomerate containing well-rounded boulders up to 0·5 m. in diameter (Plate VIa). These boulders are of resistant rock types resembling the more massive banded gneisses and granite-gneisses occurring locally.

Within this conglomerate there is a small outcrop of greenish micaceous sandstone with rough stratification. It is surrounded by rubble which obscures its relationship with the conglomerate but it is probably an intercalated lens.

Conglomerates occur at most other outcrops where the sediments overlie the Basement Complex,

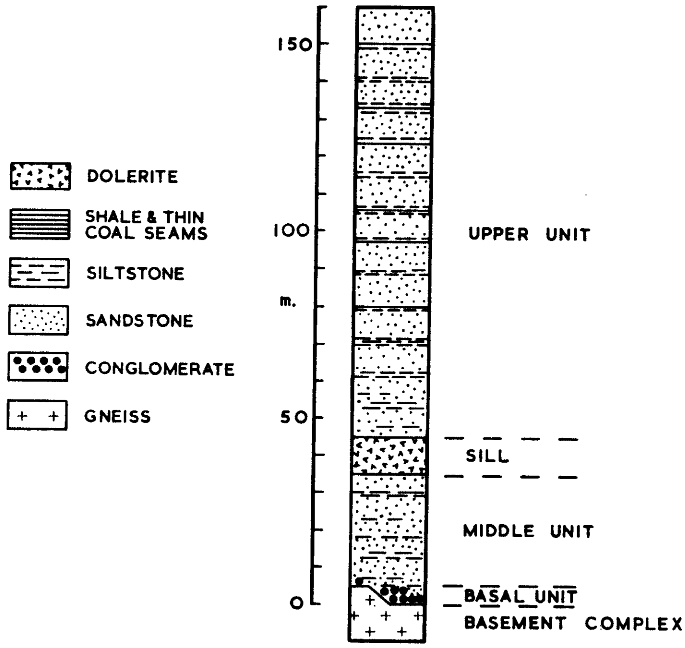

FIGURE 5

Diagrammatic section showing the sub-division of the sedimentary sequence exposed at Schivestolen.

but they cannot necessarily be correlated with this distinctive tightly packed conglomerate with its micaceous matrix.

b. *Middle unit.* The contact between the basal conglomerate and the overlying beds at station Z.320 is sharp (Plate VIb). Although this probably represents a period of erosion, it is not thought to indicate any major hiatus.

Directly overlying the basal conglomerate are finely laminated siltstones and sandstones which are sometimes cross-laminated. Ripple-marks and ripple-drift occur occasionally, as do small brown calcareous concretions. Higher in the succession, these beds become coarser and more massive until they grade into the sandstones of the upper unit. The upper limit of the middle unit has been arbitrarily placed directly below the dolerite sill which is approximately 30 m. above the base of the succession. Although the sill transgresses individual beds, its position is relatively constant and any changes are not significant in view of the thickness over which the transition occurs.

c. *Upper unit.* As the sandstone of the middle unit becomes more massive, dark siltstone or shale intercalations become commoner. In the upper part of the sequence, a regular alternation of sandstone and finer beds forms the typical development of the upper unit. The sandstone beds are about 7 m. thick (Plate VIIa) and they are frequently cross-stratified (Plate VIc) with fine shale partings sometimes accentuating the stratification. The rock is off-white to grey in colour and the weathered surface is sometimes stained reddish brown.

Siderite concretions, up to 1 m. in diameter and 0·3 m. thick, occur sporadically in the uppermost part of the upper unit (Plate VIc). These have an outer weathered blue-black surface, shown by X-ray diffraction analysis to consist of goethite and a small amount of quartz. The unweathered rock is dark brown, dense and well indurated. Most of the original detrital grains have been replaced by siderite but there are scattered corroded remnants of quartz.

The siltstone and shale beds are softer and more easily eroded than the sandstones, and thus their outcrops are either obscured by debris or exposed beneath overhanging sandstone beds. These finer intercalations vary from 1 to 2 m. in thickness and they sometimes contain thin coal seams (Plate VId). These are usually about 2–10 cm. thick but their thickness increases towards the top of the succession where one seam is 0·5 m. thick. Fragmental plant matter is sometimes preserved in the adjacent beds but it is invariably macerated. Beds of sandstone a few centimetres thick are sometimes intercalated with these finer strata.

2. *Lidkvarvet*

At the summit of Lidkvarvet 10 m. of sediments overlie the gneisses of the Basement Complex with an angular uncomformity. The majority of the strata are white to buff sandstones or mauve, yellow and red siltstones. The finer beds in this succession are frequently ripple-marked or they show ripple-drift and cross-lamination. Mud balls, sometimes armoured, are present and calcareous concentrations are abundant. These are usually light brown oblate ellipsoids, about 3–12 cm. in diameter with a darker weathered surface. The stratification appears to pass through these concretions.

Scattered pebbles and cobbles occur at all horizons and there is considerable lateral variation. Over a horizontal distance of 20–30 m. one thin gravelly bed increases in thickness and coarseness to become 2·5 m. of coarse conglomerate. Most of the cobbles and boulders are rounded but in the lowest beds some are angular. The quartz-mica-schist, quartzite and gneiss forming the clasts could all have been derived from locally exposed Basement Complex rocks.

3. *Locality "A"**

A thin capping of sediments has been preserved at the summit of the precipice east of Leabotnen. These beds were deposited on an undulating surface and as a result of compaction the beds now follow the topography of the underlying Basement Complex (Plate IIId). The total thickness exposed at this locality is 5–6 m.

The basal contact is usually concealed by snow or rubble but the lowest bed appears to be a dark, finely laminated siltstone or shale containing boulders up to 1 m. in diameter. This bed grades upwards into coarser laminated sandstones and siltstones sometimes showing surface markings on the bedding planes which may be invertebrate tracks.

The sandstone of the overlying horizon has occasional carbonaceous partings and very poorly preserved leaf impressions are widespread but not common. At one small locality, plant remains are more abundant and well preserved (p. 29).

The uppermost bed at this locality is a light-coloured, more massive sandstone which is cross-bedded (Plate VIIb). This also contains occasional poorly preserved leaf impressions and there are small ferruginous concretions about 1 cm. in diameter.

4. *Locality "B"*†

A small pocket of sediments is exposed in a trough incised in the Basement Complex at this locality. The trough is about 30 m. wide and the thickness of strata revealed is 3–4 m. The inward dips at the sides of the trough are a result of compaction.

At the base of this sequence is a thin band of well-indurated quartzite less than 0·3 m. thick. This is overlain by 1 m. of white sandstone containing scattered pebbles, and the uppermost bed consists of 2·5 m. of conglomerate. This has a sandy micaceous matrix and, although most of the cobbles are about 10–20 cm. long (Plate VIId), some attain a diameter of 0·5 m. especially near the top of the bed (Plate VIIc). Some of the clasts are well rounded and they have probably been transported for a considerable distance.

A glacially polished *roche moutonnée* of Basement Complex pegmatitic rock is present on the floor of the trough near the base of the sediments (Plate VIIIb). Although it appears unlikely that the present ice sheet could have formed it without first removing the adjacent sedimentary rocks, it is separated from the latter by about 2 m. of snow and debris so that the age relationship cannot be determined with absolute certainty.

5. *XU-fjella*

Three small outcrops of sediments in XU-fjella were visited and a fourth was examined from a distance with binoculars.

*The numbers of specimens collected at this locality are prefixed Z.342, 392, 393, 399A and B.
†The numbers of specimens from this locality are prefixed Z.341 and 394.

About 20–30 m. of well-bedded light-coloured sandstone are present above Storsveenfjellet but the base is not exposed. East of Hauglandkleppen, sediments resembling those at Storsveenfjellet are exposed in an ice cliff, where the exposure is at a slightly lower elevation than the Basement Complex rocks forming the summit of Hauglandkleppen.

Sandwiched between the basalt flows and the Basement Complex at Bjørnnutane are 2 m. of fine and coarse greenish grey sandstones (Plate VIIIa). The exposure is poor but conglomerates appear to be absent.

The small exposure of coarse buff or white sandstone, sometimes gritty, at station Z.371 is stained red and yellow near the contact with the overlying basalt flow. There are 2–3 m. of sediments but the base is not exposed.

6. *Correlation*

The sequence of basal, middle and upper units is exposed in full at Schivestolen and, although there is no direct evidence for the correlation of the sequences at the different localities, it seems unlikely that they represent more than one major period of deposition. Because of facies changes, lithological correlation of the different exposures would not necessarily give true time correlations. However, the similarities between the outcrop at Lidkvarvet and the middle unit, and between the outcrops of XU-fjella and locality "A" and the upper unit should be noted.

C. Petrography

1. *Basal unit*

The basal beds contain much locally derived detritus and consequently they contain certain minerals (such as biotite) which are less common higher in the sequence.

Most of the conglomerates have a greenish biotite-rich matrix which is sometimes sandy. These rocks are difficult to section and their petrology is better shown by intercalated sandstone beds such as that at station Z.353. Specimen Z.353.2 is a tightly packed sandstone of well-sorted angular to subangular grains with an average diameter of 0·3 mm. (In all cases sorting was estimated visually in thin section.)

More than 50 per cent of the sand-sized grains are of strained quartz and some of these are composite. Grains of highly saussuritized plagioclase are present together with others which are fresh and polysynthetically twinned. Extinction angles suggest that the latter is andesine but since there are few well-orientated grains it could be more calcic. Microcline and untwinned perthitic potash feldspar are less common and there is also some detrital epidote and clinozoisite. Grains of garnet and zircon are rare.

The abundant flakes of detrital biotite up to 0·5 mm. in diameter are often bent and crushed between sand grains (Plate Xa). Some of the biotite contains orientated inclusions of (?) rutile, as does the biotite in certain rocks of the Basement Complex. Muscovite flakes occur less frequently and they are also bent around sand grains. The matrix consists largely of fine biotite which is sometimes compressed into thin films between grains.

2. *Middle and upper units*

These units differ mainly in the relative proportions and thickness of coarse and fine strata, but petrologically they are quite similar to one another and also to the sandstones of Lidkvarvet, XU-fjella and locality "A".

Most of these sediments have been moderately sorted and many have a calcite cement. This calcite may replace the detrital grains to varying degrees and this can hinder estimations of roundness. Some of the coarser sandstones at Lidkvarvet have a fine chalcedonic cement which occasionally replaces clastic grains. These sandstones also contain patches of interstitial calcite and flakes of authigenic sericite. Finer-grained sediments, particularly those from near the base of the succession, often have a fine matrix rather than a cement.

Specimen Z.393.12 is a fine-grained sandstone collected from a bed containing plant remains, about 3 m. above the Basement Complex. It has a dense siliceous matrix and in addition to detrital mica it contains red-brown flakes or rods of what appears to be finely divided plant material (Plate Xb). The fine sand grains (0·2 mm. in diameter) are well sorted (Plate Xc) but there are occasional grains about

1 mm. across and finer bands about 1 mm. thick which are less well sorted. Quartz constitutes more than 60 per cent of the clastic grains and there is also perthitic potash feldspar, plagioclase, myrmekite, apatite, zircon and iron ore. Muscovite flakes with a diameter of up to 1 mm. and a thickness of less than 0·01 mm. are aligned parallel to the stratification. Biotite flakes are smaller and less common.

The coarser sediments contain a smaller proportion of mica flakes but they are not entirely absent. Specimen Z.371.1 is a coarse sandstone with a maximum grain-size of 2 mm. and an average grain-size of 0·5 mm. The sand has been moderately sorted and the grains are sub-rounded or rarely rounded. The cement is chalcedonic but there is also secondary interstitial calcite. About 80 per cent of the grains are of quartz, although this may partly be a result of selective replacement of feldspar grains by the cement. Microcline and untwinned feldspar are the only other detrital minerals present.

D. Palaeontology and Age

Apart from trace fossils in the form of tracks or sinuous lines on bedding planes, the only fossil remains found in the sediments are leaf and stem impressions and coal. The most prolific fossil site is locality "A", where poorly preserved leaves and stems are scattered throughout the sandstones and siltstones. As a rule, whole leaves are present in the sandstone where all detail is lost, but in the finer beds where detail is preserved the plant matter is fragmental.

Within a small area about 10 m. wide and 30 m. long at locality "A" plant fossils are more plentiful and in a better state of preservation within a bed of soft, dark fine sandstone 2–3 m. thick. The leaves and stems are preserved as carbonaceous impressions in the unweathered rock and as bleached outlines where they have been exposed to weathering. Much of the plant material is fragmental or matted but there are also well-preserved leaves and stems, especially within the paper-thin carbonaceous partings in the sandstone.

The entire sequence at this locality consists of less than 10 m. of sediments overlying the Basement Complex and the contact is obscured by snow and scree. Erosion and overburden make it difficult to trace this bed laterally but where it is re-exposed about 50 m. to the south-west plant remains are virtually absent.

A single specimen of what appears to be fossil wood with diagonal surface markings was collected at station Z.352, approximately 40 m. above the base of the succession.

A representative selection of these specimens has been examined by Dr. E. P. Plumstead, University of the Witwatersrand, Republic of South Africa. She has identified a glossopterid flora which represents the lowermost *Glossopteris* horizon yet recorded in Antarctica, and a full description of the flora has been published elsewhere (Plumstead, 1974). This sequence is assigned to the Lower Permian, although the lowest beds may be Upper Carboniferous in age.

A search for possible plant macro-fossils associated with the coal seams of Schivestolen revealed only macerated carbonaceous matter.

E. Provenance and Depositional Environment

The widespread plant remains and the complete absence of marine fossils from the sedimentary sequence are indicative of deposition in a non-marine environment.

