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RODNEY A. GAYER AND ROGER H. WALLIS

THE PETROLOGY OF THE HARKERBREEN GROUP OF THE LOWER HECLA HOEK OF NY FRIESLAND AND OLAV V LAND, SPITSBERGEN

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Contents

Abstract

Petrographic descriptions of metamorphic lithologies of the five recently erected formations of the Harkerbreen group are given. The nature of their sedimentary origin is discussed and it is concluded that deposition occurred in a large shallow water basin – at times possibly intertidal – with the accumulation of predominantly fine to medium grained material. Two thin but widespread tilloid horizons in the Rittervatnet formation are described. A large proportion of the detritus is either acid and basic tuff and agglomerate or reworked acid volcanic material. Facies changes seem to indicate an east–west variation parallel to subsequent fold axes.

Introduction

During the summers of 1961, 1962 and 1963, one of us (R.A.G.) worked in the Mosselbukta/Femmilsjøen region of northwest Ny Friesland, and later, during the summers of 1964 and 1965, the other (R. H. W.) investigated the northern portion of the peninsula in Mosselhalvøya and sections through the western belt farther south in Ny Friesland and Olav V Land (Fig. 1). The information arising from these studies, together with that from the continuing work of W. B. HARLAND, has been incorporated in a reappraisal of Lower Hecla Hoek stratigraphy (HARLAND, WALLIS and GAYER 1966; and Fig. 2).

The Harkerbreen group as defined in HARLAND *et al.* (1966) outcrops on each side of the north-south Atomfjella Dome (HARLAND, 1959) in south Ny Friesland (Fig. 1). The easterly succession passes conformably upwards through the Planetfjella Group to unmetamorphosed Middle Hecla Hoek. The principal area of new work is well to the north of the area where the Hecla Hoek stratigraphical scheme was formulated (e. g. HARLAND and WILSON 1956; BAYLY 1957; HARLAND 1959; and Fig. 1). The continuation of the Atomfjella Dome can be recognised in the north, but here, due to the northward plunge of the dome axis, the base of the Harkerbreen group does not outcrop and the east and west successions coalesce across the axis. A tectonic break beneath the Planetfjella group cuts out the higher divisions of the Harkerbreen group in the east, whilst they are lost beneath Wijdefjorden in the west. Thus only in the least accessible and currently the least known area, east of the Atomfjella Dome in south Ny Friesland, is a complete sequence through the group found and even here exposures are confined to discontinuous glacier walls and isolated nunataks. The authors have not worked here (see Fig. 1), but descriptions of the Tordenryggen and Bleikfjellet formations can be found in HARLAND *et al.* (1966) and BAYLY (1957).

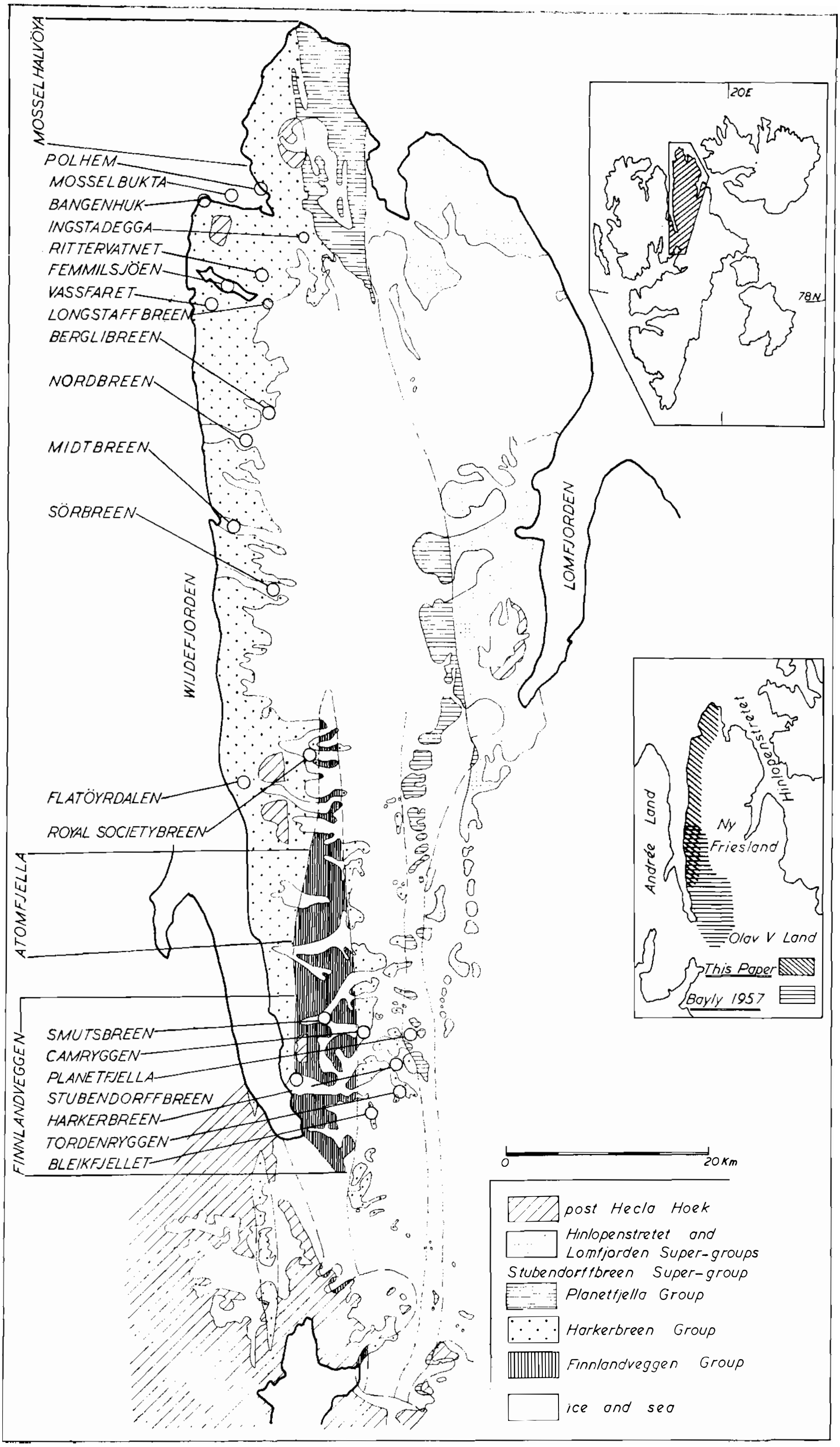

Fig. 1. *Diagrammatic map to show areas of outcrop of Harkerbreen group from* HARLAND, WALLIS *and* GAYER *(1966). Lower inset shows areas of rocks described in* BAYLY *(1957) and in this paper.*

The generally good exposures along the west coast of Ny Friesland and across the Mosselbukta/Femmilsjøen and Mosselhalvøya regions allow for more detailed study, and indeed the earliest recorded geological observations of these rocks were made in Mosselhalvøya and along the west coast of Wijdefjorden by BLOMSTRAND (1864). Although the general position of these rocks in their Lower Hecla Hoek framework has been outlined in HARLAND *et al.* (1966), a more detailed petrological account is required both to amplify this work and to lead to a more detailed picture of Lower Hecla Hoek deposition.

This paper is thus one of a series dealing with Hecla Hoek petrology; the Planetfjella group (WALLIS, in prep.) and the Middle and Upper Hecla Hoek (WILSON, 1958 and 1961; GOBBETT and WILSON, 1960; and WILSON and HARLAND, 1964).

It is difficult to give a petrological account of the rocks without some reference to structure. The rocks are highly folded about N–S axes (HARLAND 1959) and where detailed observations have been made in the Femmilsjøen region a complex history of folding has been found. A structural analysis of this region is in preparation.

These folds affect the present work in three ways. Firstly, although breaking the continuity of possible exposure across the strike, they produce an intermittent outcrop, in the fold limbs, of sections within a horizon which would otherwise have been further apart. Secondly, the E–W shortening is accommodated by both limited vertical and marked N–S extension. Thus any original distribution of facies will, after deformation, give the impression of N–S constancy and E–W variation. Thirdly, the assessment of thickness is made very difficult and the estimates given in this paper have been derived from the outcrop widths of the units by careful inspection of the styles of folds which have affected the unit.

The nomenclature of metamorphic rocks used in this paper is that formulated in WALLIS *et al.* (in press, submitted for publication before preparation of this paper) for Spitsbergen metamorphics in general. The scheme used is given below in outline:

Common metamorphic minerals are placed in five groups as follows:

1) Quartz group; 2) "Mica" group (andalusite, chlorites, chloritoid, cordierite, garnet, kyanite, micas, sillimanite, staurolite; 3) Feldspar group; 4) "Pyrobole" group (amphiboles, epidotes, pyroxenes); 5) Carbonate group.

The percentage of these groups defines the following rock classes:

Quartzite and Hornblendite contain $>80\%$ quartz and hornblende respectively. Psammite and Amphibolite contain $>50\%$ to 80% quartz and pyrobole respectively. Pelite, Feldspathite and Marble contain $>50\%$ of mica group, feldspar and carbonate respectively. Subpsammite, Subpelite, Subfeldspathite, Subamphibolite, Submarble contain $>35\%$ to 50% of their mineral groups. Polymictite contains not more than 35% of any mineral group.

