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RODNEY A. GAYER

The geology of the
Femmilsjøen region of north-west
Ny Friesland, Spitsbergen



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Abstract

Analysis of the north-western part of the north-south Caledonian chain in Ny Friesland reveals a multi-stage development of the orogenic cycle.

The subsequent deformation of the more than 4,500 m of sediments, volcanics and dolerite sheets exposed in the region was initiated with the development of isoclinal folds on north-south axes during a primary thrust regime. The associated east-west compression was interrupted by a period of static conditions during which a second set of dolerite sheets and acid rocks were intruded into the still hot, folded succession. Renewed east-west compression produced medium tight folds, again on north-south axes, accompanied by boudinage of the more competent lithologies. This stage of the orogeny constitutes a primary radial regime. It is argued that renewed folding about north-south axes during a third stage of compression represents flowage of anticlinal crests into adjacent synclines in a response to continued east-west compression.

The final episode of the Ny Friesland Orogeny was the development of oblique joints and strike-slip oblique faults indicating the operation of a primary wrench regime.

Introduction

The area to be described in this paper forms the northern portion of the western section of Ny Friesland and extends southwards from latitude 79°55', Mosselbukta and Mosseldalen, to latitude 79°45', south of Femmilsjøen and Longstaffbreen (Fig. 1). The north of Ny Friesland ice-cap, Åsgårdfonna, occupies the south-eastern part of the area from which flow two glaciers: Tåbreen, leading northwards and forming the eastern limit of the area, and Longstaffbreen, leading westwards into Femmilsjøen. The inland plateau on which the ice-cap rests extends to the north and west of the ice margins and forms an area of little rock exposure, being largely covered by snow and ground moraine. However, to the west, the plateau is dissected into a rectangular grid of north-south and east-west valleys that give excellent continuous exposures. To the north the plateau is cut by the deep-sided Mosseldalen that marks the northern limit of the area. The shore of Wijdefjorden forms the western margin of the area and offers good exposures in the present beach and in the old wave cut platforms.

The rocks exposed in this area form part of the lowest division of the Hecla Hoek succession and throughout the area have undergone deformation and metamorphism during the Caledonian Orogeny. The Hecla Hoek has been divided into three supergroups: an upper – the Hinlopenstretet Supergroup; a middle – the Lomfjorden Supergroup; a lower – the Stubendorffbreen Supergroup, to which belong the rocks of this area. The Hinlopenstretet Supergroup comprises Ordovician and Cambrian strata and an underlying tillite bearing formation, so that the Stubendorffbreen Supergroup is late but not latest Precambrian.

The stratigraphy of the Stubendorffbreen Supergroup was formulated by

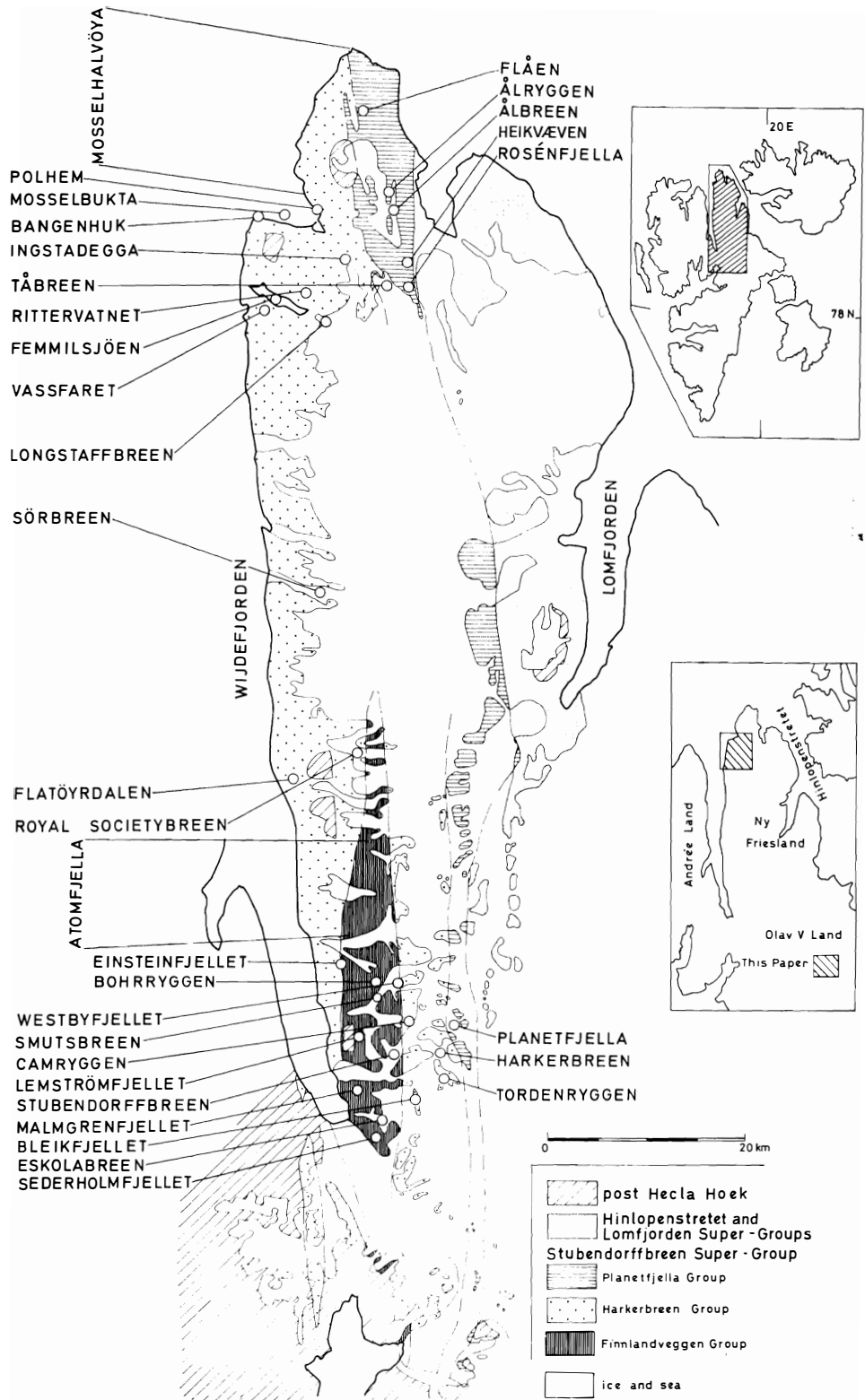


Fig. 1. Diagrammatic map of Ny Friesland to show the outcrops of the main stratigraphical divisions of the Lower Hecla Hoek, after HARLAND, WALLIS and GAYER (1966). Lower inset shows the area described in this paper.