The finely laminated sandstones at Lidkvarvet with cross-laminations, ripple-marks and pebbly bands were deposited in swiftly flowing water. Armoured mud balls were recorded at this locality; Bell (1940) has suggested that these form almost exclusively as a result of rapid erosion and undercutting of clay banks or less frequently through erosion of clay from stream beds. This suggests that some degree of erosion was taking place within the area of deposition at this time; this could have been achieved by the lateral migration of a stream channel.

The upper unit, with its more regular lithology, is a consequence of the more uniform conditions which would prevail after the partial infilling of a stable depositional basin. Irregularities on the floor of the basin were covered and the sediments were no longer partly locally derived. The fine cross-stratification of the sandstones in the upper unit and the presence of finer beds with coal horizons show that this part of the succession was also water-lain. It is therefore considered that these beds were deposited either in a lake or on a wide flood plain. The association of macerated plant matter with the coal and the absence of roots, stems and whole leaves suggest that the coal is allochthonous.

Most of the detrital material in the lowest beds could have been derived locally, and the boulders and cobbles in the conglomerates are of rocks similar to those at present exposed in the vicinity. However, the presence of detrital garnet within 5 m. of the base of the sequence at Schivestolen is evidence that some material was being transported over considerable distances. The nearest known outcrop of garnetiferous rocks is 8 km. to the south at station Z.375, but this outcrop is probably too small to have supplied any significant amounts of this mineral. Another anomaly is the fine quartzite at the base of the succession at locality "B". The detrital grains are mainly quartz which is not strained; this is in contrast to the overlying conglomerate which contains highly strained quartz similar to that in the adjacent sheared gneisses.

At most of the localities, where only the base of the succession is exposed, the current bedding reflects the local topography of the erosion surface and not an overall direction of transport. No current-bedding directions were measured at Schivestolen but the direction of transport seemed to be mainly from the south-east.

There are few definite indications as to the climate which prevailed during sedimentation. The *roche moutonnée* exposed near the base of the sediments at locality "B" may have been formed during the present glaciation of Antarctica but, if it pre-dates the sediments (as seems more likely from the field relations), this would imply a cold climate during at least the early part of the sedimentation. The conglomerate at this locality could well be a tillite. The fossil flora represents the lowest *Glossopteris* horizon yet recorded from Antarctica (Plumstead, 1974), and it is perhaps significant that in other Southern Hemisphere continents the lowest *Glossopteris* horizons overlie or are closely associated with evidence of glaciation (Plumstead, 1962).

There are no indications of glacial action in any other part of the sequence, so if glaciation did precede sedimentation then the climate must have been ameliorating.

Some of the detrital minerals in the lower strata are species which are easily broken down by weathering (e.g. members of the epidote group), but their absence higher in the succession suggests that this is a result of a comparatively nearby source rather than a necessarily cold climate.

F. Structure

1. *Tilting*

At most localities, the shallow dip of the sediments cannot be measured accurately or it is influenced by the configuration of the underlying erosion surface, but the large exposure at Schivestolen exhibits clearly a south-easterly dip of 3–4° (Plate IId).

It is difficult to ascertain whether this tilting occurred before or after the outpouring of the basaltic lavas because of the difficulty of estimating their dip. As far as could be determined, the dip is less than that of the sediments and thus it is inferred that the tilting was pre-Jurassic.

2. *Faulting*

Despite the distance between the outcrops of sediments at Schivestolen, Storsveenfjellet and Lidkvarvet, their altitudes are similar and the slight differences can be largely explained by the gentle dip. Consequently, it is unlikely that there has been any major faulting between the mountain blocks of Sivorgfjella, XU-fjella and Milorgfjella in post-Permian times. Although the glaciers between these mountain blocks could occupy post-Permian graben, it seems equally unlikely that a period of major faulting would only affect the areas which are now ice-covered.

The small outcrop of Basement Complex rocks at Bjørnnutane is about 500 m. higher than the projected plane of the erosion surface. Although the absence of conglomerates or pebbly bands may indicate that this was a topographically high area on the erosion surface, the relief necessary to explain this outcrop is not compatible with the form of the erosion surface elsewhere. Thus it seems probable that the Basement Complex has been uplifted by faulting and that erosion removed much of the sedimentary cover in pre-Jurassic times. It is possible that faulting and tilting occurred contemporaneously (with the formation of tilted fault blocks) but it should be stressed that these blocks do not coincide with the present mountain blocks. This hypothesis agrees with the apparently horizontal attitude of the basaltic flows. An analogous case of faulting of the Beacon Supergroup rocks prior to the extrusion of the Kirkpatrick basalts has been described by Grindley and others (1964) from south Victoria Land.

VI. JURASSIC BASALT LAVAS

1. *Distribution and field relations*

A thick succession of basaltic flows forms almost all of Bjørnnutane and Sembberget, which are topographically the highest outcrops examined east of Sivorgfjella. They form steep bluffs and pointed nunataks where the horizontal stratification of the basalt is clearly shown by the terraced appearance of the steep rock faces (Plate VIIIc), and this effect is increased by the accumulation of snow on the ledges. This terracing seems to have been caused by the more rapid weathering of the vesicular upper and lower surfaces of the flows.

The lower contact of the lava sequence has only been located accurately at two exposures, one in Bjørnnutane and the other at station Z.371, about 2 km. to the west. At both of these localities the basal flows overlie rocks of the sedimentary sequence with apparent conformity, although regional relationships suggest that they were separated by a period of faulting and erosion.

The upper limit of the basalt sequence was not found in the field; thus at Sembberget there is a thickness of at least 300 m. and, since the base of the succession is not exposed, the total thickness could be considerably greater. At Bjørnnutane the succession is about 130 m. thick where it overlies sediments. Because of the distance between these outcrops (45 km.) and because of the complete absence of any stratigraphical markers, the relative positions of these two successions cannot be compared.

Individual lava flows vary from 3 to 20 m. in thickness and there is usually a considerable variation in the appearance of different parts of a single flow. The base is usually fractured and highly vesicular and some of the vesicles are often infilled. The greater part of the flow is usually massive basalt with a few vugs near the centre. Near the top of the flow there is another concentration of amygdales which are sometimes distributed in bands several centimetres apart. The upper surface is often irregular and cindery, and in most cases it was covered by the succeeding flow without subaerial modification.

2. *Petrology*

The composition of the individual flows is remarkably constant throughout the succession. Slight differences noticed in the field were found to be caused by textural variations, particularly the presence of flow structure. All the flows examined are of quartz-free basalt which often contains small amounts of altered olivine. The modal compositions of a representative group of specimens from the less vesicular parts of flows are shown in Table V.

Most of the specimens are of coarse porphyritic basalt (e.g. Z.308.4). The groundmass consists of plagioclase laths, allotriomorphic augite with occasional cores of pigeonite, mesostasis, pseudomorphs after olivine, and magnetite (Plate Xe). The plagioclase is labradorite (An_{54-67}) in idiomorphic laths, invariably twinned on the albite law and often on the Carlsbad law, and which are sometimes zoned. Pale pink augite, moulded on the plagioclase, tends to form aggregates of granular crystals. The augite is sometimes twinned and this is commoner in other coarser specimens. The dark brown, weakly birefringent mesostasis containing much skeletal iron ore fills the interstices and some of it has been altered to brown micaceous matter. Other patches of similar brown matter have shapes which suggest that they are pseudomorphs after olivine, and similar aggregates in some of the other specimens possess cores of olivine. Glomeroporphyritic clusters of bytownite are abundant in this and most other specimens. The crystals are in most cases polysynthetically twinned and they may be zoned, although the compositional range spanned is small. The crystals within a particular cluster often show a rough parallelism, although the preferred orientation is different for each cluster.

Specimens from the centres of flows contain few vesicles. Specimens Z.310.1 and 3, from the base and the top of a flow respectively, are highly vesicular and whereas some of the cavities are empty others contain calcite and quartz. These rocks contain much dark devitrified glass.

Two of the flows in the succession at Sembberget were seen in the field to have a different appearance from the others. One of these showed a faint flow banding on weathered surfaces but the other was paler in colour, and both appeared to be finer-grained. Thin-section examination shows that the differences are largely textural, as mineralogically these specimens are similar to the others. The flow structure of these specimens (Z.349.1 and 350.2) is shown by the orientation of the plagioclase laths whose average length is 0·2 mm. Small brown patches of an unidentifiable mineral are sometimes concentrated in streaks, and specimen Z.349.1 contains what appear to be pseudomorphs after olivine. These specimens contain

TABLE V

MODAL ANALYSES OF BASALTS AND A DOLERITE FROM NORTH-EAST HEIMEFRONTFJELLA AND SEMBBERGET

	Z.308.4	Z.310.2	Z.349.1	Z.350.1	Z.350.2	Z.370.1	Z.371.7	Z.372.1	Z.353.7
Plagioclase (groundmass)	30·7	39·3	43·5	46·8	39·6	38·2	30·8	42·8	46·0
(phenocrysts)	15·9	—	2·6	—	0·6	3·4	16·8	2·8	1·5
Augite	31·0*	35·6	45·6*	33·5	50·3*	34·6	28·2	32·6	41·3*
Pseudomorphs†	1·9	tr	0·6‡	7·2	1·1	4·0	—	3·3	2·7
Opaque minerals	3·7	10·3	5·8	3·7	3·6	8·9	4·4	5·0	5·8
Calcite	—	—	—	—	—	—	0·8	—	—
Groundmass	16·8	14·1	1·9	8·8	4·8	10·9	18·8	13·5	2·7
Vesicles	—	0·7	—	—	—	—	0·2	—	—
Plagioclase composition									
groundmass	An_{54-67}	An_{69-77}	An_{59-69}	An_{59-68}	An_{62-72}	An_{48-67}	An_{63}	An_{60-69}	An_{50-70}
phenocrysts	An_{75}	—	An_{71}	—	—	An_{73}	An_{73}	An_{74}	An_{80}

tr Trace.
*Includes some pigeonite.
†Bowlingite, iddingsite, etc.; probably after olivine. Some contain relics of olivine.
‡Some may be after orthopyroxene.

Z.308.4 Coarse basalt from the centre of a flow 17 m. thick at Bjørnnutane.
Z.310.2 Coarse basalt from the centre of a flow 6 m. thick at Bjørnnutane.
Z.349.1 Fine-grained basalt showing flow banding; from a flow at least 4 m. thick at Sembberget.
Z.350.1 Coarse subophitic basalt from a typical flow at least 5 m. thick at Sembberget.
Z.350.2 Fine-grained basalt with trachytic texture; from a light-coloured flow at Sembberget.
Z.370.1 Oxidized coarse basalt from western Bjørnnutane.
Z.371.7 Uppermost exposed part of the basal flow (at least 10 m. thick) at a small nunatak about 2 km. west of Bjørnnutane.
Z.372.1 Coarse basalt from western Bjørnnutane.
Z.353.7 Fine-grained dolerite from 2 m. below the upper contact of a 10 m. thick undifferentiated sill intruding sediments at Schivestolen.

pigeonite (2V<6°) in addition to augite, whereas the other specimens of basalt (excluding Z.308.4) contain only augite (2V≃50°).

3. *Amygdales and vugs*

Two different types of gas cavity are present in these lava flows. In the more slaggy lava at the base and the top of each flow there are spherical or less commonly tubular vesicles with a diameter of about 1 cm. These vesicles may be empty or completely filled with later minerals including calcite, quartz and much scolecite.

Larger cavities occur sporadically in the centres of some flows and sometimes these appear to be aligned along a particular plane. The largest of these vugs are about 15 cm. long and 5 cm. high, and they are usually lined with quartz crystals or cryptocrystalline silica. Calcite rhombohedra and wedge-like stilbite crystals 2–4 cm. long appear to be of the same age as the quartz. The last mineral to crystallize was apophyllite, which forms both euhedral terminated prisms (Fig. 6) and larger anhedral masses. The smaller examples of these vugs in the centres of flows are usually completely filled with cryptocrystalline silica, including agate and dark green and smoky blue forms.

Patches of a fine-grained blue-green aggregate were found in a lava flow at Sembberget. X-ray diffraction and microscopic examination of crushed fragments showed that the grains were in fact colourless heulandite crystals with a green amorphous coating.

No regional or vertical mineral zoning was recorded. If the minerals had been deposited in zones similar to those in Iceland (Walker, 1960), the presence of scolecite and the abundance of other minerals would equate this with the lowest zone there. This zone is more than 760 m. thick in Iceland and this is probably more than the total thickness exposed in Milorgfjella and Sembberget.

A white fibrous mass about 10 cm. in diameter was found on the summit of Sembberget, where it appeared to be a form of encrustation on the present rock surface but derived from minerals in a cavity

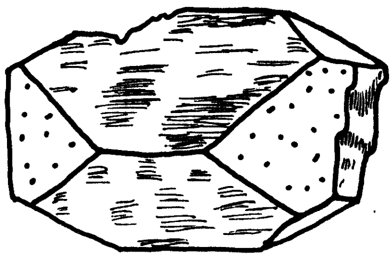

FIGURE 6

Sketch from a photograph of an euhedral crystal of apophyllite showing the habit typically developed in the occurrence at Bjørnnutane. Striated second-order prism faces, pitted first-order pyramid faces and two somewhat rough basal planes are present. The latter may be cleavage planes, as some of the crystals from this locality are terminated by the first-order pyramid only (Z.308.1; × 5).

in the basalt. It includes small fragments of basalt and it is moulded on some crystals of stilbite. X-ray diffraction analysis has revealed that it consists of thaumasite ($CaSiO_3.CaCO_3.CaSO_4.14\cdot5H_2O$) plus a trace of gypsum.* The fibrous thaumasite is uniaxial negative and its refractive indices ($\omega = 1\cdot508$, $\varepsilon = 1\cdot467$) are comparable with those for material from other localities (Vogt, 1938; Knill, 1960).