The following examples show how these terms may be further qualified and appropriate terms may be substituted. Pelite-Marble indicates uncertainty as to class; Biotite-marble = marble with less than 35% mica group but conspicuous biotite; pelitic-marble = marble with $>35\%$ mica group; pelitic-submarble =

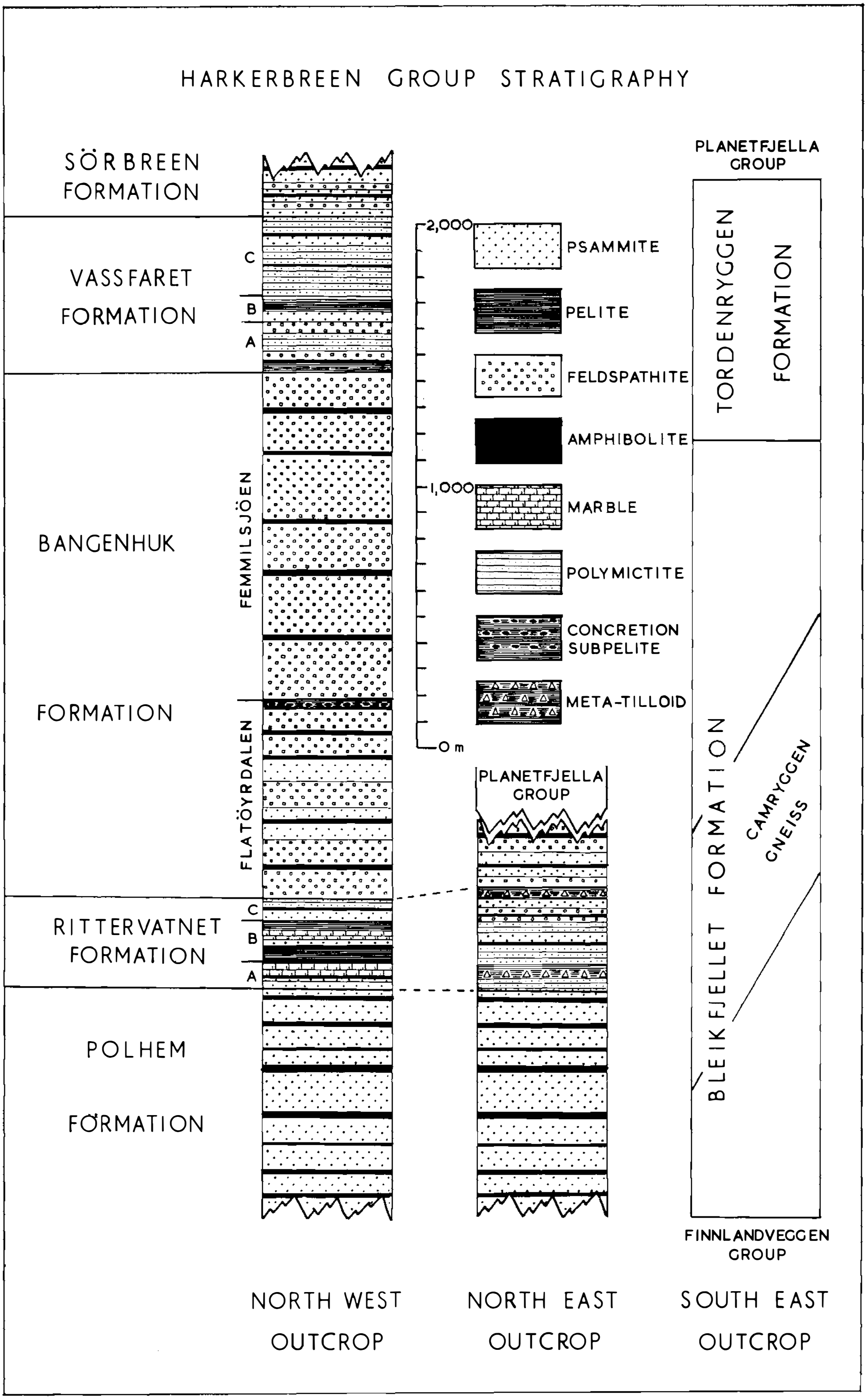

Fig. 2. *Diagrammatic stratigraphical column of the Harkerbreen group. North west refers to sections about Bangenhuk and the coast of Wijdefjorden; North east refers to Ingstadegga; South east refers to sections east of Finnlandveggen, see Fig. 1, page 6.*

submarble with >35% subordinate mica group; subpelitic-submarble = equal amounts of mica and carbonate groups, between 35% and 50%; biotitic-calcitic polymictite indicates conspicuous minerals, with no mineral group exceeding 35%.

Modal analyses of typical Harkerbreen group lithologies are given in Table I (p. 31), which uses the nomenclature outlined above.

Systematic stratigraphical description

THE SØRBREEN FORMATION (265+m)

The type locality of the formation (see Fig. 1) is in the raised wave cut platform at the mouth of Sørbreen. The formation is well exposed both to the north and south along the coast of Wijdefjorden and here individual bands can be traced for considerable distances along the strike. The formation has not been located east of the Atomfjella Dome and, in places where we have observed the eastern succession in north Ny Friesland, the junction between the Harkerbreen group and the overlying Planetfjella group is tectonic, with both the Sørbreen and Vassfaret formations and also part of the underlying Bangenhuk formation missing. In the west the upper part of the Sørbreen formation and the junction with the Planetfjella group are thought to lie beneath Wijdefjorden. The maximum thickness exposed, measured just south of Vassfaret, is 265 m.

The formation consists mainly of psammites and quartzites with thin interbanded quartzose-polymictites, foliated amphibolites and meta-acid-tuffs.

The psammites vary considerably in composition and fabric. All contain an appreciable amount of plagioclase feldspar of albite-oligoclase composition, comprising from 12 to 32% of the rock. Some contain up to 20% of potash-feldspar but this is generally less than 10%. Hornblende, epidote, biotite and muscovite are generally present but in amounts less than 10%. Accessories include iron-ore, sphene and zircon, with occasional apatite.

All types are more or less foliated. In some cases, particularly in those containing significant amounts of potash-feldspar or biotite, the foliation is well developed and gives rise to a flow cleavage with small mica crystals aligned parallel to the cleavage surfaces. Where flow cleavage is developed the surfaces always show a crenulation lineation. In most cases the foliation is due to compositional banding with variation in the proportions of epidote, biotite and hornblende. These rocks are poorly fissile and the fabric is more or less granular with sutured quartz grains and a rough alignment of biotite, epidote and hornblende crystals parallel to the banding.

In a few instances the compositional banding can be shown to be an original sedimentary feature of the rocks, since the banding picks out cross-bedding.

Individual beds of psammite are usually 5 to 10 m thick, being separated by thin beds of schistose quartzose-polymictites, schistose amphibolites or schistose meta-acid-tuff.

The quartzites are gradational in composition from the psammites and are commonly well foliated, with flattened quartz grains producing a definite cleavage. At Sørbreen these quartzites form a well defined band some 20–30 m thick and their fissility produces a characteristic debris of tile-like slabs. Similar lithologies have been recorded from the Femmilsjøen area where the thickness of the band is not so great.

The meta-tuff is a dark grey, fine-grained potash-feldspar-quartz-biotite-polymictite with a well developed foliated fabric producing a true cleavage. This cleavage is deformed by a marked crenulation. Set in the fine-grained groundmass are irregularly oriented, euhedral megacrysts of plagioclase, up to 5 mm in length. The foliation envelopes the megacrysts which are deformed by fractures, infilled with quartz and calcite, and oriented perpendicular to the foliation, thus extending the crystals in a direction parallel to the crenulation. The plagioclase crystals are more resistant to erosion and stand out of the groundmass on weathered surfaces.

This distinctive lithology forms a series of bands coloured pink or green by the prevalence of either potash-feldspar or plagioclase respectively. Some of the bands are repeated by folding but at least three horizons seem to be present. The thickest is c. 18 m thick and can be followed from its most northerly outcrop, in the headland just north of the Femmilsjøen outlet stream, southwards without a break for 60 km, until the outcrop runs out into Wijdefjorden between Royal Societybreen and Cookbreen.

Concordant amphibolite horizons occur throughout the whole of the Harkerbreen group and, with one or two exceptions, they are similar in character within the various formations. Thus, the following description of the Sørbreen amphibolites will serve for all the formations except where special reference is made.

The amphibolites occur as bands varying in thickness from less than 1 cm up to c. 30 m, and in all cases they are conformable with the foliation in the neighbouring lithologies. They form boudins within every other lithology, thus reflecting their greater competence.

Their mineralogy is simple. They contain 60 to 70% blue-green hornblende, the remaining 30 to 40% being made up principally of plagioclase feldspar (An 20 to 30%) with accessory but ubiquitous quartz, biotite, iron-ore, sphene and apatite. They sometimes carry megacrystic garnet, and in the potash-feldspar rich lithologies of the Vassfaret and Bangenhuk formations up to 20% potash-feldspar. They commonly show some retrogression from their amphibolite facies mineralogy with the development of tremolite from hornblende and chlorite from biotite, but this recrystallisation is largely mimetic with the retention of the oriented fabric.

The schistose fabric is shown principally by the tabular orientation of the hornblende crystals, which form a distinct lineation and a rather less noticeable foliation. In one or two bands of amphibolite in the Polhem formation the hornblende crystals are large (greater than 1 cm) and platy and thus form a perfect foliated schistosity. The plagioclase and quartz, and when present the potash-feldspar, form a mosaic in narrow lenses parallel to the foliation, with the constituent crystals oriented more or less in the direction of the hornblende lineation. In many of the finer grained amphibolites which possess a strongly foliated schistosity, the foliation is crenulated into small folds with axial surface separation of c. 1 cm.

The boundaries of the amphibolite bands with neighbouring lithologies are either very sharp or are gradational. In the second case there is a gradational increase in quartz and mica content. The two types of margin occur together in many exposures and thus would not appear to be due to metamorphic segregation or dissemination. There is no evidence of shearing or granulation at the margins of the gradational types sufficient to cause an intermingling of the two lithologies. Therefore, it seems reasonable to conclude that the variation was present prior to the deformation responsible for their present texture. The difference must thus be due either to an earlier period of deformation, for which there is no evidence, or to an original pre-deformation feature.

The bands can be followed for considerable distances along the strike and retain their individual identity in both their thickness and in their relationship to neighbouring bands.

THE VASSFARET FORMATION (600 m)

The type area of the formation is at Vassfaret, a group of small lakes just south of the western end of Femmilsjøen. (Fig. 1). The formation outcrops in a belt immediately to the east of the Sørbreen formation, the boundary being interfolded and indistinct. The maximum thickness recorded at Vassfaret is 600 m. The lithology is predominantly polymictic, although bands of psammite and feldspathite form characteristic horizons which serve to distinguish the various divisions. Concordant foliated schistose amphibolites, similar to those of the Sørbreen formation, are widespread throughout the sequence.

In the northern part of the outcrop three divisions of the formation can be recognised.

c) 320 m of predominantly quartz-biotite-polymictite with thin (1 m) interbanded foliated potash-feldspar-psammites, epidote-plagioclase-biotite-psammites and calcareous-polymictites.

The polymictites range in composition from quartz-plagioclase-polymictites through psammitic-subpelites to pelitic-subpsammites. They are fine grained rocks and show a well developed foliated schistosity due to the orientation of biotite, muscovite and epidote more or less parallel to the compositional banding. This schistosity is deformed by two sets of crenulations, the dominant set giving rise to a weak strain-slip cleavage in the more pelitic lithologies. Oligoclase and quartz form a granular mosaic between sheaths of parallel oriented minerals. The biotite usually shows mimetic recrystallisation and is frequently altered to chlorite. Thin bands of calcareous-polymictite grade from the typical semipelite with an increasing proportion of calcite; the latter is intergrown in the oligoclase/quartz mosaic. These bands are nowhere abundant.

Lenses of quartzite parallel to the schistosity are ubiquitous. They are deformed with the schistosity by folding, producing quartz rods in the hinges of the folds and lenses with sigmoidal cross sections in the crenulated limbs. Where these become abundant they give a striped appearance to the rock.