HARLAND and WILSON (1956) and discussed and revised (HARLAND 1959; HARLAND, WALLIS and GAYER, 1966); a summary of the stratigraphical scheme is given in Fig. 2. The petrology of the Harkerbreen Group, that constitutes the bulk of the strata in the area, has been described (GAYER and WALLIS, 1966). The petrology of the Planetfjella Group, that includes the only other strata of the area, has been described (WALLIS 1969).

This paper describes the post-depositional events that have affected the Hecla Hoek sediments and an outline only of the stratigraphical succession is included.

The earliest significant structural work in Ny Friesland was undertaken by BLOMSTRAND (1864) mainly in the extreme north of the peninsula. Other workers attempted isolated studies but the knowledge of both the stratigraphy and structure was not greatly advanced until the systematic work of the Cambridge Spitsbergen Expeditions from 1938 to the present. At the time that the present work was undertaken (1961–1963, see under "Field Work" in *Polar Record*, Vols. 11 and 12), HARLAND (1941 and 1959) had formulated an account of the major structure of Ny Friesland. This indicated a prolonged period of east-west compression resulting in a sequence of tectonic regimes (HARLAND and BAYLY, 1958). It thus became important to study a small part of the area in detail to determine a structural sequence for part of the belt and the unpublished field notes of M. B. BAYLY, based on the Cambridge Expeditions of 1954 and 1955, guided the author to choose the Femmilsjøen area for this study. For the Femmilsjøen area the following sequence has been recognised:

The intrusion of a set of dolerite sheets into a thick sequence of sedimentary and volcanic rocks preceded the earliest detected deformational phase of the Caledonian Orogeny. This phase is evidenced by isoclinal folding about north-south axes accompanied by amphibolite facies regional metamorphism. Following a period of relaxation of the east-west compressive stress, during which a second set of dolerite sheets and a small boss of granodiorite were intruded, renewed compression produced both large and small scale medium tight folds again on north-south axes. This later stage of folding was prolonged, resulting in the flowage of anticline crests into the adjacent synclines. The metamorphism, which reached its climax during the early stage of folding, gradually waned throughout the later episodes of the sequence, giving retrogressive metamorphic assemblages accompanying the last stage of compression. The final episode of the sequence was the development of oblique joints and strike-slip oblique faults.

The petrographical nomenclature of metamorphic rocks used in this paper is that formulated in WALLIS, HARLAND, GEE and GAYER (1968). In outline, the scheme used is shown in Fig. 3.

Stratigraphical summary

Nowhere in Spitsbergen are the sediments which constitute the Lower Hecla Hoek found in an unaltered state; indeed, for the most part they have been subjected to intense deformational forces and are now highly folded and metamorphosed to the amphibolite facies of regional metamorphism. It is within this

N. & W. NY FRIESLAND		S. & E. NY FRIESLAND			
LOMFJORDEN SUPERGROUP		LOMFJORDEN SUPERGROUP		ABOVE	ROCKS
ROSÉNFIJELLA MEMBER ÅLBREEN MEMBER VILDADALEN FORMATION 3,250m ÅLRYGGEN MEMBER TÅBREEN MEMBER		PLANETFJELLA GROUP (undivided)		PLANETFJELLA GROUP	STUBENDORFFBREEN SUPERGROUP
FLÅEN FORMATION 1,500m not exposed SÖRBREEN FORMATION 250m		TORDENRYGGEN FORMATION 500-1,000m		HARKERBREEN GROUP	
VASSFARET FORMATION 600m BANGENHUK FORMATION 2,000m FEMMILSJØEN MEMBER FLATØYRDALEN MEMBER		BLEIKFJELLET			
RITTERVATNET FORMATION 350m POLHEM FORMATION 900m not exposed		CAMRYGGEN GNEISS MEMBER FORMATION 2-3,000 m			
		SMUTSBREEN FORMATION 1,200m WESTBYFJELLET MEMBER BOHRRYGGEN MEMBER			FINNLANDVEGGEN GROUP
		EINSTEINFJELLET Mb			
		ESKOLABREEN FORMATION 1,500m LEMSTRØMFJELLET MEMBER MALMGRENFJELLET Mb SEDERHOLMFJELLET MEMBER			

Fig. 2. Summary chart of Lower Hecla Hoek stratigraphy in central north Spitsbergen.

setting that the stratigraphy of the Stubendorffbreen Supergroup has been determined, and although the following summary of the stratigraphy of those parts of the supergroup found in the Femmilsjøen region appears to be broadly consistent, the detail is either obliterated by deformation and metamorphism, or awaiting more specific investigation.

The rocks of the area constitute all but the lowest part of the Harkerbreen Group and the basal 400 m of the overlying Planetfjella Group; in all, some 4,500 m of a variable succession of metasediments are represented (see Fig. 2). Petrological details of the Harkerbreen Group are given in GAYER and WALLIS (1966), and of the Planetfjella Group in WALLIS (1969).

The Planetfjella Group

Only the basal part of the lower formation is present and is formed of c. 400 m of a medium grained schistose pelite/subpelite with occasional thin (1 m) bands of foliated biotite psammite. Staurolite and kyanite, together with ubiquitous megacrystic garnet are present in pelitic lithologies. Amphibolites have not been recorded from this formation.

The Harkerbreen Group

Sørbreen Formation. – 265 + m of foliated psammites and quartzites with thin interbanded schistose quartzose-polymictites and at least three bands of a distinctive meta-acid-tuff. Occasionally the psammites contain up to 20% of potash-feldspar but in general the plagioclase feldspar of albite-oligoclase composition predominates. Foliated amphibolites occur as bands varying in thickness from less than 1 cm up to c. 30 m and are in all cases conformable with the foliation in the neighbouring psammites.