Vogt (1938) has discussed the paragenesis of thaumasite; it can form at a very late stage of mineralization and it may replace either gypsum or anhydrite. Formation on the present land surface would be a very unusual setting for thaumasite and the wind-eroded surface of the specimen suggests that it was not still in the process of formation. The most probable explanation is that the thaumasite had formed not at the present surface but at a late stage of mineralization, when it not only filled the cavities which were already lined with stilbite but it also lined adjacent joints. If these joint surfaces formed the surface of the present exposure, the thaumasite might appear to be a recent encrustation. The small amount of gypsum present could be derived from break-down of the thaumasite, as gypsum has been found to be capable of forming at the surface under glacial conditions (Van Autenboer, 1964.)

4. *Intercalations*

Although approximately 300 m. of the basalt succession were examined, no major intercalations were seen. Some small partings between flows, all less than 1 m. in thickness, are of detrital or residual origin and no undoubted pyroclastic fragments were found.

The upper surfaces of some of the flows at Bjørnnutane were slightly weathered and oxidized subaerially before being covered by the succeeding flows. Near the base of the succession, a thin bed of red sandstone separates two flows, filling irregularities in the surface beneath it. Its maximum thickness is 0·5 m. above a depression in the flow beneath it, but several metres away it diminishes to a thin red parting. Small-scale current bedding in the thicker parts of the bed show that it was deposited by water.

Specimen Z.308.3, collected from a scree, shows the contact between a red sandstone and the glassy margin of a lava flow. In thin section the sandstone is similar to that of the underlying sediments and it contains detrital quartz, microcline, untwinned feldspar, zircon and garnet in a fine siliceous matrix. In addition, there are rounded fragments of volcanic material, usually dense glass containing plagioclase microlites. Some of the detrital grains are slightly shattered but there is no obvious thermal metamorphism.

Near the summit of Sembberget two flows are separated by a band of bole which has been baked to give a dense brick-red rock forming a band about 10 cm. thick. It consists mainly of angular and cleaved grains of untwinned feldspar and quartz (0·2 mm. in diameter) set in a siliceous matrix and heavily stained with iron oxide (Z.350.9).

From this it would appear that the eruptions were non-explosive and possibly from fissures. The few volcanic fragments found in sediments (as in specimen Z.308.3) could perhaps be pyroclastic but they could equally well have been derived from the erosion of the nearby flows.

5. *Age and correlation*

Specimen Z.372.1, a coarse basalt from Bjørnnutane, has been dated by the K-Ar whole rock method, yielding an age of 174±7 m. yr. (personal communication from Dr. J. C. Briden). Thus the sequence is

* See Appendix on p. 44.

assigned to the Jurassic and it can be correlated with the Ferrar Group basalts of Victoria Land (Gair, 1964.)

VII. JURASSIC DOLERITE INTRUSIONS

THE dolerite sill intruding the sediments on Schivestolen is the only basic intrusion in north-east Heimefrontfjella which is demonstrably post-Permian in age and none of the basic intrusions in the Basement Complex is strictly comparable.

1. *Field relations*

The sill crops out near the top of Schivestolen and for about 2 km. to the south and east. It is clearly visible from a distance as a dark band in the light-coloured sediments (Plate IId).

Throughout its outcrop the sill has a fairly constant thickness of about 10 m. and it maintains a position about 30 m. above the base of the sediments. It is usually concordant, although occasionally it transgresses the stratification of the sediments slightly but suddenly, and at station Z.320 a branch sill 1 m. thick parts from the upper margin and extends for some distance northward in a position a few metres above the main sill (Plate VIIId). This sill contains prominent white amygdales, as does the upper part of the main sill at some localities. There is usually marked columnar jointing.

2. *Petrology*

Specimens were collected from different levels in the sill to determine whether differentiation had occurred or whether any other form of hererogeneity existed. Apart from contamination by country rock in the upper part of the sill, the only difference noted was a slight increase in the soda content of the groundmass plagioclase towards the centre of the sill. Since the contamination is largely restricted to the small branch sill, this will be described separately.

a. *Main sill.* The modal composition of specimen Z.353.7 is given in Table V. This rock is typical except for the fact that some of the olivine has survived the deuteric alteration. It is a fine granular rock with a hypidiomorphic texture and small plagioclase laths (Plate Xf). Some of the augite crystals show simple twinning and there is a little pigeonite. Late magnetite or ilmenite is moulded on the plagioclase laths. Small crystals of olivine have been altered marginally to green and brown aggregates. Porphyritic crystals and glomeroporphyritic clusters of bytownite ($Ab_{20}An_{80}$) are present and these are sometimes associated with bowlingite pseudomorphs apparently after olivine. The bytownite may be twinned or zoned, although the zoning usually disappears where there is polysynthetic twinning.

Near the lower margin of the sill the rock is finer (Z.353.4) and there are xenolithic grains of quartz but reaction rims are not developed. Small vesicles are lined with fine mesostasis and filled with calcite and quartz. Some vesicles are asymmetrical with euhedral quartz at one end while the remainder is filled with calcite. These vesicles have the same orientation throughout the thin section but unfortunately the original attitude of the specimen is not known.

b. *Branch sill.* This part of the sill, although only 1 m. thick, is markedly heterogeneous as a result of both contamination by country rock and deuteric alteration which may in fact have been caused by the contamination. Where this part of the sill was examined it cuts across the stratification slightly and it has incorporated fragments of the friable and flaky sandstones. At this locality and at others, where only the upper margin is exposed, this sill contains small white vesicles.

Interaction between the dolerite and the xenolithic material is greatest in the lowest part of the sill, as shown by specimen Z.353.10. Streaky bands of fine dolerite are intermixed with others of xenolithic material which contains grains of quartz and unaltered detrital garnet. Many quartz grains have euhedral overgrowths in optical continuity, and secondary calcite and euhedral quartz are present. The dolerite consists of a very fine dark brown groundmass containing bytownite phenocrysts and small plagioclase laths which exhibit a distinct flow structure.

Just below the centre of the sill (Z.353.11), the dolerite resembles that of the main sill except for its finer texture and the presence of some amygdales. At a slightly higher level (Z.353.12) the ferromagnesian mineral is either biotite or some alteration product (such as iddingsite) with a similar appearance. The textural relationships, including possible relics of ophitic texture, suggest that an original clinopyroxene may have been replaced.

The deuteric action has been concentrated in the upper part of the sill, where the original ferromagnesian minerals have been replaced by calcite (Z.353.13). The plagioclase has undergone practically no alteration, even where it is in contact with other minerals that have been completely replaced. The vesicles contain, from the outside towards the centre: mesostasis, calcite and quartz. This quartz is highly strained and therefore it may be xenolithic, although it is not yet understood why vesicles would then form about such grains.

c. *Country rock alteration.* Alteration of the country rock is restricted to within 10 cm. of the dolerite sill where grains of the sandstone have partly fused and recrystallized. This is best seen between the two parts of the sill, and specimen Z.353.9 (collected from within 5 cm. of the top of the main sill) consists of corroded quartz grains scattered throughout a finely crystalline light brown matrix which sometimes displays a poorly developed spherulitic structure. Many small acicular crystals penetrate this matrix and some of the quartz grains are fringed with radiating needle-like crystals which may be in optical continuity with the original grains (Plate Xd). These crystals are too small for positive identification but they are comparable with those discussed by Searle (1962, p. 398, fig. 12), who identified similar crystals in a xenolith in basalt as tridymite which had inverted to quartz.

The preponderance of quartz (and some refractory zircon) among the relict grains is in contrast with the more arkosic composition of the sandstone farther away from the dolerite; this supports the observation of Ackermann and Walker (1960), who found in a similar occurrence of fused sandstone adjacent to a Karroo dolerite in South Africa that orthoclase was the first mineral to fuse.

Small circular patches of iron pyrites 1–3 mm. in diameter are present on some fracture surfaces of the baked country rock. As pyrites occurs in similar form on joint surfaces in the dolerite itself, it is probably of post-crystallizational hydrothermal origin.

d. *Locality "C".* A fine-grained vesicular specimen (Z.399C.1) was collected from this small outcrop 5 km. south of Schivestolen by G. W. Lovegrove but the field relations are inadequate to show whether it was intrusive or extrusive. Petrologically, it is very similar to specimen Z.353.13 and it is probably part of a similar sill.

3. *Age and correlation*

The only direct indication as to the age of the dolerite is that it is younger than the Permian sediments. There is little doubt, however, that it is Jurassic in age and that it is equivalent to the Jurassic Ferrar dolerites (Grindley, 1963) which intrude the Upper Palaeozoic sediments elsewhere in eastern Antarctica on a large scale. The Jurassic basalts of Bjørnnutane and Sembberget confirm that the Jurassic igneous activity extended to this part of Dronning Maud Land.

VIII. GEOCHEMISTRY OF THE JURASSIC BASALT LAVAS AND DOLERITE INTRUSIONS

1. *Major elements*

Eight new chemical analyses of basalts and one of a dolerite from north-east Heimefrontfjella and Sembberget are given in Table VI. These rocks have been plotted on triangular variation diagrams with the coordinates ($Fe''+Fe'''$)–Mg–Alk and Ca–Na–K (Fig. 7), together with the fields for the pigeonite- and hypersthene-tholeiites, and an olivine-tholeiite from southern Victoria Land (Gunn, 1966). The basalts from north-east Heimefrontfjella and Sembberget apparently have a very restricted compositional range which differs from those of the suites described by Gunn (1966). On the Ca–Na–K variation diagram, the most noticeable feature of these basalts is their relatively low potassium content; Table VI confirms that this is a result of a low absolute potassium content. The ($Fe''+Fe'''$)–Mg–Alk variation diagram suggests that at the expense of the alkalis they have a slightly higher relative iron content than the southern Victoria Land tholeiites. The restricted compositional range is believed to indicate the absence of any significant differentiation or contamination of the magma and therefore these chemical

TABLE VI

CHEMICAL ANALYSES OF BASALTS AND A DOLERITE FROM NORTH-EAST HEIMEFRONTFJELLA AND SEMBBERGET

	Z.308.4	Z.310.2	Z.349.1	Z.350.1	Z.350.2	Z.370.1	Z.371.7	Z.372.1	Z.353.7
SiO_2	50·91	48·09	50·35	50·60	50·81	49·40	51·96	48·19	50·92
TiO_2	1·24	1·35	1·46	1·11	1·08	1·71	0·96	1·67	1·61
Al_2O_3	14·96	14·16	14·32	14·92	14·97	14·39	14·81	14·03	13·85
Fe_2O_3	4·73	7·11	4·70	4·97	3·49	7·86	2·87	5·37	3·71
FeO	6·28	4·61	8·13	6·58	7·65	4·21	6·71	6·38	9·54
MnO	0·19	0·16	0·21	0·19	0·18	0·19	0·17	0·17	0·28
MgO	6·20	7·35	6·63	6·74	6·77	6·33	4·98	7·41	5·71
CaO	9·96	11·70	10·04	10·53	10·54	11·36	11·02	11·03	10·03
Na_2O	2·40	2·37	2·48	2·19	2·07	2·55	2·47	2·42	2·38
K_2O	0·55	0·28	0·45	0·73	0·57	0·33	0·73	0·37	0·55
H_2O+	0·68	0·22	0·18	0·59	0·56	0·23	0·80	0·74	0·83
H_2O-	1·48	1·75	0·93	1·01	0·98	1·14	0·46	1·65	0·46
P_2O_5	0·20	0·18	0·19	0·15	0·14	0·25	0·20	0·20	0·18
CO_2	0·10	0·31	0·06	0·11	0·23	0·12	1·72	0·05	0·07
TOTAL	99·88	99·64	100·13	100·42	100·04	100·07	99·86	99·68	100·12
	ANALYSES LESS TOTAL WATER (Recalculated to 100)								
SiO_2	52·10	49·24	50·85	51·20	51·58	50·05	52·70	49·53	51·52
TiO_2	1·27	1·38	1·47	1·12	1·10	1·73	0·97	1·72	1·63
Al_2O_3	15·31	14·50	14·46	15·10	15·20	14·58	15·02	14·42	14·02
Fe_2O_3	4·84	7·28	4·75	5·03	3·55	7·96	2·91	5·52	3·75
FeO	6·43	4·72	8·21	6·66	7·77	4·27	6·81	6·56	9·65
MnO	0·19	0·16	0·21	0·19	0·18	0·19	0·17	0·17	0·28
MgO	6·35	7·52	6·70	6·82	6·87	6·41	5·05	7·62	5·78
CaO	10·19	11·98	10·14	10·66	10·70	11·51	11·18	11·34	10·15
Na_2O	2·46	2·43	2·51	2·22	2·10	2·58	2·51	2·49	2·41
K_2O	0·56	0·29	0·45	0·74	0·57	0·34	0·74	0·38	0·56
P_2O_5	0·20	0·18	0·19	0·15	0·14	0·26	0·20	0·20	0·18
CO_2	0·10	0·32	0·06	0·11	0·24	0·12	1·74	0·05	0·07
	NORMS								
Q	6·67	4·36	4·10	5·00	4·92	6·51	8·50	2·37	5·02
or	3·33	1·69	2·69	4·36	3·42	1·98	4·37	2·25	3·29
ab	20·78	20·53	21·19	18·75	17·78	21·86	21·19	21·04	20·37
an	29·08	27·82	26·87	29·06	30·32	27·19	27·55	27·06	25·78
di	15·67	22·19	17·68	17·77	16·54	21·39	12·71	21·93	18·87
hy	14·33	9·08	17·20	15·01	18·93	6·05	15·16	13·49	17·54
mt	7·02	10·55	6·88	7·29	5·14	9·35	4·22	8·00	5·44
il	2·41	2·62	2·80	2·13	2·08	3·29	1·85	3·26	3·09
hm	—	—	—	—	—	1·51	—	—	—
ap	0·48	0·44	0·45	0·36	0·34	0·60	0·48	0·49	0·43
cc	0·23	0·72	0·14	0·25	0·53	0·28	3·97	0·12	0·16
	ELEMENT PERCENTAGES								
Si^{+4}	24·36	23·02	23·77	23·94	24·11	23·40	24·64	23·16	24·09
Al^{+3}	8·10	7·67	7·65	7·99	8·04	7·72	7·95	7·63	7·42
Fe^{+3}	3·39	5·09	3·32	3·52	2·48	5·57	2·04	3·86	2·62
Mg^{+2}	3·83	4·54	4·04	4·11	4·14	3·87	3·05	4·60	3·49
Fe^{+2}	5·00	3·67	6·38	5·18	6·04	3·32	5·29	5·10	7·50
Na^{+1}	1·83	1·80	1·86	1·65	1·56	1·91	1·86	1·85	1·79
Ca^{+2}	7·28	8·56	7·25	7·62	7·65	8·23	7·99	8·10	7·25
K^{+1}	0·46	0·24	0·37	0·61	0·47	0·28	0·61	0·32	0·46
Ti^{+4}	0·76	0·83	0·88	0·67	0·66	1·04	0·58	1·03	0·98
Mn^{+2}	0·15	0·12	0·16	0·15	0·14	0·15	0·13	0·13	0·22
P^{+5}	0·09	0·08	0·08	0·07	0·06	0·11	0·09	0·09	0·08
C^{+4}	0·03	0·09	0·02	0·03	0·07	0·03	0·47	0·01	0·02
O^{-2}	44·72	44·29	44·22	44·46	44·58	44·37	45·30	44·12	44·08