The psammites are similar to the well foliated varieties described in the Sørbreen formation.

No sedimentary structures have been recognised.

b) 40 m consisting of two distinctive lithological units; an upper calcareous-hornblende-biotite-polymictite and a lower banded epidote-psammite.

The upper lithological unit consists of a fine to medium grained schistose megacrystic calcite-garnet-hornblende-biotite-polymictite. The hornblende and garnet form large megacrysts set in a foliated groundmass. These polymictites are more pelitic than the quartzose-polymictites of divisions a) and c) and contain no bands of psammite. The hornblende megacrysts show a helicitic fabric, indicating an earlier crenulated foliation overprinted by the static growth of the megacryst. The garnet megacrysts are occasionally poikilitic when they show both helicitic and rolled fabrics.

The foliation in the groundmass is most clearly shown by the platy fabric of the micas. This foliation envelopes the megacrysts, demonstrating a later syntectonic recrystallisation. Quartz and oligoclase form a sutured mosaic; individual crystal groups being roughly aligned with the foliation.

The foliation is crenulated to form a lineation which is imperfectly developed due to the interference of the garnet and hornblende megacıysts. The biotite shows partial mimetic recrystallisation to larger grains, preserving the crenulated mica fabric and in places recrystallisation to larger disoriented grains.

Thin bands (less than 5 cm) within the unit contain a greater concentration of hornblende and approach amphibolite in composition. The plagioclase in these bands is almost completely converted to epidote with a granular fabric of small grains, and the hornblende is megacrystic and prismatic forming a fabric parallel to the lineation. The gradational contact with the polymictite and the presence of significant proportions of quartz suggest that these bands represent basic tuff horizons.

The lower lithological unit consists of a banded white and green oligoclase psammite, with bands 5 to 10 cm thick. The banding is due to an increase in the amount of hornblende and epidote. The fabric is granular with only partial orientation of the hornblende grains. The oligoclase and quartz form a sutured mosaic with sericitic clouding of the oligoclase.

The boundary between the two units is everywhere sharp, indicating an abrupt change in conditions of deposition. Very obscure signs of truncated bedding are preserved, as shown by the minor changes in composition within the polymictic unit. However, these changes most probably represent sheared limbs of small scale folds rather than original cross-bedding. The psammites are evenly bedded.

a) 240 m of a predominantly polymictic unit with highly characteristic calcite/epidote concretions. The division is also characterised by sharply defined bands of psammitic-feldspathite. There are also bands of light grey, poorly foliated psammites and foliated concordant amphibolites.

The division has sharp concordant contacts with both the overlying green and white psammites of division b) and the underlying feldspathites of the Femmilsjøen member of the Bangenhuk formation. Identical lithologies, however, occur as lenses within the upper part of the Femmilsjøen member, and between the Femmilsjøen member and the Flatøyrdalen member, in the northern part of the outcrop.

In the main outcrop of the division the rocks are strongly deformed with the partial obliteration of their original sedimentary nature. The lenses and the band within the underlying formation are far less deformed and their original sedimentary characteristics are well preserved.

The polymictites in the main outcrop are all well foliated quartzose rocks containing oligoclase, biotite, muscovite, clinozoisite and garnet. Hornblende is rare except in association with amphibolite bands and potash-feldspar has not been recorded.

The foliation is defined by the platy fabric of the micas. This is crenulated and envelopes the garnet megacrysts. The quartz and oligoclase form a mosaic only roughly aligned to the foliation.

Characteristic of the division are bands of psammitic-feldspathite. These are fine to medium grained, poorly foliated granular rocks. Megacrysts of pink potash-feldspar, showing microcline twinning, are set in a pink groundmass which has fine bands of dark mineral concentrations. The groundmass consists of a fine grained, sutured mosaic of oligoclase, potash-feldspar and quartz, with blue-green hornblende and biotite grains forming a platy fabric. Sphene, epidote and apatite are constant accessories.

The feldspathite bands are 20 to 30 m thick and have extremely sharp contacts with the surrounding lithologies.

Poorly foliated epidote-biotite-oligoclase-psammites occur as sharply defined bands, 10 to 20 m thick, in the polymictites. The fabric is granular with sutured grain boundaries between the quartz and plagioclase. The biotite and epidote

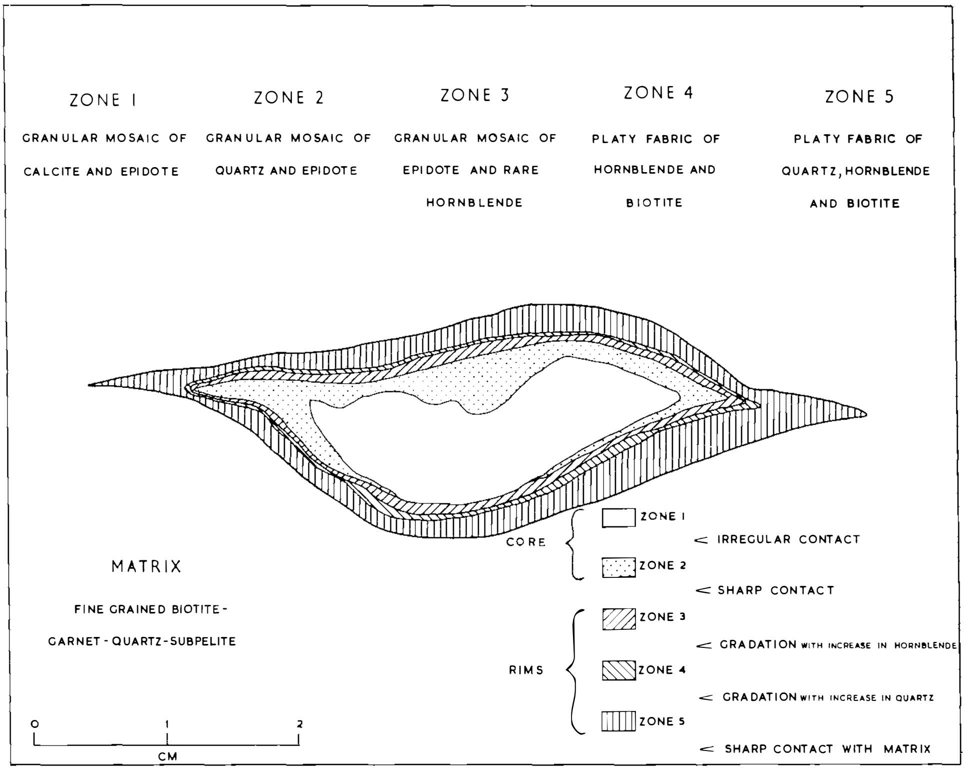

Fig. 3. *Diagrammatic cross-sectional structure of an epidote-calcite nodule of the Vassfaret and Bangenhuk formations.*

show only rough parallel orientation. The foliation is due to compositional banding, with variation in epidote, and the presence of bands containing hornblende, which in some cases reach amphibolite in composition. Where hornblende becomes conspicuous the rock has more definite foliation, this is due to the parallel orientation of the elongate hornblende and epidote crystals which form a lineated fabric.

In their less deformed state the lithologies of the division display a range of sedimentary structures. The most prominent of these is the concretionary horizon in the polymictites. The concretions are usually highly deformed, being flattened in the 'c' tectonic fabric direction and extended in the 'b' directions. They are commonly folded and then become almost indistinguishable from thin epidote bands in the polymictite. In their less deformed state the concretions have the form of isolated ovoid bodies, strings of ovoid bodies, and thin elongated lenses parallel to the banding and foliation (Plate I, A).

They vary in mineral content, the thin lenses and smaller ovoid bodies consisting of a central portion of crystalline granular epidote with a rim of epidote and hornblende. The larger ovoid bodies show a complex series of rims (Fig. 3).

The contrasting compositions produce pale green cores with dark green rims in an almost black polymictic matrix. These bodies are thought to represent metamorphosed calcareous concretions and lenses in a silt grade matrix.

The foliation in the groundmass parallels the margin of the concretion, and as the latter concretions do not truncate the compositional banding of the polymictite, they are thought to have formed penecontemporaneously with the sediment.

Associated with the concretionary polymictite is a fine banded, current bedded psammite and subpelite (Fig. 4). The thin, current bedded psammitic bands form rippled surfaces over which the finer grained sediment of the subpelite band was deposited – thicker in the troughs between the current ripples. The psammitic bands vary in thickness from 2 mm to 2 cm, whilst the subpelitic bands vary from 1 mm to 7 mm. The sedimentary structures are perfectly preserved despite both the presence of a poor foliation (which is better developed in the subpelite bands than in the psammitic bands), and the development of garnet and biotite. In more uniformly bedded varieties of this fine banded lithology the subpelitic bands are cracked, with the coarser grained material, overlying the subpelite, infilling the crack (Plate I, B). During consolidation the subpelite was compacted to a greater extent than the psammitic infilling of the crack, giving flame-like ridges of the subpelite on either side of the crack.

An association of current and slump bedding is found in the associated massive psammites within the division (Fig. 4).