Vassfaret Formation. – 600 m of predominantly schistose polymictites; divisible into three.

c) 320 m of schistose polymictites with microquartzite laminae and schistose amphibolites.

SUMMARY OF COMPOSITIONAL CLASSIFICATION OF METAMORPHIC ROCKS					
Group Name	QUARTZ GROUP	MICA GROUP	FELDSPAR GROUP	PYROBOLE GROUP	CARBONATE GROUP
minerals	quartz	andalusite chlorites chloritoid cordierite garnets kyanite micas sillimanite staurolite	microcline plagioclase orthoclase	amphiboles pyroxenes epidotes	calcite dolomite
Percentage Mineral Groups					
100%					
80%	QUARTZITE			HORNBLENDITE PYROXENITE	
Dominant					
Majority	PSAMMITE	PELITE	FELDSPATHITE	AMPHIBOLITE	MARBLE
50%					
Minority					
35%	SUBPSAMMITE	SUBPELITE	SUBFELDSPATHITE	SUBAMPHIBOLITE	SUBMARBLE
Mixed					
0%	POLYMICTITE				

Fig. 3. Summary of the nomenclature based on modal composition used for the metamorphic rocks discussed in this paper. (After WALLIS, HARLAND, GEE and GAYER 1968.)

b) 40 m of an upper schistose megacrystic calcite-hornblende-garnet-polymictite and a lower colour-banded granulose psammite with varying proportions of hornblende and epidote producing the banding. Both horizons contain schistose amphibolites.

a) 240 m of predominantly schistose polymictites with a distinctive concretionary and finely laminated subpelite and sharply defined bands of lineated or granulose potash-feldspar-feldspathites and schistose amphibolites.

Bangenhuk Formation. – C. 2,000 m of predominantly feldspathites; divisible into two members.

b) *Femmiltsjoen Member.* 1,250 m of poorly foliated, lineated potash-feldspar megacrystic feldspathites and schistose amphibolites. Two thin lenses of lithologies very similar to those of division a) of the Vassfaret Formation occur in the north of the area and the member is separated from the underlying member by a further 100 m thick similar horizon.

a) *Flatøyrdalen Member.* 735 m of banded lithologies characterised by a high proportion of feldspar, particularly potash-feldspar which may constitute up to 47% of the rock. In addition to the poorly foliated feldspathites, bands of granulose psammites and schistose amphibolites occur.

Rittervatnet Formation. – 350 m of varied lithologies. Three divisions can be recognised in the west, merging to one homogeneous unit in the east.

c) 72 m of poorly foliated psammites, finely interbanded, with subordinate granulose psammitic-feldspathites, oligoclase-feldspathites, schistose amphibolites and schistose biotite-polymictites. Two thin schistose meta-tilloid horizons occur within the division.

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

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

Polhem Formation. – 900 m of dominantly poorly foliated oligoclase-psammites interbanded with schistose amphibolites.

The units outlined above outcrop as more or less parallel north-south striking bands. Repetition occurs on a small scale in the limbs of intermediate and small scale folds but over the region as a whole a large part of the sequence is duplicated in the limbs of the major anticlinal axis that runs north-south through the centre of the region; cf. “the Atomfjella dome” of south Ny Friesland (HARLAND 1959). Thus in the west of the region progressively older units of the succession are exposed in a west-east traverse from the Sørbreen Formation in a belt along the shores of Wijdefjorden to the lowest part of the Polhem Formation along the axial trace of the anticline, just east of Longstaffbreen. Within this westerly limb of the anticline repetitions of parts of the succession occur in intermediate scale folds on the limbs of which yet smaller scale folds cause very minor repetitions, too small to affect the outcrop of the stratigraphical units described. To the east of the main anticlinal axis progressively younger units outcrop but the upper

part of the succession is missing beneath the tectonic contact of the Planetfjella Group.

Individual horizons can thus be followed both along the strike in a north-south direction and intermittently down the dip in the limbs of both intermediate and large scale folds. Due to the degree of deformation and to the uncertainty of correlation it is very difficult to detect minor variations in the metasediments of any one particular horizon in successive fold limbs. However, major changes such as that seen in the Rittervatnet Formation when it is traced across the region are readily detected (GAYER and WALLIS, 1966).

The sediments would appear to be largely clastic in origin with deposition commonly in shallow water. The nature of the amphibolites and the high proportion of potash-feldspar in most of the feldspathites is attributed to a pyroclastic origin deriving from basic and acid eruptives respectively (HARLAND and WILSON, 1956; HARLAND, WALLIS and GAYER, 1966; GAYER and WALLIS, 1966).

Post Hecla Hoek intrusive rocks

BASIC SHEETS

In addition to the schistose amphibolite bands there is, in the west of the area, a belt of lenticular basic bodies running NNW–SSE between longitude $15^{\circ}40'E$ and $16^{\circ}10'E$. In many localities strings of these lenses can be shown to represent boudins of once continuous bands, whilst in other instances extremely thick lenses, up to 300 m thick, appear to have no obvious connection with lenses north or south along the strike.

In many of the lenses the margins consist of schistose amphibolite and the centres of a metadolerite retaining an igneous ophitic or subophitic texture. They represent metamorphosed basic igneous intrusions.

Due to the intense deformation that the intrusions and country rocks have undergone, it is not clear what the original intrusive relations were. The boudins commonly show rotation due to shear and their margins are usually highly sheared. In some instances a slight discordance can be detected, but generally they are now conformable with the foliation in the host rock. It is proposed to refer to the intrusions as 'sheets' to avoid the unanswered question of whether they were dykes or sills.

In the following account it is shown that the dolerite sheets represent two sets of intrusions, separated by a deformational phase of the Caledonian Orogeny.

Composition of basic sheets

Although all the sheets have been boudined and have undergone regional metamorphism to the amphibolite facies, a fairly accurate estimate of the original composition can be obtained from the cores of the boudins that still retain an indication of their original igneous mineralogy.

The majority are quartz-hypersthene-dolerites. The quartz is intergrown with

potash-feldspar forming a micrographic texture in small interstitial areas between labradorite laths. The pyroxene and labradorite form a subophitic texture, the proportion of orthopyroxene varying considerably from one sheet to another but commonly being about 30% of the total pyroxene. With varying proportions of orthopyroxene to clinopyroxene the composition of the sheets ranges from quartz-dolerite to quartz-augite-micronorite to quartz-micronorite.