	TRACE ELEMENTS (p.p.m.)								
Cr	183	320	141	156	170	284	177	283	142
Ni	93	93	57	88	103	108	70	84	56
Cu	179	145	93	141	154	195	151	169	252
Zn	78	76	88	78	82	74	80	68	94
Ga	14	17	17	18	18	19	18	14	20
Rb	12	*	*	13	3	*	14	4	11
Sr	300	300	162	123	112	198	319	360	164
Y	19	13	25	25	26	23	22	18	32
Zr	124	65	108	122	142	99	135	95	133
Nb	6	3	5	5	5	6	6	6	5
Ba	265	141	190	208	243	230	302	214	211
La	10	*	19	9	7	14	14	11	8
Ce	43	15	24	29	26	24	30	23	22
Pb	11	7	*	7	8	*	11	7	10
Th	3	5	*	7	*	*	5	2	4
Position $[(\frac{1}{3}Si+K)-(Ca+Mg)]$	—2·53	—5·19	—3·20	—3·14	—3·28	—4·02	—2·22	—4·66	—2·25
Fe	68·7	65·9	70·6	67·9·	67·3	69·7	70·6	66·1	74·4
Mg	31·3	34·1	29·4	32·1	32·7	30·3	29·4	33·9	25·6
Fe	57·8	57·1	60·7	57·7	58·0	59·5	57·1	57·0	63·8
Mg	26·4	29·6	25·3	27·3	28·2	25·9	23·7	29·2	22·0
Alk	15·8	13·3	14·0	15·0	13·8	14·6	19·2	13·8	14·2
Ca	76·1	80·7	76·5	77·1	79·0	79·0	76·4	78·9	76·3
Na	19·1	17·0	19·6	16·7	16·1	18·3	17·8	18·0	18·8
K	4·8	2·3	3·9	6·2	4·9	2·7	5·8	3·1	4·9

*Below limit of sensitivity.

Z.308.4 Coarse basalt from the centre of a flow 17 m. thick at Bjørnnutane.
Z.310.2 Coarse basalt from the centre of a flow 6 m. thick at Bjørnnutane.
Z.349.1 Fine-grained basalt showing flow banding; from a flow at least 4 m. thick at Sembberget.
Z.350.1 Coarse subophitic basalt from a typical flow at least 5 m. thick at Sembberget.
Z.350.2 Fine-grained basalt with trachytic texture; from a light-coloured flow at Sembberget.
Z.370.1 Oxidized coarse basalt from western Bjørnnutane.
Z.371.7 Uppermost exposed part of the basal flow (at least 10 m. thick) at a small nunatak about 2 km. west of Bjørnnutane.
Z.372.1 Coarse basalt from western Bjørnnutane.
Z.353.7 Fine-grained dolerite from 2 m. below the upper contact of a 10 m. thick undifferentiated sill intruding sediments at Schivestolen.

(All analyses by L. M. Juckes.)

characteristics are interpreted as features of the initial magma composition and not a differentiation trend.

Linear plots on the coordinates SiO_2 and (Na_2O+K_2O) have been used to compare the Ferrar dolerites of southern Victoria Land with rocks from other areas (Gunn, 1962; Juckes, 1968); this type of diagram clearly illustrates the characteristically high silica content of the southern Victoria Land dolerites. The analyses in Table VI have been plotted on the same coordinates (Fig. 8) together with the field for the Ferrar dolerites of southern Victoria Land (Gunn, 1962); this diagram confirms earlier suggestions that the western Dronning Maud Land magma has a relatively lower silica content (Hamilton, 1965; Juckes, 1968). The points representing the basalts and dolerite from north-east Heimefrontfjella and Sembberget fall on a line which shows that the alkalis increase slightly with the silica content, as would be expected. This strong alignment suggests a single source from which these rocks were derived, although it is not known whether the apparent trend represents differentiation before or after extrusion. Because of the vesicular and zeolitized nature of some of the flow margins, it was preferable to analyse specimens from nearer the centres of the flows, where slight differentiation may have caused enrichment in alkalis and silica. There is no obvious relationship between silica content and stratigraphical height, although the absence of any means of correlating the different outcrops prevents a comparison between each of the specimens.

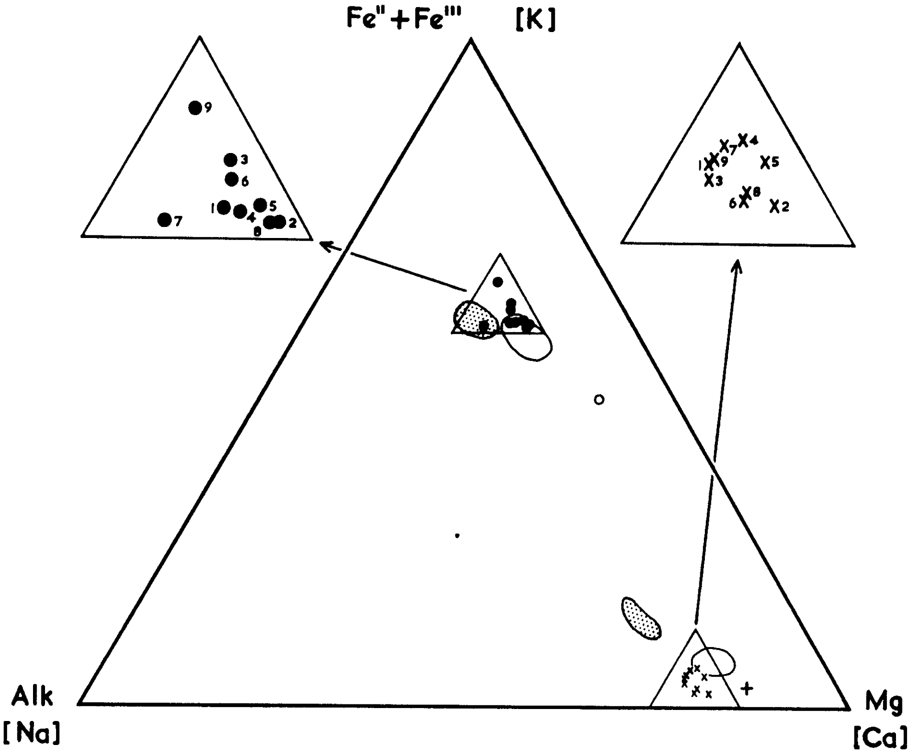

FIGURE 7

Triangular variation diagrams plotted on the coordinates (Fe''+Fe''')–Mg–Alk (●) and Ca–Na–K (×) for the basalts and dolerite from north-east Heimefrontfjella and Sembberget. The fields for the pigeonite-tholeiites (stippled), hypersthene-tholeiites (unshaded) and an olivine-tholeiite (o and +) from south Victoria Land (after Gunn, 1966) are included. The relevant parts of the diagram have been enlarged by 2·5 times to allow clearer interpretation and the addition of numbers as in Table VI.

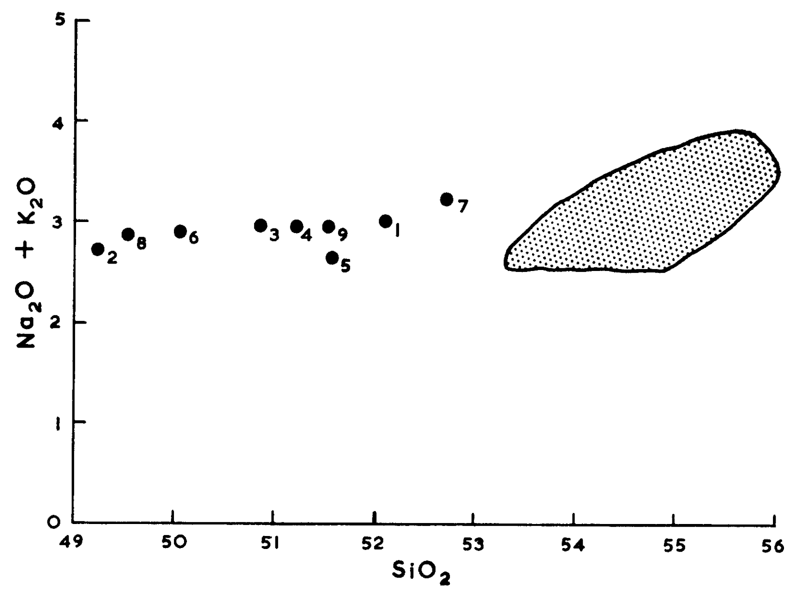

FIGURE 8

Plot of (Na_2O+K_2O) against SiO_2 for basalts and dolerite from north-east Heimefrontfjella and Sembberget (●). The stippled field represents the Ferrar dolerites of south Victoria Land (after Gunn, 1962).

2. *Trace elements*

Gunn (1966) noted that the trace-element values accentuated the differences between the "magma types" which he had recognized in southern Victoria Land. The values for certain trace elements for the basalts from western Dronning Maud Land are given in Table VI. Fig 7 shows that the major elements of these rocks are probably most similar to the hypersthene-tholeiite (Gunn, 1966) but the values for Cr, Zn and Rb are more like those of the olivine-tholeiite; the Sr values for the same rocks resemble that of the pigeonite-tholeiite.

The ratio K/Ba for dolerites from southern Victoria Land has been found to vary from 26 to 36 with differentiation (Gunn, 1965). In the basalts from western Dronning Maud Land, this ratio varies from 12 to 29 (Table VII) and, if this ratio is in fact an index of fractionation, the magma which formed these

TABLE VII

K/Rb AND K/Ba RATIOS FOR SOME BASALTS AND A DOLERITE FROM NORTH-EAST HEIMEFRONTFJELLA AND SEMBBERGET

	1	2	3	4	5	6	7	8	9
K	0·46	0·24	0·37	0·61	0·47	0·28	0·61	0·32	0·46
Rb	12	*	*	13	3	*	14	4	11
Ba	265	141	190	208	243	230	302	214	211
K/Rb	383	—	—	469	1,567	—	436	800	418
K/Ba	17	17	19	29	19	12	20	15	22

*Below limit of sensitivity (3 p.p.m.).
Values for K (per cent), Rb and Ba (p.p.m.) are from Table VI.

1. Z.308.4 Coarse basalt from the centre of a flow 17 m. thick at Bjørnnutane.
2. Z.310.2 Coarse basalt from the centre of a flow 6 m. thick at Bjørnnutane.
3. Z.349.1 Fine-grained basalt showing flow banding; from a flow at least 4 m. thick at Sembberget.
4. Z.350.1 Coarse subophitic basalt from a typical flow at least 5 m. thick at Sembberget.
5. Z.350.2 Fine-grained basalt with trachytic texture; from a light-coloured flow at Sembberget.
6. Z.370.1 Oxidized coarse basalt from western Bjørnnutane.
7. Z.371.7 Uppermost exposed part of the basal flow (at least 10 m. thick) at a small nunatak about 2 km. west of Bjørnnutane.
8. Z.372.1 Coarse basalt from western Bjørnnutane.
9. Z.353.7 Fine-grained dolerite from 2 m. below the upper contact of a 10 m. thick undifferentiated sill intruding sediments at Schivestolen.

flows must have undergone very little modification. The K/Rb ratio (Table VII is unusually high in that for only one specimen it is less than 400. The values of 1,567 and 800 for specimens Z.350.2 and 372.1, respectively, are only approximate as the Rb content is near the detection limit. For three of the specimens, Rb is below the detection limit of 3 p.p.m. (personal communication from Dr. G. L. Hendry), although it is apparent that any value equal to or less than 3 p.p.m. for these specimens would give a ratio of 800 or more. This is in marked contrast to the southern Victoria Land dolerites for which the ratio is approximately 240, and even the continental alkali-basalts of New Zealand which have a ratio of about 335 (Gunn, 1965), although Gast (1965) has observed that for rocks with a low potassium content the K/Rb ratio may be unusually high.