The conditions of deposition of the Vassfaret formation

The formation is characterised by rather rapid variations in lithology, including major variations from polymictites to psammites and minor variations in the fine compositional banding of the psammites. The high proportion of feldspar in most of the lithologies may be significant but metamorphism makes its environmental significance hard to adduce. However, the bands of fine to medium grained granular

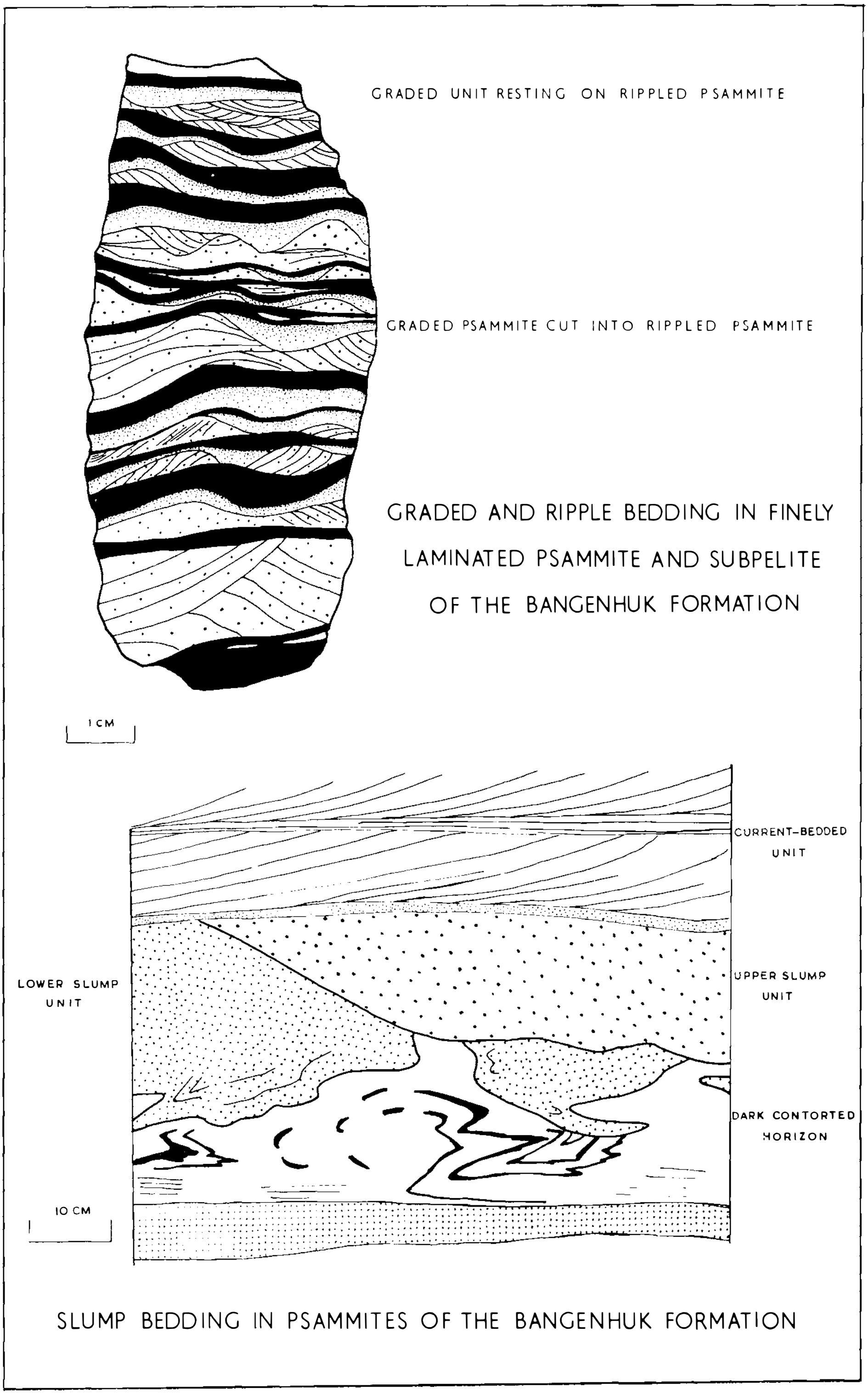

Fig. 4. *Sedimentary structures in the Bangenhuk formation.*

psammitic-feldspathite with a high proportion of potash-feldspar are thought to have been arkosic sandstones. The potash-feldspar is confined to the feldspathite bands and it seems unlikely that it was introduced after the deposition of the bands. This suggests rapid deposition in shallow water. Further discussion of the feldspathites is given in the discussion of the Bangenhuk formation.

The deformation for the most part has obliterated the sedimentary structures which are the most useful criteria of environment. However, in the outcrops of identical lithologies within the Bangenhuk formation the sedimentary structures have been very well preserved and allow some inferences to be drawn. The most important structure is the finely laminated lithology with coarse grained psammitic layers, showing current bedding grading upwards from a rippled surface to planar fine grained layers (Fig. 4). This lithology indicates regular and rapid changes in current intensity and, together with the calcareous concretion horizon, mud-cracking, and slumping suggests a tidal flat environment for their deposition (e.g. STRAATEN, 1959).

The abundance of quartz bearing amphibolites, some with sharp boundaries and others with gradational contacts, indicates a basic volcanic episode in force during the deposition of the formation. The wide lateral extent of the basic horizons favours a pyroclastic origin rather than lava flows.

THE BANGENHUK FORMATION (c. 2,000 m)

The type area of the formation is the coastal section around Bangenhuk, a headland in the northwest of Ny Friesland. The maximum thickness of 2,000 m has been measured along the shore of Femmilsjøen. The formation outcrops immediately to the east of the Vassfaret formation; the boundary, although sharp, is frequently obscured by later intrusions of aplite veins and sheets. The lithology is dominantly feldspathic and two members of contrasting fabric and homogeneity can be recognised throughout the length of Ny Friesland. In the northern part of the outcrop the two members are separated by approximately 100 m of polymictites and psammites very similar to the lithologies of the lowermost division of the Vassfaret formation, with which they are described. Two thin lenses of a similar lithology also occur within the upper member of the formation. To the south of Nordbreen the two members are in direct contact and interbanding occurs.

The Femmilsjøen member (1,250 m) is well exposed in the cliffs at the western end of Femmilsjøen, which is taken as the type area. The member varies considerably in thickness, thinning markedly to the east, and is nowhere seen to the east of the Atomfjella Dome in the north. The maximum thickness has been recorded from the westernmost outcrops at Femmilsjøen where 1,250 m are present. In the easterly outcrops north of Femmilsjøen only 500 m have been recorded. The member consists of a well lineated, medium to coarse grained gneissose feldspathite. The characteristic lineated gneissosity is produced by the interbanding and flattening of lenses and bands 5 to 10 mm thick of pink potash-feldspar, oligoclase and quartz with mafic bands and lenses 3 to 5 mm thick composed of biotite, hornblende, epidote and sphene (Plate II, A).

In thin section the most dominant fabric is granular, though a very poor foliation is seen in the rough alignment of biotite and hornblende grains in the mafic lenses and bands and in the elongate areas of quartzo-feldspathic material. The grain size varies from 0.5 mm to 3 mm in one section. The feldspars together form 50 to 63% of the rock.

Potash-feldspar constitutes 19 to 36% of the rock. It forms large lens-shaped areas of sutured grains, usually clear of inclusions, and frequently showing microcline twinning. These areas are surrounded by a fine grained mosaic of quartz, clouded plagioclase and smaller grains of potash-feldspar. Myrmekite forms embayments into the margins of the larger areas.

Plagioclase constitutes 19 to 34% of the rock. It usually shows albite twinning, having a composition varying from a soda oligoclase to andesine. Large single crystals occur in the quartzo-feldspathic lenses and are full of small inclusions of sericite, epidote and hornblende, irregularly arranged. Smaller grains, showing sericitisation along the cleavages, occur in the fine grained mosaic surrounding the larger feldspar grains.

Quartz constitutes 30 to 36% of the rock. It forms large lens shaped areas of sutured grains and also occurs as smaller grains in the mosaic surrounding the larger areas of feldspar.

Hornblende usually forms less than 10% of the rock. Commonly it occurs as tabular euhedral grains more or less parallel to the banding. In some rocks the hornblende forms megacrysts enclosing small grains of quartz and epidote.

The pleochroism is characteristic:
α = pale straw, β = dark olive green, γ = blue-green.
$2V\alpha \sim 50°$ (absorption is too intense to allow an accurate determination to be made)
$\gamma\hat{}c = 25–30°$.

Biotite forms up to 17% of the rock. Euhedral grains are oriented roughly parallel to the banding and occur in close association with hornblende and sphene.

The pleochroism is:
α = pale straw, β = greenish-brown.

Garnet is only rarely present, being associated with hornblende and biotite in the mafic bands and lenses. It forms poikilitic megacrysts with the hornblende and biotite fabric flowing around the megacrysts.

Sphene, epidote, apatite, iron-ore and zircon form constant accessories.

Along the margins of the formation, particularly in the first 3 m adjacent to the western margin against the Vassfaret formation, the rock is finer and more evenly grained and shows a distinctly more foliated fabric. The mafic bands are more clearly defined, containing biotite and elongate tabular grains of hornblende which form the more pronounced foliation. Garnet is of more general occurrence in this variety, forming distinct megacrysts around which the foliation is distorted.

This fabric is probably caused by the marked difference in competency between the lithologies of the Vassfaret formation and the Femmilsjøen member, resulting in the localisation of shearing along the contact. The contact is largely obscured by aplitic intrusions which make the original nature of the contact difficult to determine.

The Flatøyrdalen member (735 m). The type area is the northern cliffs of Flatøyrdalen in south Ny Friesland. As with the overlying member, the Flatøyrdalen member thins rapidly to the east. The maximum thickness west of the Atomfjella Dome is 735 m but the formation thins to 260 m east of the dome in the north. The member consists of banded lithologies characterised by a high proportion of feldspar and particularly potash-feldspar, which may constitute up to 47% of the rock.

The main lithology is a medium grained, banded gneissose quartzose or psammitic-feldspathite, with rather variable proportions of biotite and hornblende (Plate II, B). In composition the rock is fairly similar to the feldspathites of the Femmilsjøen member but has rather more variability. The most characteristic difference is in the texture. In the coarser grained varieties the gneissose banding is very pronounced, with mafic bands up to 5 cm wide composed of tabular blue-green hornblende which has similar optical properties to the hornblende in the feldspathites of the Femmilsjøen member, and is intergrown in sheath shaped areas with well oriented greenish-brown biotite to form a foliated fabric. Small grains of oligoclase and quartz form a sutured mosaic between the hornblende and biotite grains. The leucocratic bands are composed of large grains of myrmekitically embayed microcline, together with oligoclase. The latter is usually intensely clouded by sericite, both as large grains and as small sutured grains intergrown with quartz and small grains of potash-feldspar. In a few of the larger grains of potash-feldspar small inclusions of soda-feldspar occur with approximately parallel orientation, and in optical continuity. They appear to represent exsolution from the potash-feldspar host. These small inclusions sometimes have small myrmekite embayments into the surrounding potash-feldspar. Frequently the large potash-feldspar areas are recrystallised into a finer grained mosaic.

The coarse gneissose banding is commonly folded into small scale tight similar folds (Plate II, B) with the development of widely spaced secondary quartzo-feldspathic bands; these bands possess a similar texture to the original quartzo-feldspathic bands, and are approximately parallel to the axial surfaces of the folds. Occasionally the bands take the form of concretion pegmatites; these are lenticular bodies up to 2 m wide and 10 m long, with their long axes parallel to the mineral lineation and to the fold axes in the surrounding feldspathite. They are composed of a coarse grained sutured mosaic of quartz, clouded oligoclase and potash-feldspar. Around the margins of the lenses is a continuous selvage of orientated biotite forming a foliated fabric parallel to the lens walls.

The coarse banding of these feldspathites gives place gradually to a fine to medium grained granular quartzose and psammitic-feldspathite, with a very poor foliation given by the hornblende and biotite. The rock is composed of a sutured mosaic of quartz, clouded oligoclase and potash-feldspar, with embayments of myrmekite into the margins of the potash-feldspar grains. Biotite and blue-green hornblende occur as small grains, only roughly aligned to give a poor foliation. Epidote, sphene, zircon and apatite are accessories.