Only one instance of an olivine-hypersthene-dolerite has been found in an exposure of two boudins near the coast south of Bangenhuk. This rock contains c. 20% of euhedral olivine with thin rims of a pale green hornblende against labradorite. The labradorite makes up c. 10% of the rock and is intensely clouded by material with too small a grain size to resolve optically. The remaining 70% is made up of augite and subordinate hypersthene.

In an exposure of a string of boudins just west of the easternmost stream running into Femmilsjøen from the north, a metadolerite sheet with a unique composition has been recorded. The rock is an augite-micronorite with primary biotite and hornblende. The hypersthene is enclosed in intergrown augite and pale brown hornblende and the biotite forms idiomorphic grains within both the labradorite laths and also the hornblende and augite intergrowths. It is possible that this assemblage may be the result of assimilation of the surrounding biotite-polymictites.

The effects of metamorphism on the basic sheets

A study of the fabric and mineralogy of the basic lenses has revealed a concentric arrangement of zones of varying metamorphic recrystallisation; up to five zones can be recognised in one lens.

Zone 1. – Least altered inner core (Plate 1A), varying in thickness from 0–100 m, largely dependent on total width of sheet. Sometimes patches of zone 1 occur surrounded by zone 2. Ophitic or subophitic texture between pyroxene and feldspar is perfectly preserved. The only sign of metamorphism is a slight clouding of the plagioclase feldspar which has a composition of An 52–54%. Olivine, when present, has a thin rim of pale green hornblende onto the plagioclase, that may represent an original igneous texture or may be a result of metamorphism.

Zone 2. – Igneous ophitic or subophitic texture between pyroxene and feldspar preserved (Plates 1B, 2A and B, and 3A), varying in thickness according to width of sheet and relationship to zone 1. *Pyroxene* is irregularly rimmed with a quartz and pale green hornblende intergrowth. Surrounding this irregular rim is a more distinct and uniform rim of blue-green prismatic hornblende and garnet onto the plagioclase. Occasionally the garnet forms an outer complete rim against the plagioclase. The garnet is always idioblastic against plagioclase and is usually xenoblastic against hornblende (Plate 2A). The pyroxene cores have exsolution rods of ilmenite parallel to (010) and (100) of the pyroxene. *Plagioclase Feldspar* is intensely clouded with inclusions of clinozoisite or epidote, commonly forming along definite planes in the feldspar (Plate 2B). The plagioclase composition is An 45–52%, being more sodic in clear rims against the garnet and hornblende

of the pyroxene rims. The original lath shaped grains of the feldspar are preserved, although the margins are more irregular. *Magnetite* has complete garnet rims against plagioclase and blue-green hornblende against pyroxene (Plate 3A).

Zone 3. – Igneous ophitic or subophitic texture indistinctly preserved (Plate 3B). The zone is usually one or two metres thick and merges imperceptibly into zone 4. *Pyroxene* completely altered to a fine grained granoblastic aggregate of pale green hornblende with poikilitic quartz inclusions, rimmed with continuous blue-green prismatic hornblende. *Plagioclase* with occasional garnet and epidote inclusions. Recrystallised clear grains with a composition of An 43–44% more or less completely destroying the original lath shaped outline. *Magnetite* forms intergrowths with blue-green hornblende or red-brown biotite or as distinct areas with garnet rims to plagioclase.

Zone 4. – Complete recrystallisation to a granulose quartz-amphibolite (Plate 4A). Usually rather thin, one to two metres thick, with a sharp contact with zone 5. *Hornblende* forms a coarse grained granoblastic fabric with pale green prismatic grains. *Plagioclase* is clear, forming a granular mosaic, with a composition of An 23–28%. *Magnetite* forms idioblastic grains. *Garnet* forms idioblastic porphyroblasts with occasional poikiloblastic fabric of included quartz and epidote grains. *Epidote*, *Sphene* and *Apatite* form constant accessories.

Zone 5. – Marginal zone, composed of schistose amphibolite with foliation parallel to the margin (Plate 4B). Usually constant thickness of about three to five metres thick. *Hornblende* forms blue-green tabular grains with an oriented fabric, showing the schistosity. *Plagioclase* forms a mosaic of clear granular grains with the hornblende and has a composition of An 24–27%. *Epidote* grains oriented parallel to the hornblende schistosity. *Potash-feldspar* occurs in the quartz-hornblende mosaic within the boundaries of those intrusions occurring within the potash-feldspar-feldspathites. *Sphene*, *Apatite* and *Garnet* occur as accessories in most cases.

The boudined sheets can be grouped into two categories.

- 1) Those which are generally sigmoidally shaped and with a NNW trend. In all cases they have a thick foliated margin and normally display all five zones, although some of the narrower lenses may have the zones possessing igneous texture missing.
- 2) Those which show straight necking and trend in a more northerly direction than type 1). In the Bangenhuk Formation feldspathites they have thin or no foliated margins.

In either case the rock representing the basic sheet in the neck of the boudin is invariably a foliated and lineated schistose amphibolite of zone 5 mineralogy and texture. This rock is indistinguishable from the schistose amphibolites with sharply defined boundaries referred to as pyroclastic deposits above and it may be that some of the narrower amphibolites with sharp contacts represent thin metamorphosed basic sheets.

Contact relations of type 2) boudins, indicating two sets of dolerite intrusion

Many boudins of type 2) are bordered on either side by up to 5 m of a feldspathite possessing an atypical texture gradually merging into a feldspathite with the normal lineated gneissose fabric. The upper (west) contacts of the boudins show thin (less than 1 m) recrystallised margins of zones 4 and 5 against coarse grained, poorly *lineated* feldspathite, whilst the lower (east) contacts have margins of igneous textured zone 3 against coarse grained *granulose* feldspathite. Where the margins retain their igneous texture, they are consistently finer grained than the centres of the boudins and the textures are porphyritic with phenocrysts of augite and lath shaped plagioclase set in a fine grained mass of green hornblende (Plate 5A). Occasionally thin veins of the bordering granulose feldspathite cut the boudin margins and sheet like xenoliths of granulose feldspathite are isolated in the metadolerite margins. In two instances numerous veins of the granulose feldspathite along the boundary penetrate the finer grained margins of the metadolerite, forming a ramifying network and isolating angular blocks of metadolerite (Fig. 4). Within the margins of the metadolerite there are many isolated grains of quartz, oligoclase and potash-feldspar and small patches of feldspathite with indistinct borders.