The K/Rb ratios for the specimens described by von Brunn (1964) are more comparable with those of the Ferrar dolerites of south Victoria Land and the Tasmanian dolerites (Erlank and Hofmeyr, 1968) as the values range from 144 to 267 with the exception of one dyke which has a K/Rb ratio of 615. These low values have been attributed by the authors to selective crustal contamination, an hypothesis which is supported by other trace-element values. The marked contrast between these low ratios and those for the basalts from Heimefrontfjella is difficult to explain, but it should be noted that the absolute ages of the dolerite intrusions described by von Brunn (1964) and Erlank and Hofmeyr (1968) are not yet known and that some or all of them may prove to be unrelated to the Ferrar suite.

3. *Conclusions*

The variability of the Ferrar suite was noted by Hamilton (1965), who suggested that the silica content might decrease from Victoria Land across the continent to Coats Land. This suggestion has been confirmed by Juckes (1968), who found that the basic rocks of western Dronning Maud Land also had a significantly lower potash content. Although these rocks appear to form a part of the Ferrar suite, the consistent differences in both the major and minor element contents seem to warrant their recognition as a distinct sub-suite.

It therefore appears that the generally accepted concept of the Ferrar dolerites being a relatively uniform suite requires some revision and it is relevant to re-examine some of the evidence supporting this hypothesis.

It has been suggested that, whereas the Ferrar dolerites include "several distinct magmas", they form a single differentiation series which is less variable than either the Tasmanian or the Karroo suites (Gunn, 1962, p. 860, fig. 22). However, the specimens on which Gunn's fig. 22 was based were apparently collected from a comparatively small area, and the addition of data from other parts of Antarctica reveals a much wider variation (Juckes, 1968, fig. 7).

The ages of the dolerites from the area of western Dronning Maud Land described by von Brunn (1964) are not yet known but he has tentatively correlated them with the Ferrar suite. He regarded the chemical analyses of these rocks as being comparable with those of "magma types from other tholeiitic provinces"; unfortunately, the marked differences in the SiO_2, MgO, CaO and K_2O contents between these dolerites and those from southern Victoria Land are obscured by transcription errors in some of these constituents in analysis 6 (von Brunn, 1964, table 1) if, as seems likely, this has been taken from analysis A, table 13 (Gunn, 1962).

The ages of the south Victoria Land dolerites range from 147 to 163 m. yr. (McDougall, 1963). So far, three age determinations have been done on basic rocks from this part of Dronning Maud Land. Rex (1967) has reported ages of 168 and 172 m. yr. for two specimens of dolerite from Vestfjella, and a specimen of basalt from Bjørnnutane (Z.372.1) has an age of 174 ± 7 m. yr. (personal communication from Dr. J. C. Briden). Whether these slight differences are significant can only be established by further age determinations, but there could well be a broad correlation between age and chemical composition in the Ferrar dolerites.

Certain of the chemical peculiarities of the basalts from north-east Heimefrontfjella and Sembberget may have some bearing on the origin of the magma; the restricted compositional range and the unusual K/Rb and K/Ba ratios have already been cited as possible evidence that this magma has undergone very little modification. The plagioclase phenocrysts which are present in most specimens indicate that there was some degree of crystallization of the magma during its ascent but because of the chemical evidence it is believed that crystallization was responsible for little if any fractionation of the ascending magma column.

High K/Rb ratios are not unusual in rocks with a low potassium content (Gast, 1965) and from a study of such rocks Gast inferred that they could be derived from a source in the upper mantle with a K/Rb ratio of 1,500 or more. In the opinion of Taylor (1965), most normal magmatic processes cause enrichment of Rb relative to K. Therefore, these basalts may be very close in composition to the parental magma when it formed in depth, probably in the upper mantle (Engel and Engel, 1964; Gast, 1965; Gunn, 1965) and possibly by partial melting.

IX. SUMMARY AND CONCLUSIONS

THE geology of the Basement Complex of north-east Heimefrontfjella is consistent with the pattern for Dronning Maud Land which has been established from the descriptions of the gneisses and schists of southern Heimefrontfjella (Worsfold, 1967*b*), the wide range of assemblages formed by regional metamorphism in the area near Jutulstraumen (Roots, 1953) and the high-grade gneisses and migmatites of the Sør-Rondane (Van Autenboer and others, 1964). The grade of regional metamorphism in parts of north-east Heimefrontfjella seems to be slightly lower than in the other areas, but this could be partly a result of the extensive retrograde metamorphism. The more detailed correlation with the Basement Complex of southern Heimefrontfjella (Worsfold, 1967*b*) is good and some of the rock units described

X. ACKNOWLEDGEMENTS

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Thanks are due to Professor F. W. Shotton for providing laboratory facilities in the Department of Geology, University of Birmingham, and to Dr. R. J. Adie for his careful supervision during the preparation of this report. I am also grateful to my colleagues at the University of Birmingham for much helpful discussion and criticism.

Dr. E. P. Plumstead, University of the Witwatersrand, who examined the plant fossils, kindly provided preliminary information concerning their approximate age. Thanks are also due to Dr. J. C. Briden for carrying out the palaeomagnetic and isotopic age determinations, and to Drs. J. Tarney and G. L. Hendry for their patient guidance in geochemical and X-ray fluorescence techniques.

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APPENDIX

X-RAY DIFFRACTION DATA ON THAUMASITE FROM SEMBBERGET

The *d*-spacings and peak intensities for the 21 peaks with an intensity of 15 or more (an intensity of 100 being assigned to the largest peak) for specimen Z.350.7A from Sembberget (p. 32) are given in Table VIII. Cu Kα radiation was used, the diffractometer scanning speed was 2° 2θ/min. and the time constant was 1 sec. This scanning speed is too fast for very accurate location of peaks, although it is adequate for identification purposes.

TABLE VIII

X-RAY DIFFRACTION DATA FOR SPECIMEN Z.350.7A

d	*I*	*d*	*I*
9·61*	100	2·71*	40
7·53†	60	2·57*	20
5·54*	80	2·50*	30
4·86*	15	2·19	15
4·55*	15	2·16	30
4·27†	50	2·14*	25
3·79†	50	2·11	15
3·52*	20	2·09*	15
3·40*	45	1·91†	20
3·17*	30	1·81†	20
3·06†	50		

*Peaks correlated with those on A.S.T.M. card 2–0061 (thaumasite).
†Peaks correlated with those on A.S.T.M. card 6–0046 (gypsum).

The peaks attributed to gypsum include six of the eight largest ones given for gypsum on A.S.T.M. card 6–0046. The other two gypsum peaks are present but their intensity is less than 15.

All but three of the remaining peaks coincide with those of thaumasite (A.S.T.M. card 2–0061), including ten of the eleven largest peaks. The other peak is present but its intensity is less than 15. This and other discrepancies in peak intensity, and the apparent absence of one smaller but significant peak given on the A.S.T.M. card, are probably caused by the high degree of preferred orientation which would result from the fibrous nature of the specimen.

by Worsfold continue into north-east Heimefrontfjella, although the detailed sub-division used by Worsfold has not been applied.

There does not seem to be any systematic variation in the grade of metamorphism from west to east along these mountain ranges, although the occurrence of rocks from deeper levels nearer the coast in other parts of eastern Antarctica (Voronov, 1964) is comparable with the relationship between Heimefrontfjella and Mannefallknausane (Juckes, 1968).

The post-Permian stratigraphy of north-east Heimefrontfjella provides information which not only contributes to the understanding of the geological history of eastern Antarctica but also has considerable relevance to the theory of continental drift.

The discovery of the *Glossopteris* flora in the sediments at locality "A" is important in that it establishes the extension of the Beacon Supergroup into Dronning Maud Land. Sediments exposed farther to the east in western Dronning Maud Land have sometimes been correlated with the Beacon Supergroup (e.g. Gunn, 1963), but in his original description Roots (1953) declined to suggest a possible age in the absence of any evidence. Further details of the stratigraphy were given by Reece (1958) who made no suggestions regarding the age, although he did not contradict their correlation with the Beacon Supergroup (King, 1958). Neethling (1964), who re-visited the area worked by Roots and Reece, deferred any definite correlation, but he noted the similarity to certain pre-Beacon sequences for which Klimov and others (1964) have suggested a late Precambrian age. Certainly these sediments are lithologically different from those of north-east Heimefrontfjella, largely as a result of the mild metamorphism which they have undergone.

Plumstead (1962) has discussed the relevance of palaeobotanical evidence to continental drift with particular reference to the *Glossopteris* flora. The full significance of the specimens from locality "A" will not be known until they have been fully described, although a preliminary examination has shown that they belong to the lowest *Glossopteris* horizon yet discovered in Antarctica (personal communication from Dr. E. P. Plumstead).

The late Palaeozoic to Mesozoic sequences in the other southern continents are either intruded by or overlain by Jurassic dolerites or basalts (King, 1958). From his reconstruction of Gondwanaland, King in fact predicted that an extension of the Jurassic basalts and the associated intrusive phases of the eastern coast of southern Africa should be sought in Dronning Maud Land.

The possibility that the silica content of the Jurassic basic magma varied across Antarctica was probably first suggested by Hamilton (1965), who noted that this could be equated with a tendency for the composition of the magma to approach that of the adjacent magma suite (Tasmanian or Karroo) on the reconstructions of Gondwanaland. The lower silica content of the basalts from Dronning Maud Land has been confirmed, although direct comparison with the vast and complex Karroo suite would be difficult. Comparison with the composition of the average Karroo magma, as suggested by Hamilton (1965, table 3, column 10), shows that this has a higher silica content than the basalts from Dronning Maud Land and therefore, if these two areas were once adjacent parts of a supercontinent, the regional variations in the silica content of the Jurassic magma were more complex than a simple progressive decrease.

It seems probable that the Jurassic magma of western Dronning Maud Land underwent very little modification during its ascent, probably from the upper mantle. If this is so, the higher silica and potash contents in Victoria Land could have been caused by fractionation or contamination of the ascending column of magma. Alternatively, it is possible that the magma in that area was generated under slightly different physical or chemical conditions and that it had a different initial composition.

Blundell (Stephenson, 1966) has shown by palaeomagnetic measurements that the Jurassic palaeomagnetic poles of the southern continents and India do not coincide, and this has been assumed to be evidence supporting the theory of continental drift. However, the south pole deduced from measurements on Jurassic igneous rocks from different parts of Antarctica do coincide (Stephenson, 1966, map 6) and the south pole deduced from the Jurassic basaltic lavas of north-east Heimefrontfjella is in agreement with these (personal communication from Dr. J. C. Briden). The fact that these positions of the Jurassic south pole agree despite the distance of 3,000 km. which separates Heimefrontfjella from some of the localities in Victoria Land for which data are available makes it extremely difficult to explain the discrepancies between individual continents without invoking relative movement between them.

PLATES

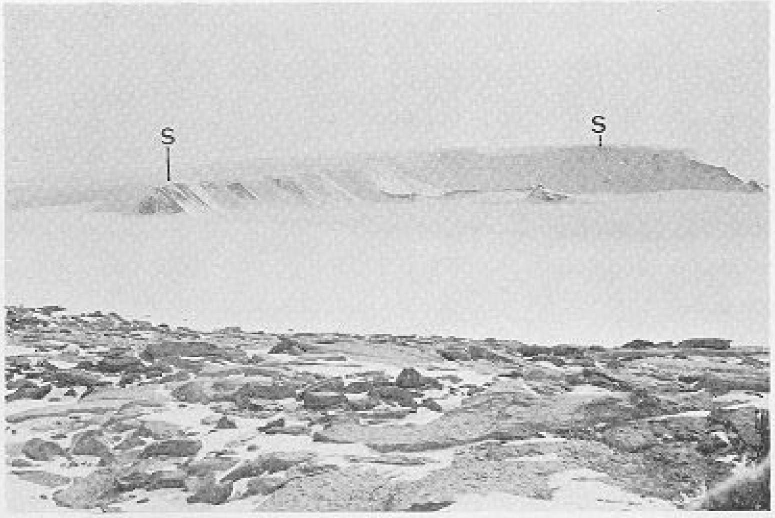
PLATE I

a. A view from Storsveenfjellet showing the north-eastern scarp of Sivorgfjella. Sediments (S) are exposed at the top of Lidkvarvet (left) and south of Berggravrista.

b. A view of part of Milorgfjella looking east, showing Waglenabben beyond the end of Laudalkammen.

c. Moraines with ice-filled depressions north-west of Schivestolen. The moraines disappear beneath the snow cover in the distance.

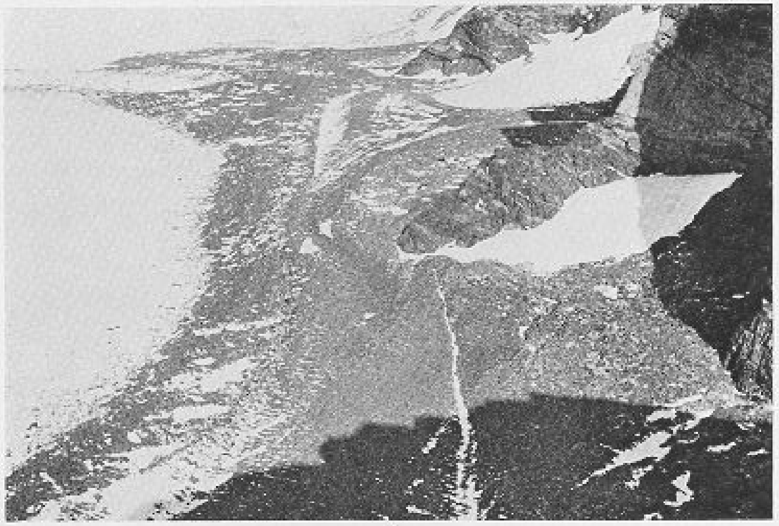
d. A view south-eastwards into Buråsbotnen showing the lateral moraines with transverse ridges north-east of Schivestolen. The light-coloured area at the extreme left is blue ice.



a

b

c



d

PLATE I

PLATE II

a. A standing stone in a line of moraine on the blue ice south-west of Schivestolen.