Interbanded with the feldspathite are bands of finely banded granular feldspathic-psammite with a much smaller proportion of potash-feldspar. The rock is fine to medium grained and is composed of a sutured mosaic of quartz and clouded oligoclase with small grains of potash-feldspar in the sutured fabric. The banding is caused by an increase in the proportion of biotite, hornblende and epidote, all showing a parallel orientation, forming a foliated fabric parallel to the banding.

A characteristic lithology occurs in the eastern outcrops east of the main Atomfjella Dome axis. This is a medium grained granular quartzose-feldspathite with large megacrysts of pink feldspar. In thin section these megacrysts are seen to be composed of potash-feldspar, occasionally showing microcline twinning and enclosing patches of albite-twinned oligoclase in optical continuity with each other and approximately aligned to the cleavages in the potash-feldspar. In some of the megacrysts the oligoclase inclusions form more than 50% of the grain, whilst in others they constitute less than 10%. It is not certain what the origin of this texture is. It could either represent exsolution from an original potash-feldspar containing appreciable quantities of soda and a little lime, or replacement of an original oligoclase by potash-feldspar. Subsequent to the development of the texture, the potash-feldspar has been marginally replaced by embayments of myrmekite. The groundmass is composed of a medium grained sutured mosaic of quartz, clouded oligoclase and potash-feldspar with grains of blue-green hornblende, biotite and epidote forming a crude foliated fabric. Small areas of calcite are present in interstitial patches and small euhedral garnet grains are also present, in some instances associated with the biotite and hornblende.

Schistose amphibolites similar to those of the Sørbreen formation, with both sharp and gradational contacts with the feldspathite, are present throughout the member. The margins of both types contain a significant proportion of potash-feldspar.

The conditions of deposition of the Bangenhuk formation

The sedimentary origin of the formation is shown by the compositional banding of the lithologies, by the interbanding of psammites of unquestionable sedimentary origin and by the presence of amphibolites thought to represent basic pyroclastic deposits. The large proportion of potash-feldspar in most of the lithologies is of more ambiguous origin. The sharp nature of some of the boundaries with lithologies containing little or no potash-feldspar would seem to indicate an originally high potash-feldspar content. It is clear that the potash-feldspar must have been present before the onset of the earliest recognisable deformation, as both the individual potash-feldspar grains and the horizons containing them show the effects of this earliest deformation.

The granular feldspathites are very similar to the psammitic-feldspathites of the lowest division of the Vassfaret formation, except that those of the Bangenhuk formation are very much thicker. The interbedding with sedimentary psammites and the even grain-size suggest an arkosic clastic sedimentary deposit. The coarser gneissose and megacryst feldspathites are thought to represent acid pyroclastic deposits, their variation due to the differing grain-size and fabric of the original deposit. On this interpretation the thick, largely homogeneous sequence of Femmilsjøen feldspathites would represent a coarse acid tuff/agglomerate, whereas the various bands within the Flatøyrdalen member would represent re-worked pyroclastics, the constituent bands being defined by varying admixtures of clastic grains and differing degrees of re-working. Some may even represent lava flows.

In the north, both the absence of the Femmilsjøen member and the rather thinner development of the Flatøyrdalen member in the eastern part of the outcrop may be partly due to tectonic cut-out beneath the Planetfjella group. However, some of the thinning is original and suggests a more distant area of sedimentation, away from the centres of volcanic activity. Following the outburst of acid volcanic activity shown by the thick feldspathites of the Bangenhuk formation, the thinner granular feldspathite bands in the lowest division of the Vassfaret formation indicate either a waning in volcanic intensity or a more distant source.

THE RITTERVATNET FORMATION (350 m)

The formation outcrops west and east of the main Atomfjella Dome axis. It has been observed in most detail in the northern part of the outcrop, around the small lake Rittervatnet, just north of the eastern end of Femmilsjøen, and this is taken as the type locality.

The formation consists of a series of distinctive lithologies strongly interfolded with both the overlying Bangenhuk formation and the underlying Polhem formation. The marked contrast between successive lithologies, together with the unique character of some of the horizons, allows the structure to be accurately reconstructed, which in turn allows changes within individual horizons to be traced across the strike. In the type area three divisions can be recognised.

c) Consists of 72 m of psammites with subordinate thinly banded psammitic-subfeldspathites, feldspathites, concordant amphibolites and biotite subpelites. In outcrop the member shows a thinly, evenly banded appearance between the various lithologies, the bands being 5 cm to 1 m in width, with fairly sharp boundaries grading over c. 1–2 cm. (Plate III, A).

The psammites are medium grained, poorly foliated rocks and are composed of 50 to 70% of quartz, with varying proportions of plagioclase, epidote, hornblende, biotite, muscovite and chlorite. The plagioclase is intensely clouded with small grains of sericite, making a determination of the composition difficult. It occurs as irregular grains intergrown in the sutured quartz mosaic and rarely exceeds 10% of the rock. Epidote occurs in significant proportions in most of the psammites and in some cases constitutes up to 30% of the rock. It forms well oriented elongate grains producing a poor foliation in the bands with high epidote content, when the quartz-plagioclase mosaic develops into elongate lenses. Hornblende, largely altered to chlorite, only rarely occurs in significant amounts when associated with amphibolite bands. It forms tabular grains oriented parallel to the foliated fabric. Biotite is more abundant than muscovite and together they commonly form less than 10% of the rock, except in association with subpelite bands. They form isolated euhedral grains or sheath-like aggregates oriented approximately parallel to the foliation. Sphene, apatite and zircon are characteristic accessories.

Feldspathites and psammitic-subfeldspathites occur as thin bands associated with the concordant amphibolite bands, and the fine interbanding of these three lithologies to form composite bands up to 10 m wide is a characteristic of the member (Plate III, A).

The feldspathites and psammitic-subfeldspathites are medium to coarse grained rocks containing approximately equal proportions of quartz and plagioclase intergrown in a sutured mosaic. The plagioclase feldspar, as in the psammites, is intensely clouded with small grains of epidote and sericite. Commonly the only other mineral to occur in significant amounts is epidote, which forms elongate grains oriented to give the rock a good lineation. Biotite occasionally occurs but in amounts less than 10%.

In the rapid gradation to amphibolite, blue-green hornblende forms large tabular grains perfectly aligned to produce a marked foliated schistosity, with the quartz-plagioclase mosaic forming elongate areas also parallel to the foliation.

The biotite-subpelites constitute a subordinate lithology occurring as thin bands 5 to 10 cm thick in the psammites. The bands have sharply defined boundaries with less than 1 cm of gradational rock between the two lithologies. They are composed of biotite, quartz and plagioclase in approximately equal proportions, with accessory muscovite, epidote, chlorite and hornblende. The euhedral biotite is well orientated parallel to the foliation.

b) 160 m of a uniform graphite-pelitic/subpelitic lithology, with thin horizons of marble and quartzite. As with the other members of the formation, this contains thin bands of foliated schistose concordant amphibolites.

The pelites are distinguished from all other pelites in the area in containing a significant proportion of graphite. They contain 40 to 60% of mica, with straw-green biotite in excess of muscovite. Quartz commonly forms up to 35% of the rock and clouded plagioclase is present in amounts just exceeding 10%. Garnet is always present in small amounts. Accessories include pyrite, epidote, zircon and tourmaline. The graphite and micas form a well orientated fabric, giving the rock a strongly foliated schistosity, with the quartz and oligoclase occurring in a mosaic of flattened elongate grains parallel to the mica foliation. The garnet forms poikilitic megacrysts, containing small inclusions of quartz and iron-ore, about which the foliation is distorted. Blue-green or brownish-green tourmaline occurs in small acicular grains scattered throughout the rock and sometimes concentrated in narrow bands, when its proportion rises to over 10%. The biotite is commonly partially altered to chlorite or prehnite in narrow selvages parallel to the cleavage.

The rock invariably shows a crenulation of the mica-graphite foliation which in thin section is seen to be overprinted by a later recrystallisation of the micas, in part mimetic and in part as larger randomly oriented grains. Narrow lenses and bands of deformed microquartzite horizons give the rock a slightly streaked appearance.

The marble bands are always thin, being less than 0.5 m wide. They occur as sharply defined pure marble horizons or as gradational bands with higher calcite content in the pelites.

The pure marbles contain up to 80% of coarse grained granular calcite, giving the rock a sugary appearance. Quartz and plagioclase, intensely clouded by sericite, usually only occur in amounts under 10%. Biotite and muscovite form the only other minerals to occur in significant amounts. They show a good platy fabric which, if they are present in sufficient proportions, gives the rock a poorly foliated fabric.

In the gradational bands the rock rarely reaches a marble in composition and commonly is a calcite-subpelite. As in the pelites, biotite forms a good foliated fabric, with the calcite intergrown with the plagioclase and quartz in a mosaic of grains roughly aligned to the foliation. Scapolite also occurs in these lithologies and can form up to 20% of the rock. Associated with the scapolite are bands rich in tourmaline. Garnet occurs as poikilitic megacrysts about which the biotite fabric is deformed.

Bands of quartzite form thin horizons 0.5 m wide, with very sharp boundaries with the surrounding lithologies. They commonly occur in association with the calcareous bands. In thin section they show a coarse grained sutured quartz mosaic with scattered small grains of muscovite and tremolite. Occasionally the muscovite and tremolite occur in distinct bands which in hand specimen appear as slightly darker bands in the quartzite, parallel to the margins of the quartzite.

a) Consists of 160 m of the most distinctive lithologies of the Harkerbreen group. The upper part of the division is composed of a thick white marble and the lower part of an equally distinctive bluish-white quartzite. Between the two, and between the marble and the pelites of division b), thick foliated garnet amphibolites occur.

The marble consists of a granular calcite rock containing over 80% of calcite. In weathered outcrops the rock is sugary, crumbling readily to form scree, and the only good exposures are in vertical faces or in extremely fresh outcrops. In addition to calcite the rock contains up to 10% of a purplish-brown biotite, regularly distributed throughout the rock, forming an indistinct platy fabric. Scapolite, quartz and plagioclase occur in accessory amounts intergrown with the calcite. Bands of tremolite, forming large radiating crystal aggregates in the plane of the foliation and the banding, occur at intervals throughout the marble. These bands serve to pick out the structure in otherwise massive and homogeneous rocks.

The quartzites are exceedingly pure, being composed of over 90% of coarse grained sutured quartz. In outcrop the rock shows a distinct banding, distinguishing it from vein quartz which it otherwise resembles. The banding is indistinct in thin section and appears to be due to a slight concentration of muscovite, tremolite or kyanite. These accessory minerals have a distinct preferred orientation but occur in too small amounts to give the rock a foliated or lineated fabric.