In thin section the granulose feldspathite along the margins of the metadolerite and in the ramifying veins consists of a heterogranular rock with large grains of

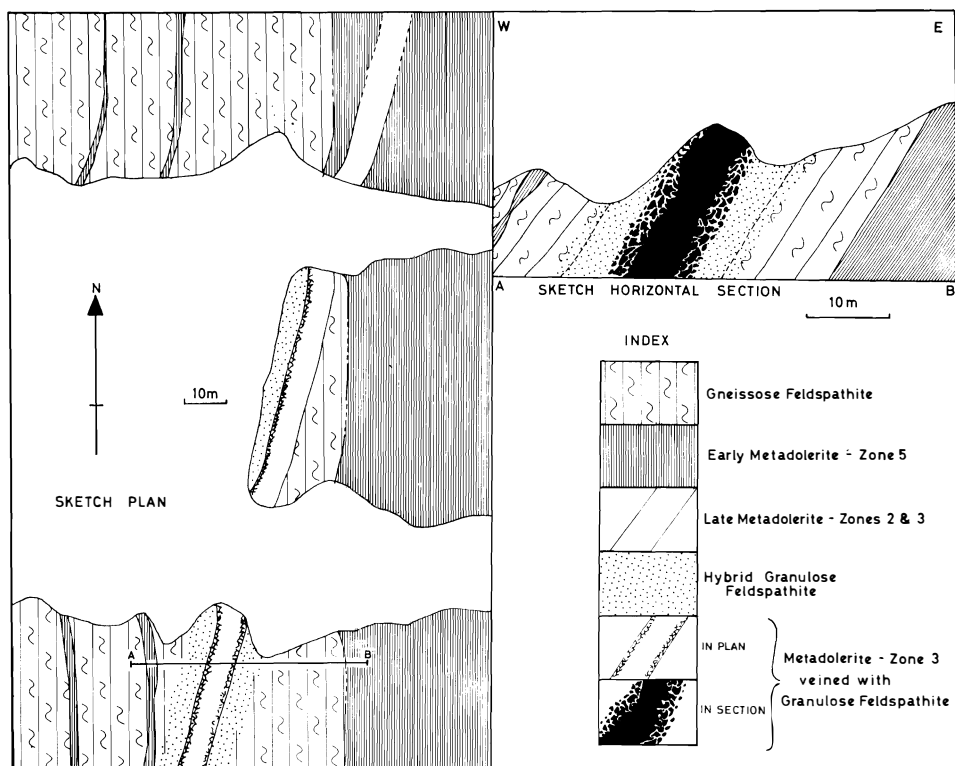


Fig. 4. Diagrammatic representation of the rheomorphic effects shown at the edges of the younger set of metadolerite sheets intruding the Femmilsjøen Member south of Femmilsjøen.

quartz, oligoclase and potash-feldspar set in a fine grained ground-mass of granular hornblende, biotite and clouded laths of plagioclase, with inclusions of epidote and garnet, and areas of quartz/plagioclase micrographic intergrowth. There are also small areas of lath shaped clouded grains of plagioclase set in fine grained granular blue-green hornblende similar to the marginal metadolerite. The large grains of potash-feldspar have a continuous rim of fine grained quartz-plagioclase myrmekite, representing a soda replacement of the potash-feldspar.

The fine grained margins of the metadolerite (Plate 5B) consist of clouded lath shaped grains of plagioclase with inclusions of garnet and epidote set in a fine grained granular hornblende ground-mass. The isolated grains of quartz, plagioclase and potash-feldspar show reaction phenomena with the enclosing metadolerite. The quartz grains are invariably surrounded by a rim of blue-green hornblende grains and the potash-feldspar is rimmed by a quartz-plagioclase myrmekite, sometimes replacing the entire grain, and very similar to the potash-feldspar grains in the adjacent granulo-feldspathite. The plagioclase is a soda oligoclase and does not show the same amount of clouding as do the plagioclase laths in the enclosing metadolerite. The patches of feldspathite are similar to the granulo-feldspathite.

The centre of the sheet is a normal medium grained metahypersthene dolerite of zones 2 and 1.

The following explanation is offered for these contact features.

Firstly the presence of foliation, sometimes at both margins and sometimes in only one and in all cases in the boudin necks, indicates that the dolerite sheets have been subject to deformation sufficient to boudin the sheets and have been metamorphosed to the amphibolite facies. The lower margins of some of the metadolerites in which the igneous texture is retained are thought to have been in some manner protected from the deformation.

Isolated crystals of quartz, plagioclase and potash-feldspar in the margin of a sheet show reaction phenomena with the enclosing metadolerite. This is interpreted as evidence of instability with respect to the dolerite and suggests that the grains were xenocrysts in the dolerite, probably derived by assimilation of the country feldspathite. A similar interpretation is placed on the patches of feldspathite in the metadolerite, which it is thought represent partially assimilated xenoliths.

The texture of the bordering feldspathite, the reaction rims to the potash-feldspar grains and the ramifying network of veins of feldspathite into the metadolerite margin is interpreted as rheomorphism at the boundary of the metadolerite with partial melting of the feldspathite.

The absence of foliation in these rheomorphosed rocks and the associated metadolerite margins compared with the thick foliated zones around type 1) boudins suggest that the two types of boudins represent two igneous intrusive periods separated by a period of deformation in which the earlier sheets and the country rock received a foliation.

Where the margin of the sheet retains its igneous texture, the finer grained margin shows that the intrusion cooled against country rock but was not chilled to a glass.

In only one case has the intrusive relationship between the two types of boudined sheet been seen. In this instance a thick metadolerite with a wide foliated margin is cut by a narrow metahypersthene-dolerite with margins still retaining an igneous texture. In all other known cases the point of intersection has been obliterated by later deformation.