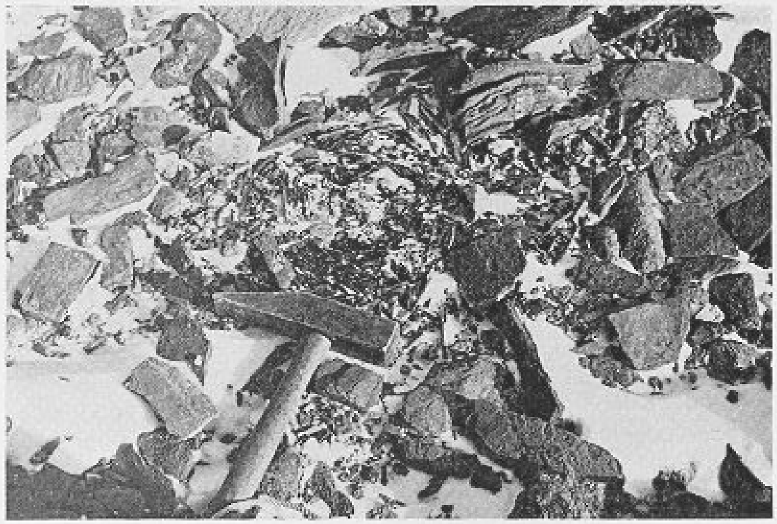
b. Debris-lined terrace below the north-west face of Sembberget.

c. Patterned ground; a sorted circle at locality "A". The hammer head is 20 cm. long.

d. A view of the main massif of Milorgfjella from the west, showing the steep ridges. The gently dipping sediments capping Schivestolen are intruded by a dolerite sill (d) which is visible as a dark line.

a

b



c

d

PLATE II

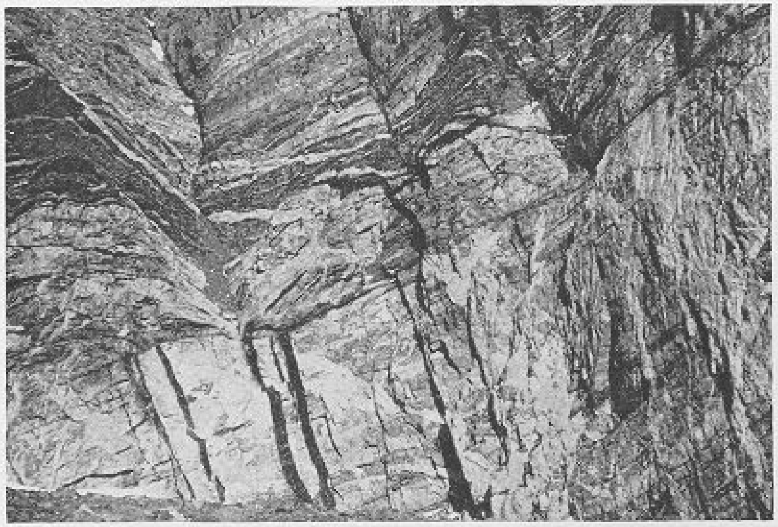
PLATE III

a. Biotite-gneisses of the main massif of Milorgfjella intruded by acid dykes and younger basic dykes at station Z.348. The largest basic dyke is 3 m. wide; these dykes have been truncated by a thrust approximately parallel to the foliation of the gneisses.

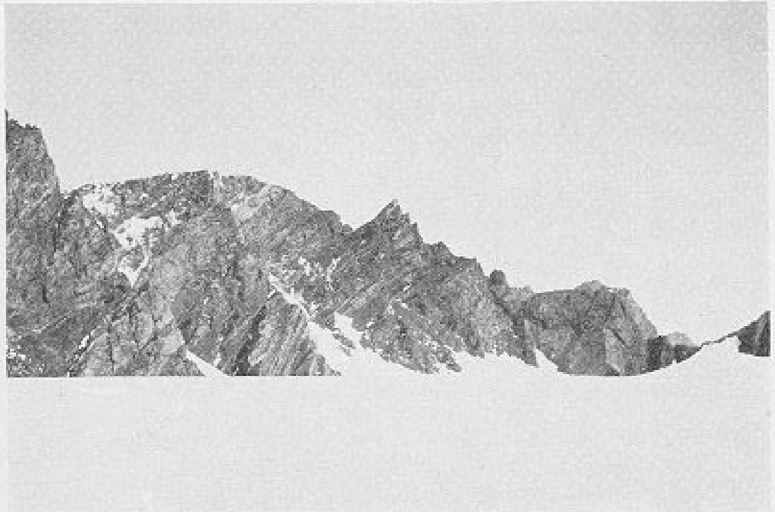
b. A view of Laudalkammen from the north-east showing the tectonic contact between the granite (right) and the sheared gneisses. The mylonitic rocks near the contact have been deformed by drag folding. The peak near the centre of the photograph is about 200 m. high.

c. Bands of amphibolite with a total thickness of about 20 m. aligned along a fault zone at station Z.316. The southern side (left) has been downthrown.

d. A view south-west towards locality "A" (just above the top of letter A) and Schivestolen. The sediments in the middle distance reproduce the gently undulating topography of the underlying erosion surface. The thickness of the sediments is about 5 m. and the rocks in the foreground are Basement Complex gneisses.



a



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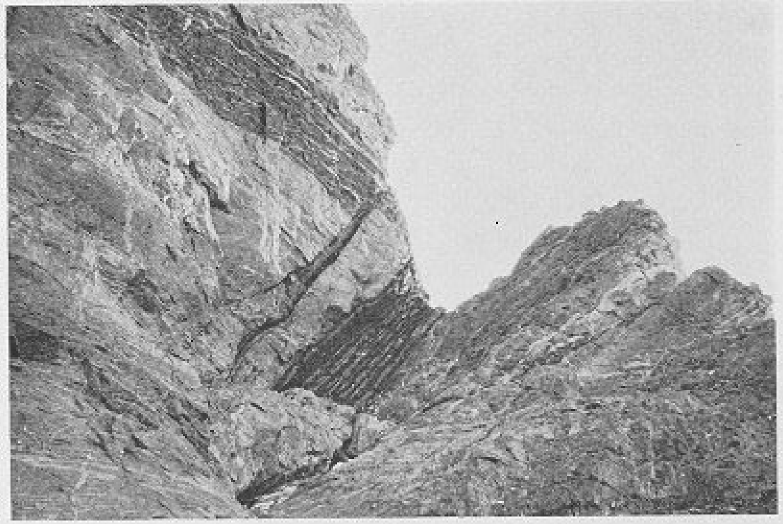


c

d

PLATE III

PLATE IV

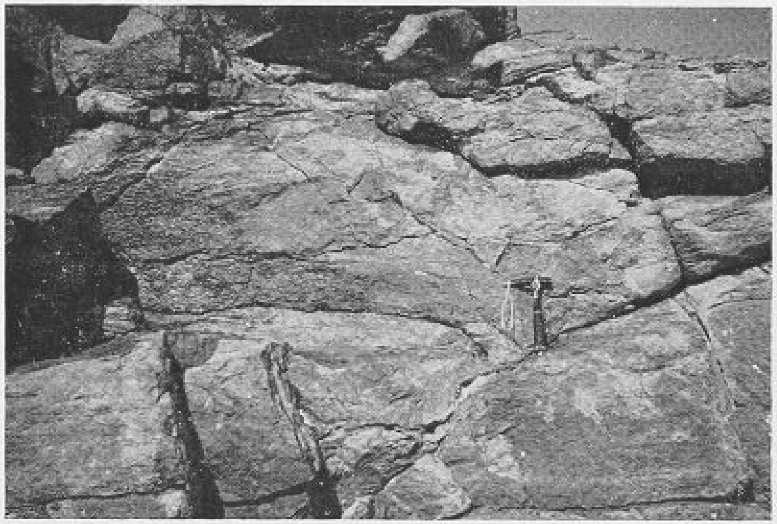
a. Gneissic granite (right) intruding porphyroblastic biotite-gneisses at station Z.312. The hammer shaft is 32 cm. long.

b. Granitic and pegmatitic veins cutting biotite-gneisses and amphibolites near station Z.348. The cleft is occupied by a sheared basic dyke 10 m. wide.

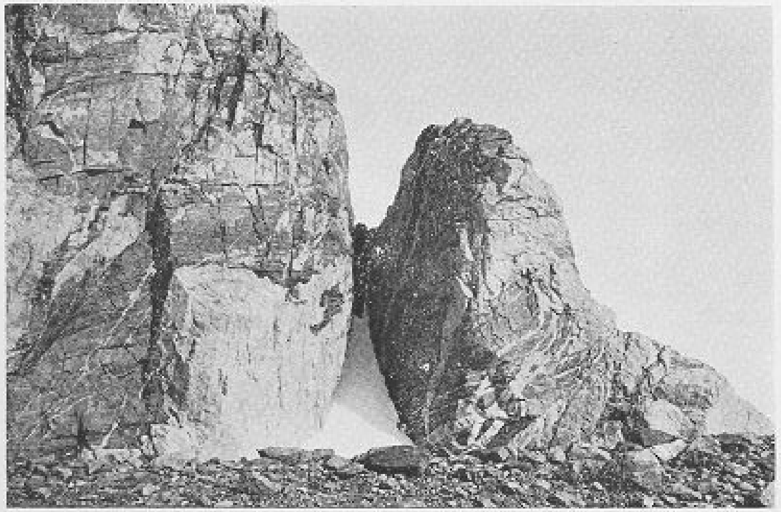
c. Pegmatitic veins, containing coarse books of biotite, cutting biotite-gneisses and amphibolites at station Z.348. The hammer shaft is 38 cm. long.

d. Small folds in *para*gneisses at station Z.377. The height of the exposure in the photograph is about 4 m.

PLATE IV



a



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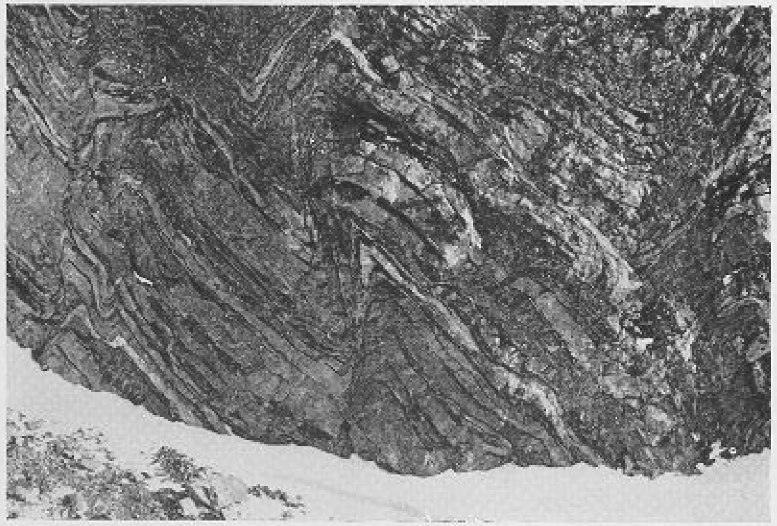


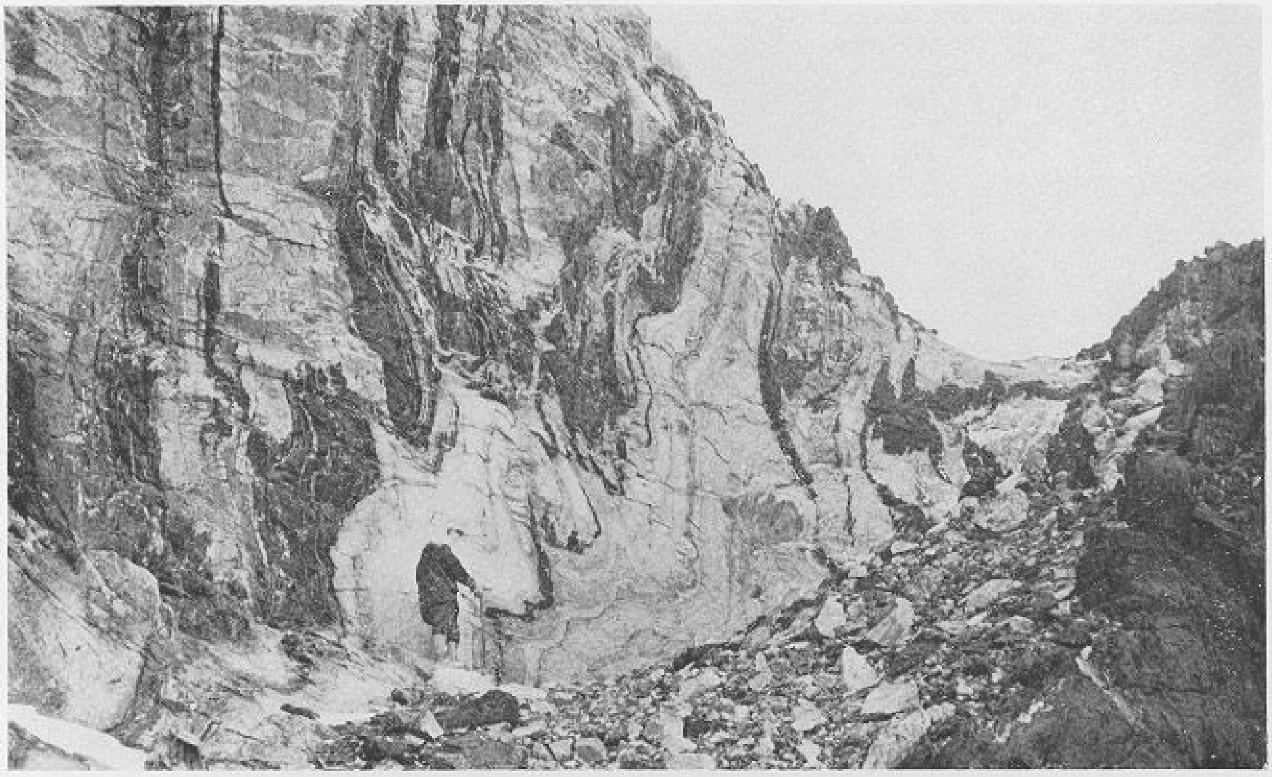
d

PLATE V

a. Contorted marble bands (the light bands behind and to the right of the figure) in *para*gneisses and amphibolites at Hauglandkleppen.

b. The margin of a metamorphosed basic dyke at station Z.375, showing its slightly transgressive relationship to the adjacent gneisses. About 3 m. of the contact is shown in the photograph.

c. Fractured blocks of amphibolite in hornblende-biotite-gneiss which has undergone plastic deformation; Waglenabben. The hammer head is 12 cm. long.