Both lithologies have extremely sharp boundaries with the intervening garnet-amphibolites and the underlying banded psammites and amphibolites of the Polhem formation. Immediately to the east of Rittervatnet the three divisions of the formation are involved in a series of tight folds which also interfold the formation with those above and below it.

In the exposed limbs of these folds the lithologies of the three divisions show

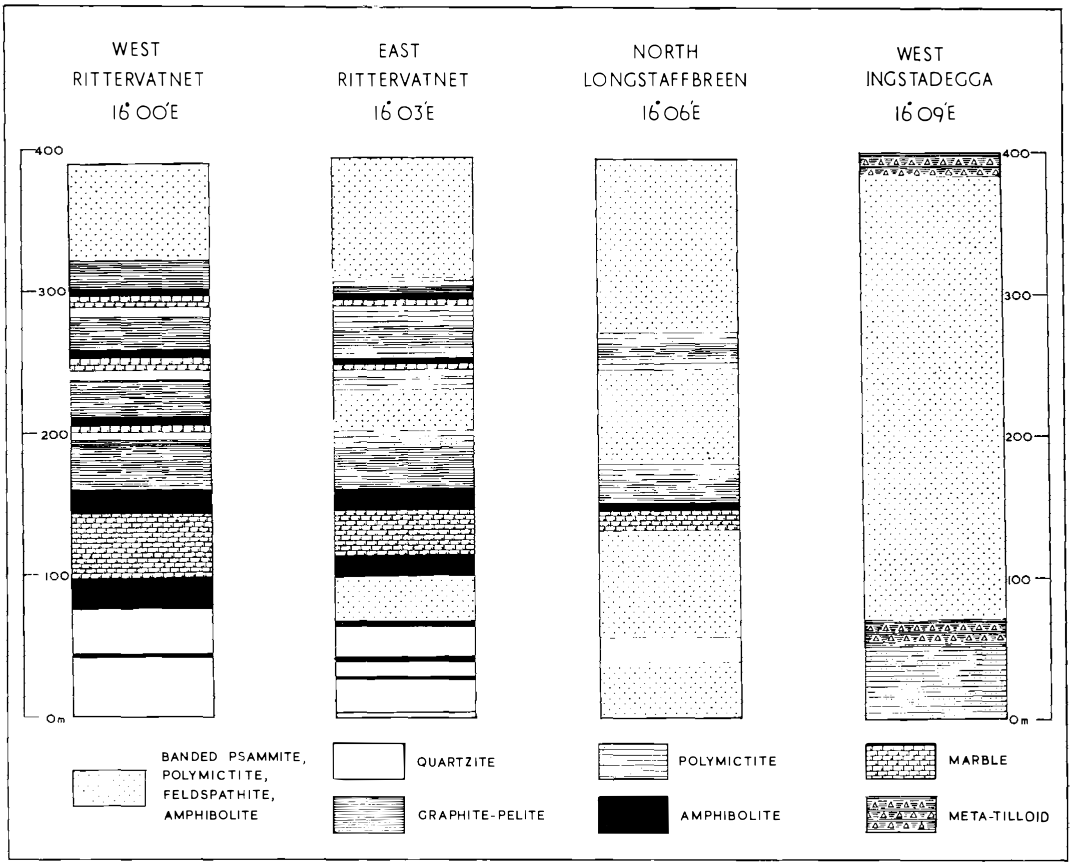

Fig. 5. *Diagrammatic representation of lateral variation of the Rittervatnet formation at c. Latitude 79° 50' N.*

a progressive change towards those seen in the outcrops of the Rittervatnet formation 4 kms away, to the east of the Atomfjella Dome axis.

The changes are only visible in the fold limbs but there appears to be a gradual transition (Fig. 5). However, there is a larger break of 4 km in exposure across the main Atomfjella Dome axis and the lithologies to the east show a marked contrast to those of the west. Divisions a) and b) have not been recognised in the east, and lithologies similar to division c) are very much thicker. However, the thinly banded nature of the lithology is still retained although the composition of the bands is somewhat different. The subpelitic bands, which are very much subordinate in the western outcrops of division c), constitute about 50% of the lithology in the east and the proportion of the psammitic bands is correspondingly reduced. The thinly-banded association of feldspathites, psammitic-subfeldspathites and amphibolites is present in about the same frequency in both groups of outcrops.

However, the most notable difference between the east and west is the frequent occurrence in the east of at least two horizons of meta-tilloid within the sequence (Plate III, B). One of these immediately underlies the potash-feldspar-feldspathites of the Bangenhuk formation and the other occurs at a horizon about 200 m above the base of the formation.

The upper meta-tilloid is 5 to 15 m thick and is composed of pebbles, cobbles and boulders of quartzites, psammites, potash-feldspar-feldspathite and granite (s. l.) scattered through a matrix of a medium to coarse grained, foliated feldspathitic pelite. Usually the matrix constitutes more than 50% of the rock and is composed of 40 to 50% green biotite forming platy grains, with 35 to 40% slightly sericitised oligoclase in large irregular grains intergrown in a mosaic with 10 to 35% of quartz. Up to 10% blue-green hornblende occurs, in large well formed grains partially replaced by tremolite. Garnet commonly occurs as megacrysts with a rolled fabric and accessories include green tourmaline, calcite, zircon, apatite and ore.

The phenoclasts range in composition:

Psammite (40%) is the commonest type and is a poorly lineated granular rock with quartz and clouded oligoclase feldspar forming a sutured mosaic, while biotite and hornblende produce the poor lineation. Epidote, zircon, apatite and sphene are always present, usually in amounts less than 5%.

Gneissose potash-feldspar-feldspathites (30%) occur in a variety of textures. The commonest is a finely banded gneissose rock very similar to varieties seen in the feldspathites of the Bangenhuk formation. The gneissosity is shown by bands of biotite and hornblende with a foliated schistosity, interbanded with layers of granular quartz, oligoclase and potash-feldspar.

Another distinctive texture is a coarse grained gneissose rock with megacrystic grains of pink potash-feldspar. The mafic bands swing around these to produce a distinct augen gneissosity.

Granite (20%) is the third most abundant type. It occurs with a variety of textures, none of which show any signs of an oriented fabric, and all retain their granitic texture. Hornblende and biotite commonly form clusters of smaller recrystallised grains and plagioclase is usually intensely clouded by sericite. The commonest texture is medium grained but a porphyritic granite, with phenocrysts of potash-feldspar, and coarse and fine-grained granites also occur.

The remaining 10% of the phenoclasts are vein-quartz and a garnet-quartz rock. This consists of euhedral garnet megacrysts, showing a helicitic fabric of small included quartz grains, set in a coarse grained mosaic with occasional grains of green biotite intergrown within the quartz fabric; these rocks are thought to have originated as calcareous lithologies.

Due to the intense deformation that the rock has undergone, it is very difficult to assess the original shape and size of the phenoclasts. In their deformed state they are elongate ellipsoidal bodies with their long axes lying parallel to the lineation of the enclosing feldspathitic-pelite. Because of the differing competencies of the phenoclasts, the amounts of distortion from their original shape differ. The granitic phenoclasts show the least deformation and are usually almost spherical with well rounded outlines. The diameters of these phenoclasts varies from c. 1 cm to 2 m, and the most frequent value is c. 5 cm. The gneissose feldspathite and psammite phenoclasts are so highly deformed that only an approximate estimate of their original shape can be made and this indicates a similar size range to the granitic phenoclasts.

In general the elliptical cross-sections of the deformed phenoclasts show fairly smoothly curved outlines, presumably reflecting an original rounding of the phenoclast. Occasionally angular outlines are found and it is thought that these represent originally angular phenoclasts.

The second meta-tilloid horizon occurs in the lower part of the formation and is 10 to 20 m in width. It differs from the upper horizon in the composition of its matrix and in the composition and banding of its phenoclast content.

The matrix is a fine to medium grained biotite psammite, with a well developed foliated schistosity shown by the biotite fabric. Quartz and clouded oligoclase form a sutured mosaic.

The lowest 3 to 5 m of the horizon contain up to 80% of foliated amphibolite phenoclasts, with the remaining 20% made up of vein quartz and granular psammite phenoclasts. The top 3 to 5 m contain up to 80% of vein quartz phenoclasts, with the remainder composed of foliated amphibolite and granular psammite phenoclasts. The middle portion contains about equal proportions of vein quartz, granular psammite and foliated amphibolite phenoclasts. Gneissose feldspathite phenoclasts occur only very rarely throughout the horizon and granitic phenoclasts have not been recorded. It should be noted that all the phenoclast types, with the exception of the gneissose feldspathites, can be matched in the underlying lithologies of the division.

In both meta-tilloid horizons the foliation in the matrix envelopes the phenoclasts. The foliation in the foliated phenoclasts is, in almost all instances, parallel to the foliation in the matrix and suggests a contemporaneous origin for the internal and external fabrics. Where the internal foliation is slightly discordant, later rotation could explain the discordance.

In addition to the main outcrops of the meta-tilloid horizons immediately east of the Atomfjella Dome axis, a metatilloid horizon has also been recorded from the thinly banded lithologies of division c) west of the Dome axis, from Berglibreen just to the north of Nordbreen, and from Midtbreen. In the extreme east of the northern outcrop in south-east Mosseldalen the meta-tilloid is associated with a calcareous facies development of the Rittervatnet formation similar to division b) of the western outcrops.

The conditions of deposition of the Rittervatnet formation

The lithologies of the formation suggest that the sediments were deposited in relatively shallow water with rapid changes of environment during deposition.

The most marked changes in facies across the area occurred during the deposition of divisions a) and b) (Fig. 5). While calcareous deposits and pure quartz sands were forming in the west, banded lithologies of impure quartz sand interbedded with silt and pyroclastic material were being deposited in the east, with the rudaceous meta-tilloid horizons most noticeably developed in these banded lithologies. Still further east the calcareous facies was again dominant. The change from calcareous to sandy and silty facies occurred along a line running approximately N–S through the eastern end of Femmilsjøen, suggesting a deeper water environment to the east. The presence of graphite in the pelites in division b) may indicate quieter anaerobic conditions of deposition. The origin of this carbonaceous material is unknown but presumably must have been organic.

The conditions which brought about the deposition of the banded lithologies gradually spread to the west until, during the deposition of division c), similar conditions prevailed over the entire area.

By this interpretation most, if not all, the deposits are of shallow water origin. On this assumption it is interesting to discuss the mechanism of deposition of the meta-tilloids.