The conditions of metamorphism of the basic sheets

The zonal arrangement in the metadolerite boudins raises questions concerning the conditions of metamorphism.

The zones 2–5 are very similar to stages 1–4 of the progressive metamorphism of basic dykes during the Laxfordian metamorphism in the Lewisian of Scotland where SUTTON and WATSON (1950) attributed the differences in metamorphic product to an increase in temperature and pressure conditions during metamorphism. This explanation cannot be applied in the case of the Ny Friesland metadolerites where the changes occur across one metadolerite body. The four stages in the metamorphism of basic dykes in the Bakersville and Roan mountain areas of N. Carolina (WILCOX and POLDERVAART, 1958) are analogous to the Ny Friesland zones but at a higher facies of metamorphism. WILCOX and POLDERVAART attributed the changes to variations in water vapour pressure, an interpretation that would appear to explain satisfactorily the zoning in the Ny Friesland metadolerites.

The zones undoubtedly show increasing hydration of the igneous pyroxenes to hornblende and of the igneous labradorite to epidote, garnet and soda plagioclase. However, the foliated margins – zone 5 – have a syn-tectonic fabric, whilst all the remaining zones have a non-oriented static fabric. This implies that the margins were subjected to stress during the metamorphism whilst the interior of the sheets recrystallised in a non-stressed condition.

It would appear that two factors have contributed to the zonation of the sheets. Firstly a decrease in water vapour pressure towards the centre of the sheets and secondly a decrease in shear stress from the margins towards the centres.

It is possible that the two are connected in a manner similar to that described for metamorphosed gabbroic rocks in the Adirondack mountains (BUDDINGTON 1952); the margins of the competent anhydrous dolerite sheets against the less competent hydrous feldspathite became regions of high shearing stress during the deformation, allowing hydrous fluids to permeate into the dolerite more freely where the dolerite was strongly deformed and less freely towards the undeformed central portions. The possibility that the two factors were unrelated and in fact made their impressions on the dolerites at different times is discounted. If it were the case, the increasing hydration of the dolerites towards the centres of individual sheets could be explained as a result of intrusion of the dolerites at depth and under considerable load pressure into country rock which was still hot. This would allow water from the feldspathites to enter the dolerites and react with the igneous minerals to produce the zonation now observed. At a later date, during the deformation of the sheets, the margins recrystallised under shearing stress producing the syn-tectonic fabric of zone 5. It would then be expected to find

the foliated zone 5 against varying zones of hydration depending on the extent to which foliation has been developed. The fact that the foliated zone 5 is always found against zone 4 suggests a causal relationship and indicates the former explanation.

The tectonic conditions at the time of emplacement of the basic sheets

From a structural viewpoint it is important to understand both the tectonic conditions at the time of emplacement of the dolerites and also the effects of later deformational phases. Indeed, a full understanding of the one cannot be gained without an understanding of the other.

The presence of chilled margins (SUTTON and WATSON, 1950) and the evidence of xenolithic margins and small penetrating dykelets from the main dolerite dyke into the country rock (WILCOX and POLDERVAART, 1958) have been used to demonstrate relatively brittle, unstressed country rock. O'HARA (1961 and 1962) has observed granulose amphibolite metadolerites against granulite facies country rock. He concluded that the dykes were intruded into hot, unstressed country rock as did TARNEY (1963) who recognised eight types of basic intrusions in the Assynt region of the N. W. HIGHLANDS. He listed these in their approximate order of intrusion and pointed out that the earliest were the most altered and the latest were the least altered. He concluded that these observations agreed with O'HARA's conclusion that the Scourie dykes were intruded into the gneiss during the waning metamorphic effects of the early regional metamorphism.

Using these criteria in considering the dolerite dykes of Ny Friesland, no conclusions concerning the emplacement of the earlier set of dolerites can be made; their subsequently developed foliated margins obliterate the earlier marginal textures. The correlation between this foliation and that developed during the earliest deformational phase indicates the intrusion of the dolerites before the onset of orogenic conditions. The later set of dolerites, however, show relationships strongly suggestive of intrusion whilst the country rocks were still hot, although the surrounding feldspathites are of comparable metamorphic facies to the metadolerite margins. The presence of rheomorphic margins in the country rock may support this hypothesis. The absence of a foliated margin in many cases suggests that the rocks were unstressed at the time of intrusion, and the presence of xenolithic margins suggests that the country rocks were fairly rigid.

The later deformation and metamorphism would account for the presence of the foliated margins in many of the sheets of this period.

ACID INTRUSIONS

In addition to the amphibolite and metadolerite sheets there are many fine-grained leucocratic aplite dykes intruded most commonly into the feldspathites of the Bangenhuk Formation.

These are normally thin, 10 cm to 3 m wide, and are almost always parallel to the strike of the gneissosity in the enclosing feldspathites. Frequently, however, they dip at a high angle to the gneissose foliation of the feldspathites. They are

finegrained granular rocks, being composed of a sutured mosaic of quartz, potash-feldspar and oligoclase. The oligoclase is frequently clouded with small grains of sericite and epidote. Small embayments of myrmekite occur around the margins of the potash-feldspar grains.

These aplitic intrusions appear to be connected with a small boss of granodiorite exposed in the core of an antiform just south of Femmiltsjøen. This boss is c. 100 m wide and 400 m long, the long axis being approximately parallel to the gneissosity in the feldspathite. The contacts are typically intrusive with stoping of the banded psammites and polymictites of the Flatøyrdalen Member of the Bangenhuk Formation and small penetrating veins of the granodiorite into the wall rock (Fig. 5).