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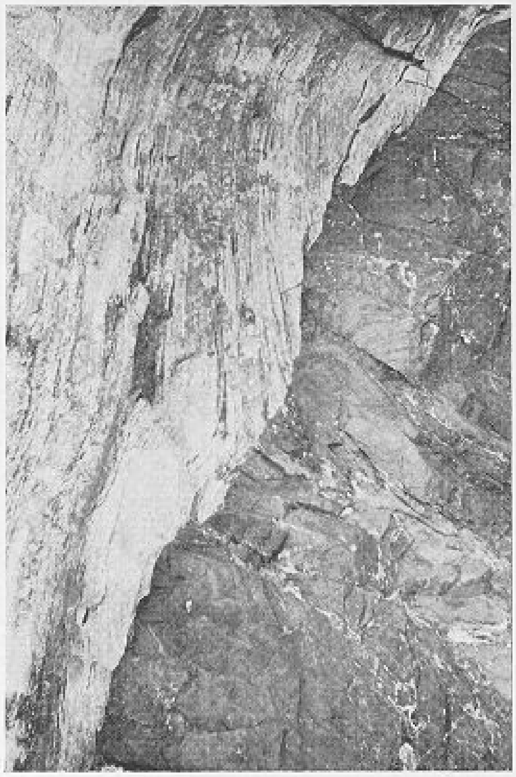

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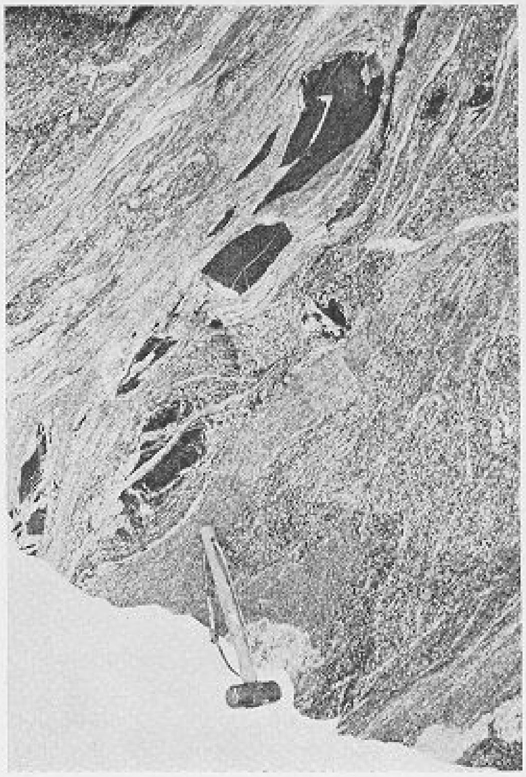

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PLATE VI

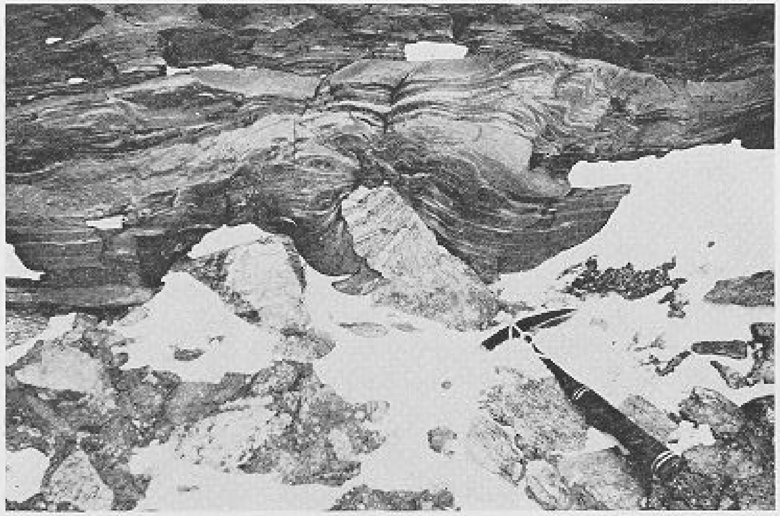
a. Tightly packed basal conglomerates overlain by fine-bedded sandstones at station Z.353. The small outcrop of sandstone within the conglomerates (right) is about 2 m. thick.

b. Differential compaction of sediments of the middle unit over boulders of gneiss in the irregular upper surface of the basal conglomerates at station Z.353. The hammer shaft is 32 cm. long.

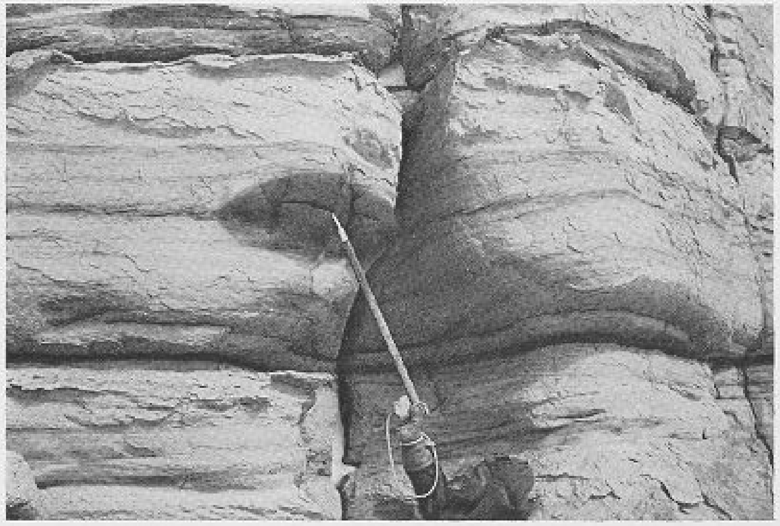
c. Siderite concretion in cross-bedded sandstones of the upper unit at Schivestolen.

d. Coal seam in siltstones of the upper unit; Schivestolen. The hammer head is 20 cm. long.

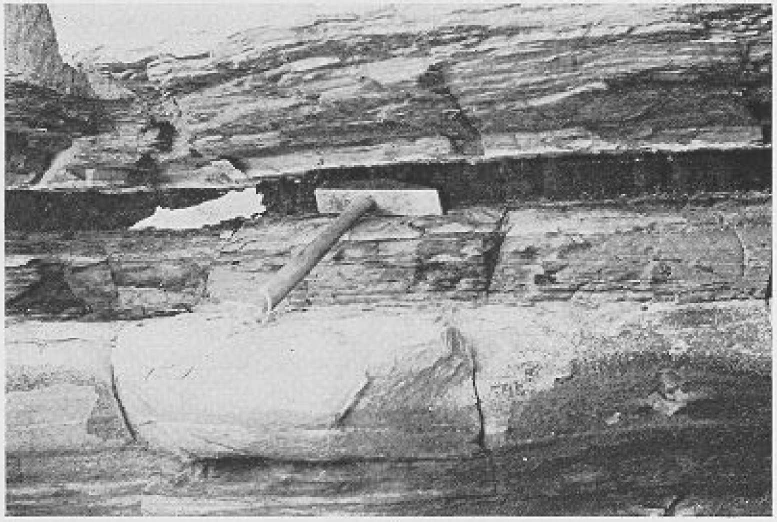
a



b



c



d

PLATE VI

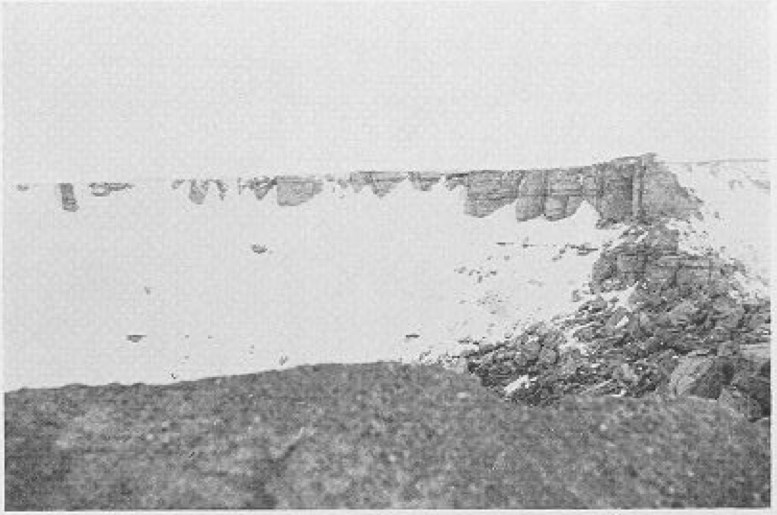
PLATE VII

a. A view south-east from the summit of Schivestolen showing the sandstones of the upper unit.

b. Bed of sandstone about 1·5 m. thick at the top of the succession at locality "A". Fine dark siltstones are exposed amongst the rubble in the foreground.

c. Boulder in the conglomerates at locality "B".

d. Tightly packed conglomerates at locality "B". The hammer shaft is 38 cm. long.



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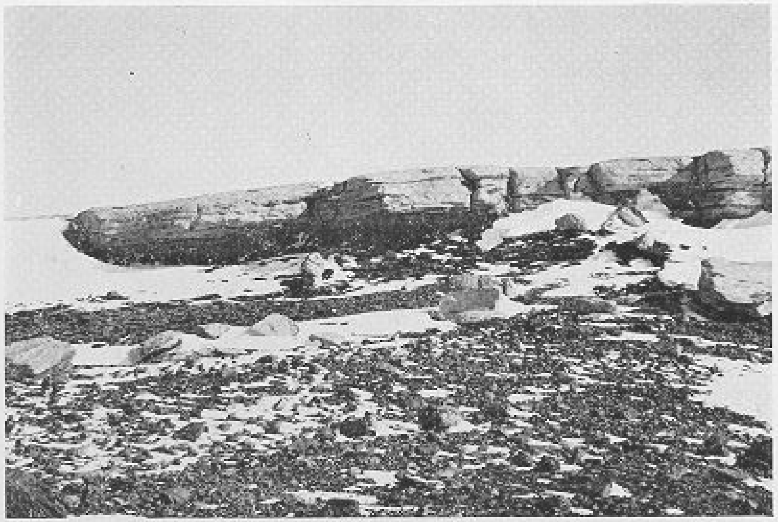

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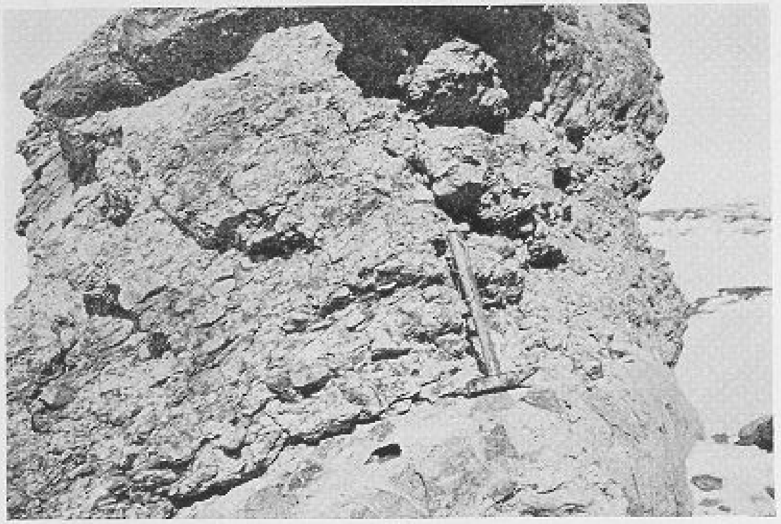

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PLATE VII

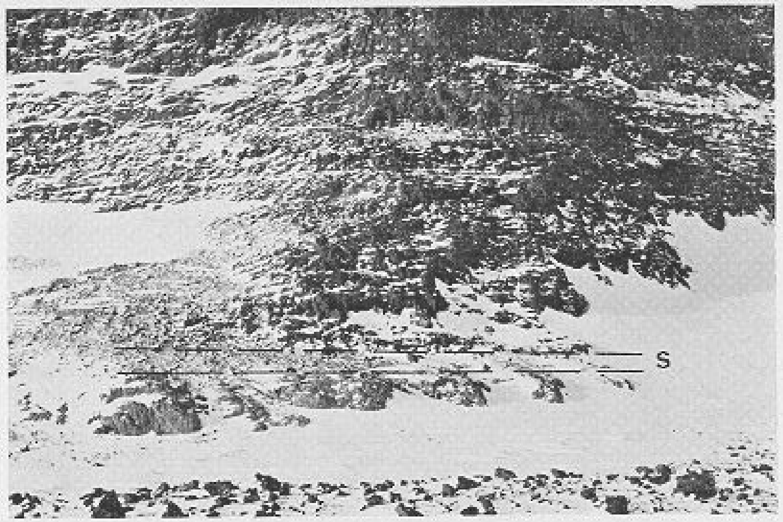
PLATE VIII

a. The base of the sequence of basalt flows at Bjørnnutane. The lighter outcrops at the base of the exposure are of Basement Complex gneisses and the outcrop at the lower left is about 3 m. high. Small outcrops of sandstone (S) are present on the scree- and snow-covered slope separating the basalts from the gneisses.

b. *Roche moutonnée* of pegmatite with loose sandstone blocks on the right; locality "B". The hammer shaft is 38 cm. long.

c. A view of Sembberget from the west, showing the horizontal stratification of the basalt flows. The nunatak is about 300 m. high.

d. Branching dolerite sill with columnar jointing in the sediments at station Z.353. The upper branch is 1 m. thick.