The tilloids occur as relatively thin horizons over a fairly extensive area. They are associated with sediments seemingly indicative of shallow water conditions. The phenoclasts of the lower horizon can be matched with underlying lithologies of the Lower Hecla Hoek sequence, with the exception of rare gneissose feldspathites, and a local origin is possible. The upper horizon, however, contains over 20% of phenoclasts that cannot be matched with lithologies in the Lower Hecla Hoek sequence and a more distant source is indicated. The phenoclasts are characteristically well rounded, boulders up to 2 m in diameter occur, and in general the phenoclasts are moderately well sorted. The degree of sorting of the matrix, which comprises more than 50% of the rock, cannot be ascertained due to metamorphic recrystallisation.

Thus a mechanism must be sought which would spread a thin sheet of conglomerate in shallow water over a wide area, rounding and roughly sorting phenoclasts derived from a distant source. At the same time it must be able to carry boulders up to 2 m in diameter and also more than 50% of a presumably fine grained matrix.

Of the various subaqueous mechanisms, transport by beach or fluvial current action would seem to be excluded by the greater proportion of fine grained matrix to phenoclasts (PETTIJOHN, 1957). If our assumptions are correct, this would appear to leave only rafting and deposition from icebergs or the action of subaqueous mudstreams and turbidity flows, as possible mechanisms to explain the nature, extent and association of the deposit.

The degree of rounding and moderate sorting of the phenoclasts perhaps favours the latter mechanism, although if the deposit is indeed a shallow water sediment, it is difficult to envisage a turbidity flow of great lateral extent carrying large boulders. On the other hand, rounding of the phenoclasts may have occurred prior to ice-rafting, and this offers the most satisfactory explanation for the features of the deposit as already proposed (HARLAND *et al.*, 1966).

THE POLHEM FORMATION (900 m+)

The type area is situated in the coastal exposures around Polhem, north of Mosselbukta. The formation is composed of coarsely banded psammites and amphibolites, similar to those of the Sørbreen formation, giving the outcrops a striking banded black and white appearance. The bands vary from 1 m to 20 m in width and may have either sharp or gradational boundaries. They retain their individual identity for considerable distances along the strike of the outcrop.

The psammites vary in composition and texture from one band to another. They all contain about 60% of quartz and the different varieties represent variations in the proportions of the associated minerals.

The most abundant type is a medium grained, poorly schistose oligoclase-psammite. The rock is a uniform light grey in colour. Sericitised oligoclase constitutes 20 to 30% of the rock and is intergrown with the quartz to form a sutured mosaic. Muscovite occurs in excess of a greenish or brown biotite and together they occur in amounts up to 15% of the rock. They form small euhedral grains oriented to give the rock its poor schistosity, with both foliated and lineated mineral elements. Pale green pleochroic epidote occurs in amounts less than 10%, forming small grains scattered throughout the rock. Sphene, apatite and zircon are constant accessories.

Almost as abundant is a medium grained, finely banded schistose oligoclase-psammite. In hand specimen the banding gives the appearance of graded bedding, with dark bands 2 to 5 mm thick grading into lighter bands of approximately equal thickness. Greenish or brown biotite occurs to the exclusion of muscovite and is concentrated with epidote to give the banding seen in hand specimen. The parallel alignment of the biotite grains forms a good foliated and lineated fabric. In thin section the dark mineral concentrations appear to grade off evenly on either side of each band and no indication of the unilateral grading, seen in hand specimen, has been observed.

Epidote-psammite bands from 5 cm to 1 m in thickness occur within the oligoclase-psammites. Their boundaries are usually sharp and the rock has a granular fabric with no indication of banding. In addition to the 60% quartz and 20% sericitised oligoclase, these bands contain up to 20% of a pale green pleochroic epidote. Biotite, sphene, apatite, iron-ore and zircon form the accessories.

Coarse grained schistose hornblende-oligoclase psammites occur both in the gradational contacts with amphibolite bands and as discrete bands within the oligoclase-psammites. Blue-green hornblende occurs in approximately equal proportions with sericitised oligoclase and biotite. The hornblende and biotite form euhedral grains with a well marked parallel orientation giving the rock a foliated and lineated fabric.

Potash-feldspar is very rare in the psammites and has been found in significant amounts in only one variety. This is a medium grained granular potash-feldspar-psammite containing about 10% of calcite. The potash-feldspar is partially clouded and shows microcline twinning. It is intergrown with the calcite and quartz to form a sutured mosaic. Bright green pleochroic epidote and oligoclase are also present in amounts less than 10%.

Calcite occurs in small amounts in thin bands within most of the varieties described but these are nowhere abundant.

Subordinate to the psammitic and amphibolitic bands, subfeldspathites occur as discrete bands 1 to 5 m thick. They are coarse grained schistose rocks containing up to 40% of a patchily sericitised oligoclase intergrown with approximately equal proportions of euhedral greenish-brown biotite and poikilitic tabular grains of green hornblende, with inclusions of small grains of quartz, to form a mosaic showing only slight preferred orientation. Quartz forms up to 10% of the rock and occurs as small xenoblastic grains and in larger patches showing a sutured mosaic.

Biotite-subpelites are very rare and occur as thin bands associated with the banded oligoclase-psammites. It is the absence of biotite-subpelitic bands that distinguishes the Polhem formation from the eastern lithologies of the overlying Rittervatnet formation. At the eastern margin of the outcrop the boundary between the two formations has been taken beneath the last thick biotite-subpelitic band of the Rittervatnet formation.

The conditions of deposition of the Polhem formation

The lithologies of the formation all contain about 20% or more of plagioclase feldspar in addition to a high proportion of quartz in the psammites. These therefore represent metamorphosed arkosic sandstones and can be distinguished from the Bangenhuk Formation feldspathic sediments in containing no potash-feldspar and a much smaller proportion of total feldspar. The lack of sedimentary structures other than the compositional banding can be attributed to metamorphic recrystallisation and deformation. No information about the environment of deposition can be gained except that the sediments were accumulated fairly rapidly; there is no indication that the plagioclase was derived directly from the re-working of pyroclastic material. As with the other Harkerbreen group lithologies, the presence of gradational amphibolitic bands is thought to represent basic volcanic activity during deposition. In this formation the amphibolite bands appear to be thicker and more numerous than in any other Lower Hecla Hoek formation.

Discussion – The basin of deposition

Although it is difficult to reconstruct depositional environments and facies changes during Harkerbreen group times, due to the almost complete metamorphic obliteration of the sedimentary fabric and to the tectonic displacement and distortion, it is perhaps of interest to piece together such evidence as we have concerning the development of the area of deposition, especially in northwest Ny Friesland.

The total outcrop of the Harkerbreen group in Ny Friesland appears to lie entirely within the limits of the Caledonian geosyncline (HARLAND *et al.* 1966). There are, however, abundant signs of the proximity of land throughout Harkerbreen group times.
These are: –

1) well sorted psammites and quartzites;
2) arkosic sands in almost all the formations;
3) the presence of re-worked acid pyroclastic material, thicker in the west;
4) interbedding with possible intertidal zone deposits;
5) basic volcanics, derived from aerial eruptions.

Wherever the indications of land are directional, these suggest a landmass to the west of Ny Friesland; the geanticline of HARLAND (1960).

Throughout the time of the Polhem and Rittervatnet formations the sediments are thought to have been laid down in shallow water, but no structures are preserved to show the source of the sediments, and the origin of the granite clasts is at present unknown. The Polhem formation plagioclase-arkoses suggest rapid accumulation of sediments with little chemical weathering. However, the Rittervatnet formation quartzites are mature sediments and the marbles suggest relatively slow deposition in shallow water. The facies distribution in the Rittervatnet formation suggests a slightly deeper water environment, with less mature sediments to the east, and it is in this environment that the tilloids are best developed; possibly the ice on which the tilloid sediment was rafted was unable to encroach upon the shallow water areas to the west.

Bangenhuk formation times saw the onset of acid volcanic activity accompanying the basic volcanic activity that had been operating intermittently throughout the earlier two formations. The feldspathites of the Bangenhuk formation include both primary pyroclastic deposits – tuffs, agglomerates – and also reworked deposits presumably from a landmass built up by the volcanic activity. The thickening of the formation to the west, together with the coarsening of the grain-size and an increase in the proportion of primary pyroclastic material, also suggests that the centres of volcanic activity might have been to the west. These centres are presumed to coincide with geanticlinal uplift within the geocyncline. The interdigitation with possible intertidal zone deposits also emphasises the shallowness of the depositional environment, and thus correlates the rate of subsidence of the basin very closely with the rate of sedimentation – a correlation that must have been more or less valid throughout Harkerbreen group times.

Acid volcanic activity reached its climax with the Femmilsjøen member which contains more than 90% acid pyroclastics. The Vassfaret and Sørbreen formations reflect a rapid fall off in acidic volcanic activity, although basic volcanics are present in about the same proportions as in the earlier formations.

Summary of conclusions

The petrology of the Harkerbreen group described in this paper is based largely on outcrops in the strip along the west coast of Ny Friesland, and in the Mosselbukta/Femmilsjøen area of northern Ny Friesland. The sequence described is as follows:

Sørbreen Formation 265+m quartzites, psammites, feldspathites and amphibolites, representing pure and impure sands interbedded with both acid and basic pyroclastic horizons.

Vassfaret Formation 600 m divisible into three:

c) 320 m of polymictites with microquartzite laminae and amphibolites.
b) 40 m of an upper, calcite-hornblende-garnet-polymictite and a lower, colour-banded psammite, both horizons containing amphibolites.

a) 240 m of interbanded polymictites, psammites and feldspathites with a distinctive concretionary and finely laminated subpelite, and amphibolites.

The sediments of the formation are thought to have been deposited in shallow water with the subpelites of division a), possibly formed in the intertidal zone. The amphibolites and possibly some of the feldspathites are thought to indicate sharply delineated periods of volcanic activity.

Bangenhuk Formation c. 2,000 m, divisible into two members, both dominantly feldspathic and separable on fabric:

b) *The Femmilsjøen member* (1,250 m) is a massive sequence of poorly foliated, lineated feldspathites and amphibolites;

a) *The Flatøyrdalen member* (735 m) is a composite unit of both well and poorly foliated feldspathites, psammites and amphibolites. The foliated feldspathites are usually highly folded and have developed pegmatites.

In the north the members are separated by a thin horizon of lithologies similar to division a) of the Vassfaret formation and lenses of similar lithologies occur within the Femmilsjøen member. Farther south this development is not seen and the two members are interbanded along their junction.

The formation is thought to represent a great thickness of acid pyroclastic material, with the variation in fabric largely due to the amount of re-working that the pyroclastics have suffered. Basic pyroclastics are also present. Deposition may have occurred either in shallow water or above water level, as is indicated by the included sediments.