The central portion of the intrusion is composed of a porphyritic granodiorite with large phenocrysts of potash-feldspar showing microcline twinning and embayments of myrmekite around their margins. The groundmass is composed of a coarse grained mosaic of quartz and oligoclase, both of which have been recrystallised to a finer grained sutured fabric. The oligoclase is intensely clouded with sericite. Small amounts of biotite and magnetite are present. In widely spaced but definite bands biotite is more concentrated and aligned to give a very crude foliation. Towards the margin the rock becomes finer grained and loses its por-

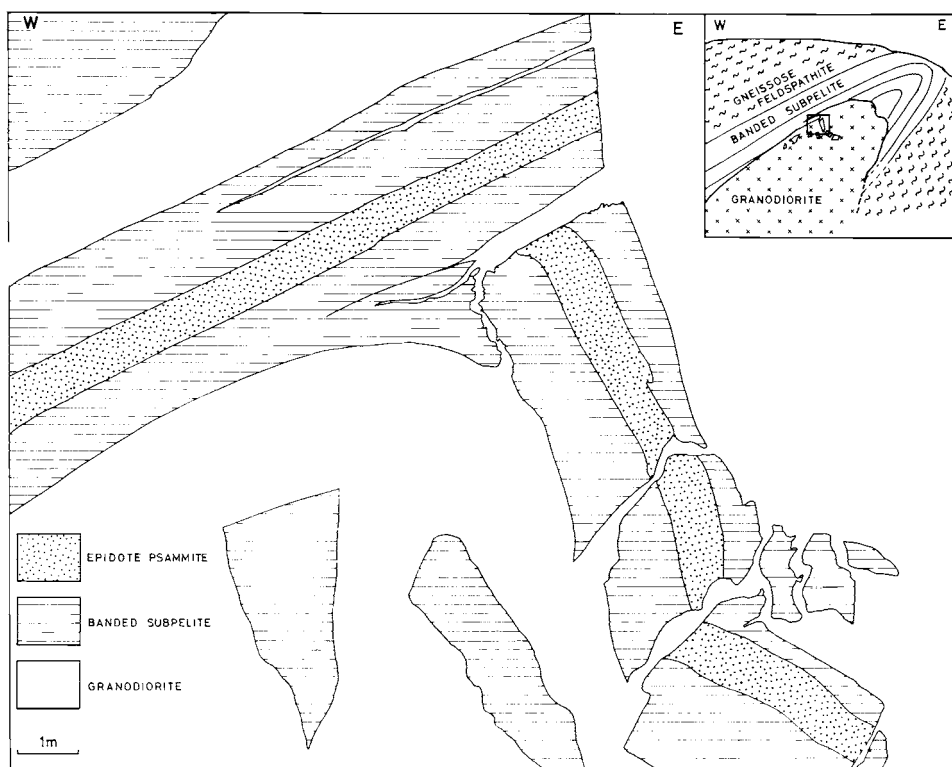


Fig. 5. *Stoping of the metasediments at the contact with a small granodiorite intrusion into the Bangenhuk Formation south of Femmiltsjøen (drawing from a colour transparency).*

Inset to show the relative position in the intrusion.

phyritic texture. The foliation is slightly better developed and is seen to be approximately parallel to that of the bordering rocks. This finer grained rock is very similar in appearance to the aplite sheets.

Structural analysis

The tectonic structures developed in the Lower Hecla Hoek sediments and associated intrusives are conveniently described and analysed by treating the following five categories of structure independently: folding, foliation, lineation, boudinage, and jointing and faulting. The great variety of style and scale on which the various structural elements are developed makes a comprehensive description of all possible varieties impractical in an account of this nature. In general the descriptions are limited to the commonly occurring types of structure with an indication of the variation and to those structures that appear to be more significant in the interrelation of the different categories. The study leads to the geometrical and time relationships between the various categories of structure.

FOLDING

Folds occur abundantly in all the formations within the region, with the exception of the Femmilsjøen Member of the Bangenhuk Formation.

Style

In general the folds can be grouped into three distinct styles:

- 1) near isoclinal geometrically similar folds with angular to sub-angular hinges and a limb to hinge thickness ratio of between 7:1 and 10:1. (Plates 6A and 6B.)
- 2) tight folds with an angle between the limbs of between 40°–60°; geometrically similar folds in part disharmonic within discrete bands of differing lithology, with sub-angular to rounded hinges and a limb to hinge thickness ratio of between 1.5:1 and 3:1. (Fig. 6; Plates 7A and 7B.)
- 3) open folds with an angle between the limbs of greater than 90°, in part concentric and in part between concentric and similar, with rounded hinges in all lithologies.

Variations in style within the three groups occur in different lithologies and appear to be caused by the differing competency of the lithology folded. Folds in relatively incompetent lithologies, e. g. pelites, polymictites, potash-feldspar feldspathites, and marbles have more angular hinges and a smaller angle between the limbs than those developed in relatively competent lithologies, e. g. psammites and amphibolites. The three distinct styles of folding would thus seem to reflect different stress and temperature conditions operating during their formation.

Many of the folds of style 2 do not have a constant thickness measured parallel to their axial surfaces and are therefore not pure similar folds; the thickness is usually greater in the fold limbs. These folds are commonly developed in banded psammite and subpelite lithologies, where the folds in the more competent psammite bands have been flattened during the deformation, giving rise to modi-