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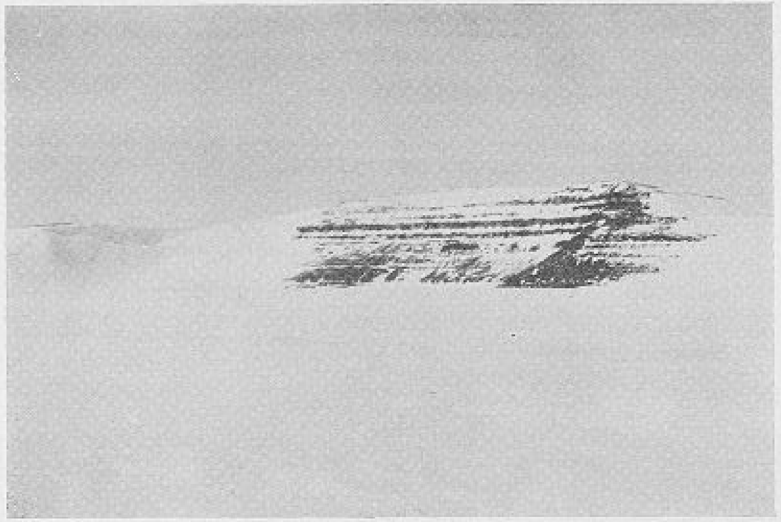

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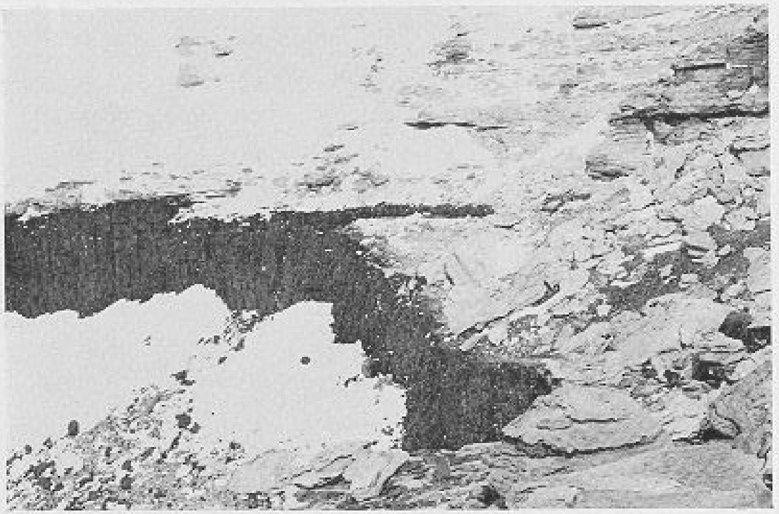

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PLATE VIII

PLATE IX

a. A metamorphosed dolerite composed of plagioclase and augite mantled by hornblende. Ilmenite and garnet (G) are also present (Z.375.5; ordinary light; × 60).

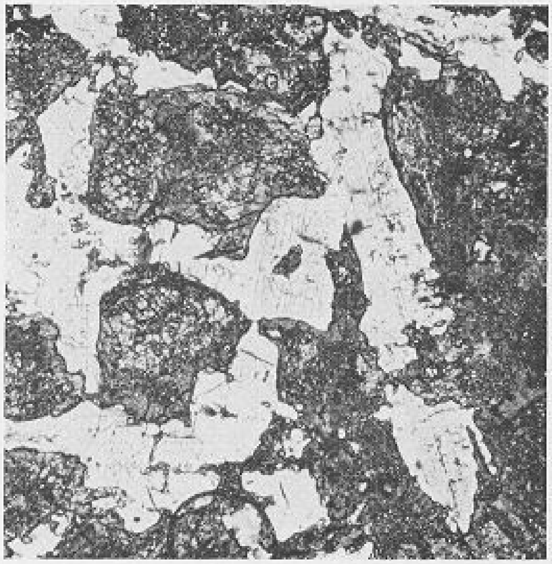
b. Recrystallized amphibolite consisting of hornblende, plagioclase, quartz, sphene and possibly rutile. The original igneous texture has been completely destroyed (Z.375.3; ordinary light; × 60).

c. Sheared and recrystallized quartz alongside a porphyroclast of microcline in a highly sheared gneiss (Z.339 2; X-nicols; × 150).

d. Porphyroclasts of plagioclase and potash feldspar set in a matrix of fine recrystallized quartz in a mylonitic rock (Z.337.1; X-nicols; × 150).

e. Deformed plagioclase with albite twinning in a gneissic granite from Laudalkammen (Z.332.2; X-nicols; × 60).

f. A pseudomorph of quartz and calcite, probably after olivine, in the chilled margin of a basic dyke 1 m. wide (Z.313.7; ordinary light; × 150).



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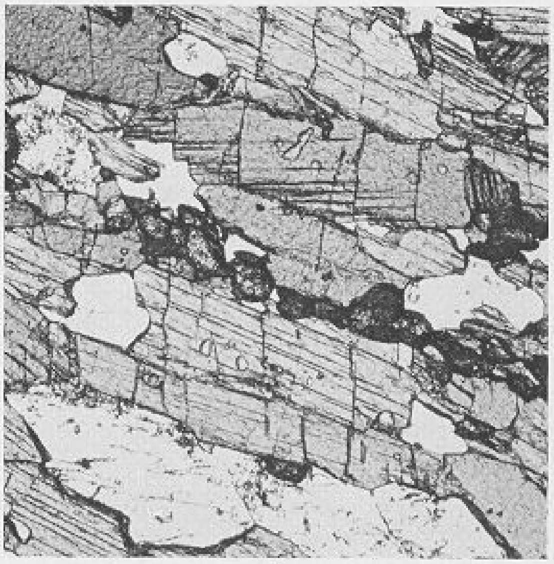

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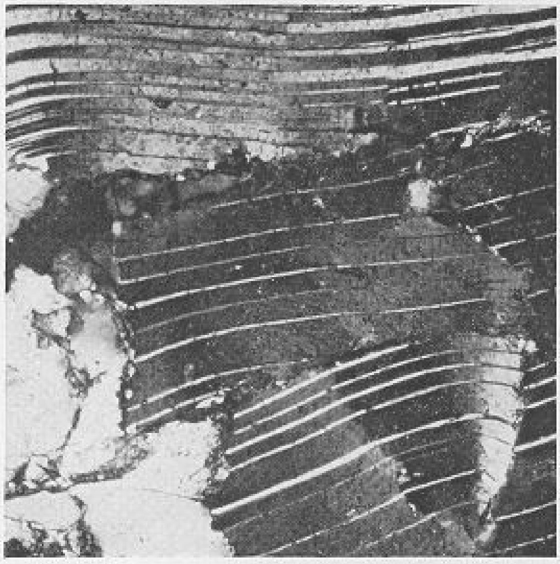

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PLATE X

a. A micaceous sandstone showing a detrital biotite flake bent and crushed between grains of quartz and feldspar. The interstitial matrix consists largely of biotite (Z.353.2; ordinary light; × 150).

b. (?) Plant matter in a sandstone which contains plant macro-fossils (Z.393.12; ordinary light; × 150).

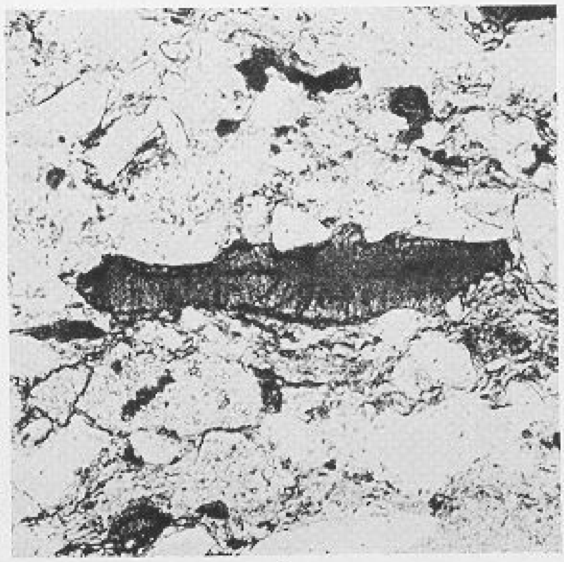
c. The texture of a well-sorted sandstone about 3 m. from the base of the succession at locality "A" (Z.393.12; X-nicols; × 150).

d. Partly fused sandstone collected 5 cm. from the margin of a dolerite sill. The grains are of quartz, and the acicular fringes are probably tridymite which has inverted to quartz (Z.353.9; ordinary light; × 150).

e. Plagioclase phenocrysts in a basalt from Bjørnnutane. The mineral with a high relief is clinopyroxene and the dark patch to the right of centre is glass (Z.308.4; X-nicols; × 55).

f. A dolerite from Schivestolen showing the granular texture and plagioclase phenocrysts. The mineral with a high relief is clinopyroxene (Z.353.7; X-nicols; × 55).

a



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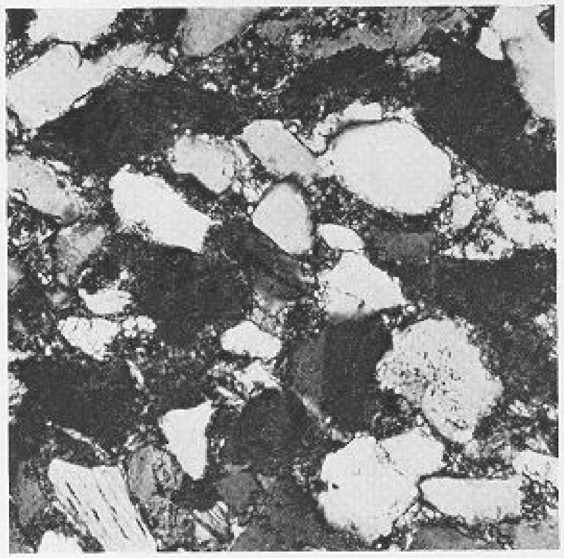

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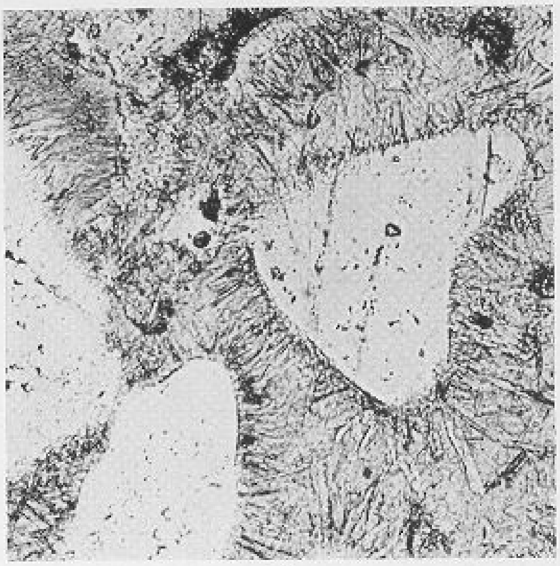

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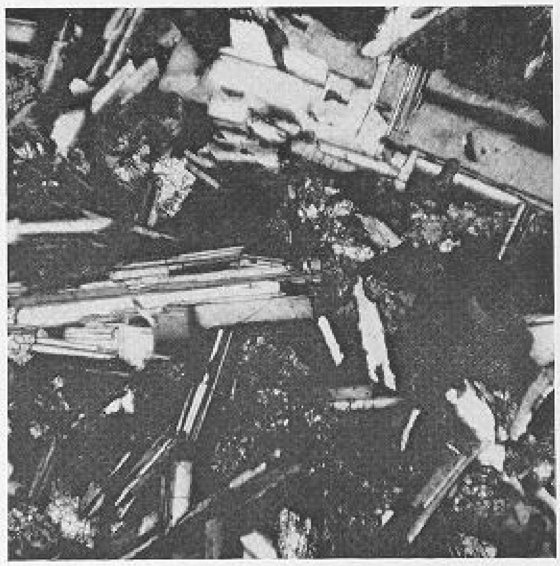

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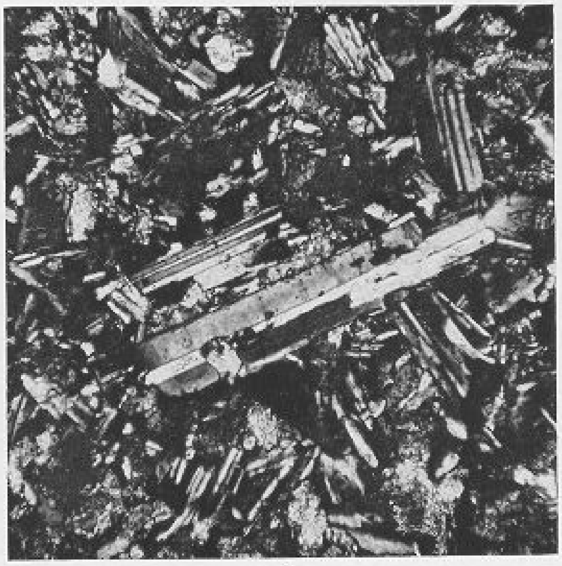

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