Rittervatnet Formation 350 m, divisible into three in the west, but only one division can be recognised 4 kms away in the east.

c) 72 m of a banded sequence of psammites, feldspathites, polymictites and amphibolites with gradational contacts between lithologies. Ubiquitous in the east and occasionally in the west, the division contains two thin meta-tilloid horizons attributed to ice-rafting.

b) 160 m of graphite-pelite with thin interbanded calcareous and quartzitic horizons and amphibolites.

a) 160 m of a thick marble and a pure bluish-with quartzite separated by thick garnet-amphibolites.

The formation may represent shallow water deposition with both quartz sand and limestone being deposited. The occurence of graphite in the pelites of division b) suggests the presence of organic remains preserved in reducing conditions.

Polhem Formation 900 m+, dominantly psammites and amphibolites, either in sharply defined bands or with gradational contacts. The presence of significant proportions of oligoclase suggests an origin as an arkose.

Table I.

Modes of some Ny Friesland Harkerbreen group lithologies.

Formation	Horizon	Specimen no.	Quartz	Plagio-clase feldspar	Potash-feldspar	Micas	Garnet	Horn-blende	Calcite	Epidote	Sphene/ ore	Petrographic name
	Sørbreen formation	0286	51	3	17	28				1		Psammite
	Division C	R687	30	34		23				12	1	Polymictite
Vassfaret formation	Division B	R606	15	2				57		24		Amphibolite
Vassfaret formation	Division B	R616	32	14		37		10	7	1		Subpelite
Vassfaret formation	Division A	0145	29	19	33	9		9			1	Feldspathite
Vassfaret formation	Division A	R616	58	32		5		5		3		Psammite
	Femmilsjøen member	R779	33	26	36	4					1	Feldspathite
	Femmilsjøen member	085	36	19	36	9					1	Psammitic-feldspathite
Bangenhuk formation	Flatøyrdalen member	R897	27	32	32	8					1	Feldspathite
Bangenhuk formation	Flatøyrdalen member	R880	42	22	30	6						Psammitic-feldspathite
Bangenhuk formation	Flatøyrdalen member	x1554	32	39	3	22			2		1	Subfeldspathite
Bangenhuk formation	Flatøyrdalen member	T626		23	22	1		54				Feldspathitic-amphibolite
Rittervatnet formation	Division C	R917.1		29				69		1	1	Amphibolite
Rittervatnet formation	Division C	R917.2		55		2		39		2	2	Amphibolitic-feldspathite
Rittervatnet formation	Division C	R859	11	43		27		19				Subfeldspathite
Rittervatnet formation	Division C	R865	9	43		41		6		1		Subpelite-subfeldspathite
Rittervatnet formation	Division C	R919	69	7	12	12						Psammite
Rittervatnet formation	Division B	R892	37	11		52						Psammitic-pelite
Rittervatnet formation	Division A	R763	2	3		8			87			Marble
Rittervatnet formation	Division A	R909	96			2	2					Quartzite
	Polhem formation	R573	58	24		12				5	1	Psammite

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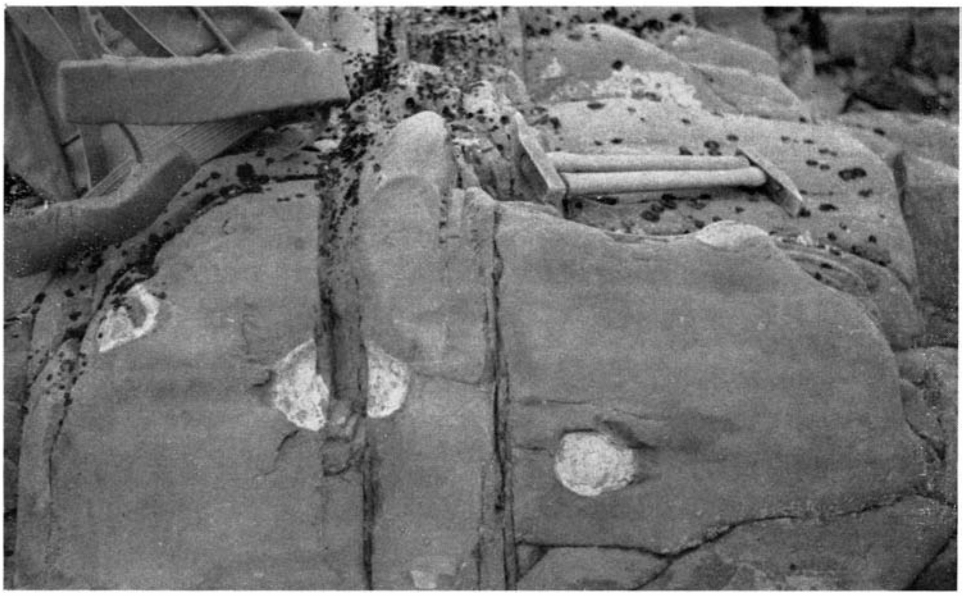
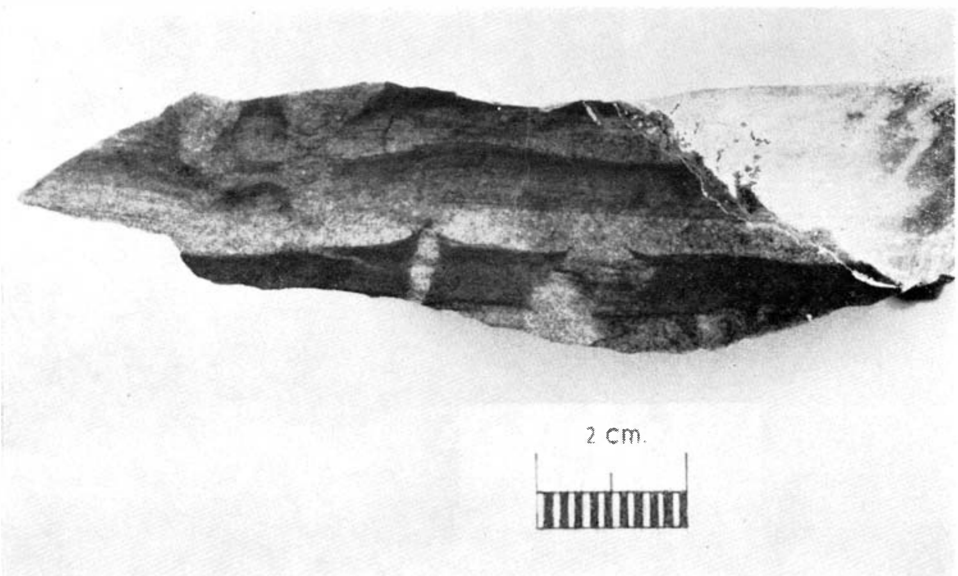
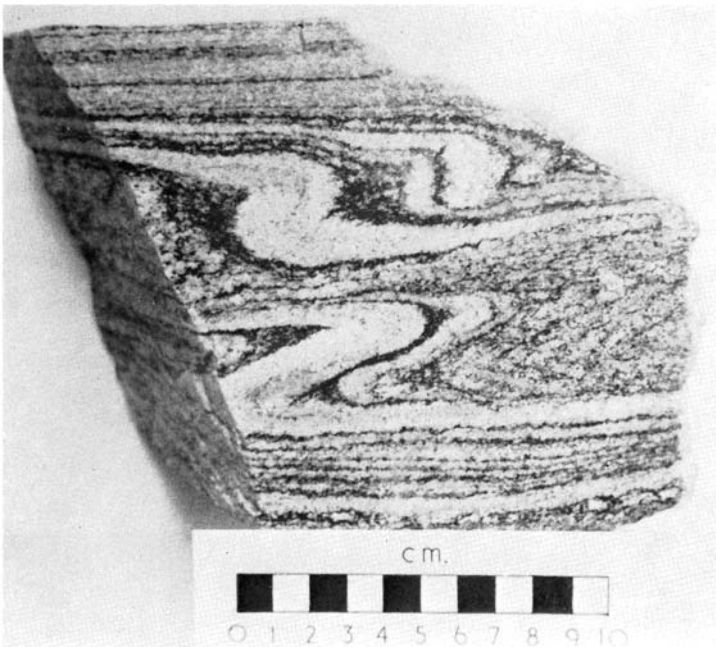


A. *Calcite-epidote concretions in polymictite of the Bangenhuk formation.*



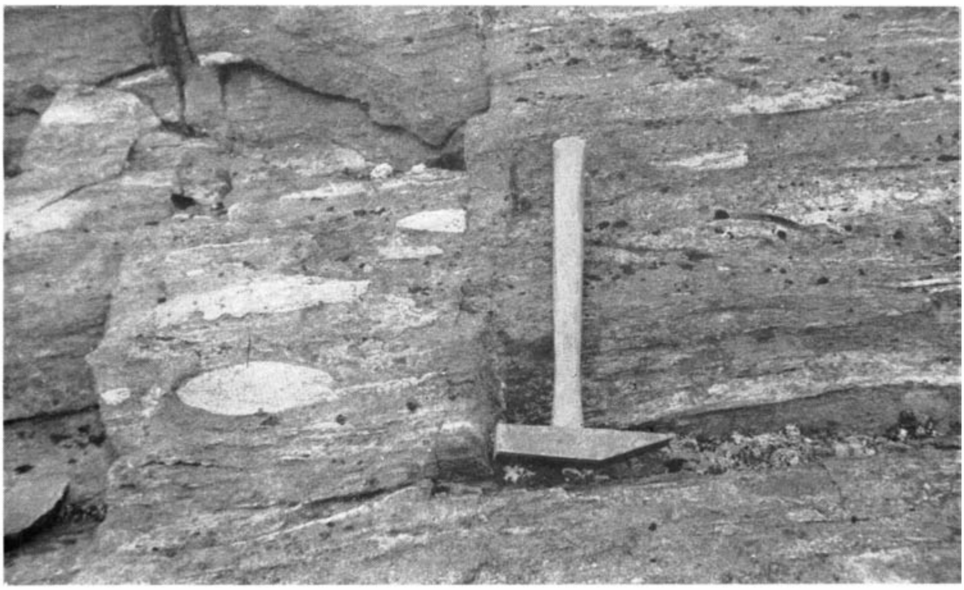
B. *Mud cracks in subpelitic lithology in the Bangenhuk formation.*

A. *Lineated gneissose feldspahite of the Femmilsjøen member of the Bangenhuk formation.*



B. *Small folds in banded gneissose feldspathites of the Flatøyrdalen member of the Bangenhuk formation.*

A. *Banded feldspathite, psammite and amphibolite in the Rittervatnet formation.*



B. *Meta-tilloid horizon in the Rittervatnet formation.*

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