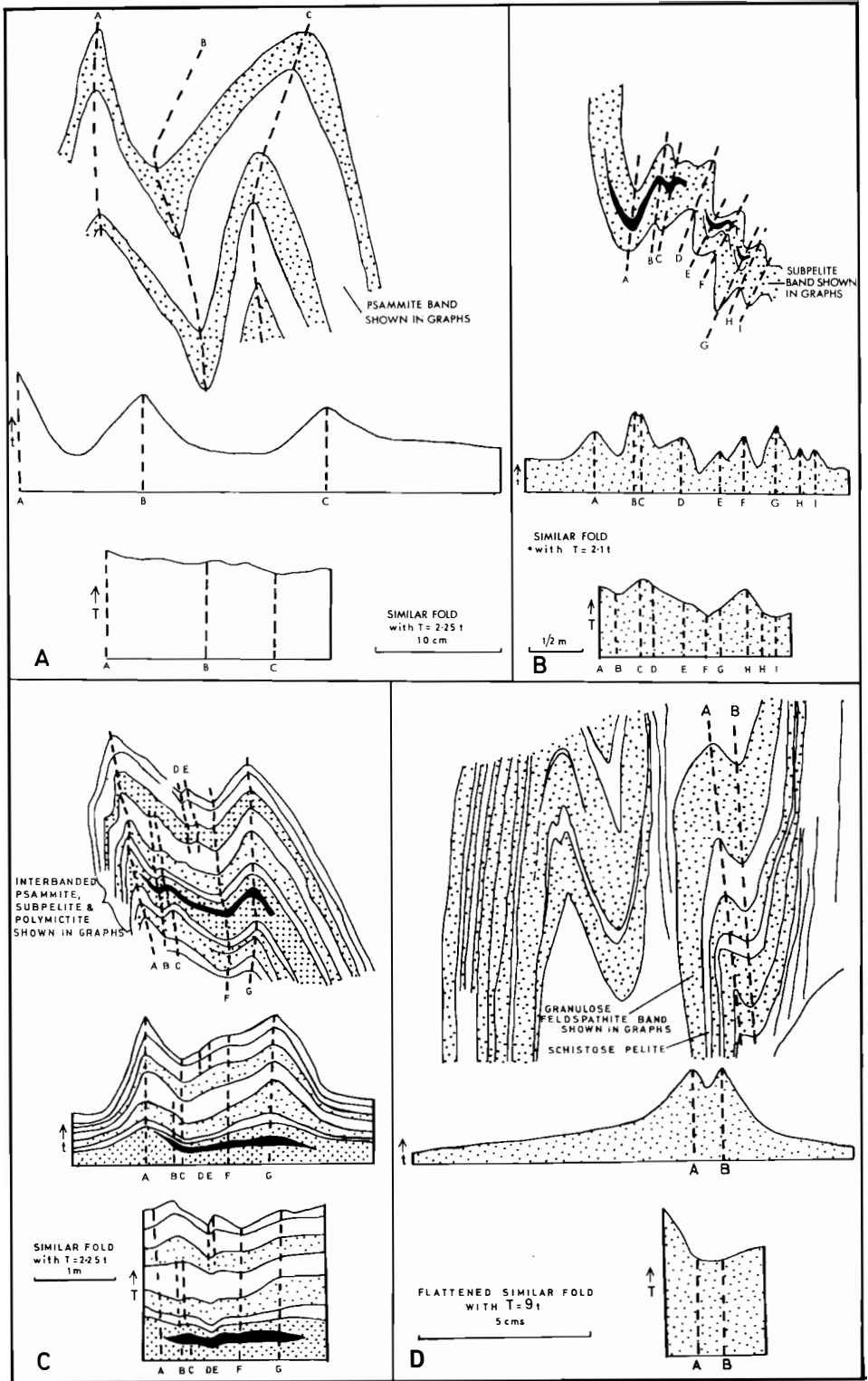


Fig. 6. Four examples of phase II folds to show the variation in style. The graphs illustrate the variation in thickness of the bands around the fold; 'T' represents the thickness measured parallel to the axial surface traces of the folds, and 't' the thickness perpendicular to the banding.

fied similar folds (Plate 8A) (RAMSAY 1962a). Many of the style 2 folds in the psammities interbanded with amphibolites are disharmonic against either an unfolded amphibolite band or a thrust amphibolite band. Away from the amphibolite, the fold approaches a pure similar style.

Phases of folding

Wherever folds of differing styles coincide, style 2 folds re-fold style 1, and style 3 folds re-fold both style 2 and 1. Thus, although the fold axes of all three styles are more or less homoaxial, with shallow north or south plunges, it would appear that the three styles of folding represent three consecutive phases of folding (see e. g. WEISS 1959 and RAMSAY 1960); each phase being less intense than the previous. It is impossible to conclude from purely geometrical considerations whether the phases were a result of a continuous waning stress field or whether they represent two or three separate periods of stress activity (e. g. FLINN 1962, and WYNNE-EDWARDS 1963).

Phase I folding – the earliest folds recognised in the area. In all cases the folds are of style 1 and do not appear to vary with the lithology folded. In the areas where sufficient measurements of their attitude have been made, the fold axes plunge both to the NNW and to the SSE and lie in a plane striking 345° and dipping steeply to the east (Fig. 7). This arrangement suggests that the folds have been re-folded by geometrically similar folds and confirms the observed folding of phase I axial surfaces by phase II similar folds seen in many outcrops throughout the area (Plates 6A and 6B). In the majority of cases the pattern of superimposed folding seen in vertical dip-sections indicates parallelism of the axes of the two phases of folding (Plate 6B) (RAMSAY 1962b). In some sections in the west of the region the patterns suggest a lack of parallelism (Plate 6A), agreeing with the slight obliquity of phase II and I fold axes (cf. Figs. 7 and 8).

Only small and intermediate scale folds of this generation have been developed and no large scale repetitions of the stratigraphical units appear to have resulted from phase I folding.

Phase II folding. – Folds of this phase are of style 2 and form the most conspicuous folds throughout the area (Plates 7A and 7B). The style is rather variable, being to some extent dependent on the competence of the lithology folded. In massive psammities and amphibolites the hinges are rounded to sub-rounded and the angles between the limbs vary between 30° to 50° . In pelites, subpelites and thinly banded psammities, and polymictites the hinges are sub-angular with an angle between the limbs of about 30° . These folds approach style 1 folding but never show the extreme thickening in the hinge associated with style 1.

Throughout the area, except in the extreme east of the region, the fold axes plunge about 10° to 180° (Figs. 8 and 9). The axial surfaces dip variably to the east and west and appear to have been folded by a large scale antiform of phase III folding (Fig. 10). In the east of the region the fold axes plunge up to 10° to 360° which may represent a change in orientation of the stress or later cross-folding or an originally uneven surface.

Folds on all scales up to about 500 m axial surface separation are developed and give rise to major repetitions of stratigraphical formations.

Phase III folding – the latest folds recognised in the area. The folds are always of style 3 folding and are best developed in the central and eastern regions. The fold axes plunge about 10° to 180° (Fig. 10) and are parallel to the axes of phase II folds. The axial surfaces are more or less planar and dip steeply to the east and west or are vertical.

A major antiform of this generation forms the largest fold of the area, giving predominantly west-dipping surfaces in the west and east-dipping surfaces in the east of the area. This antiform repeats most of the stratigraphical succession across the area.

Overall pattern of folding. – The most conspicuous folds on both small and intermediate scales are phase II structures. There are many localities where the geometrical relationship between folds of differing scales can be seen but the best suited to study is an intermediate antiform-synform pair exposed in a gully leading from the south into Mosseldalen. The synform, with an axis plunging 12° to 185° and an axial surface dipping 40° east, is very well exposed (Plate 7B)

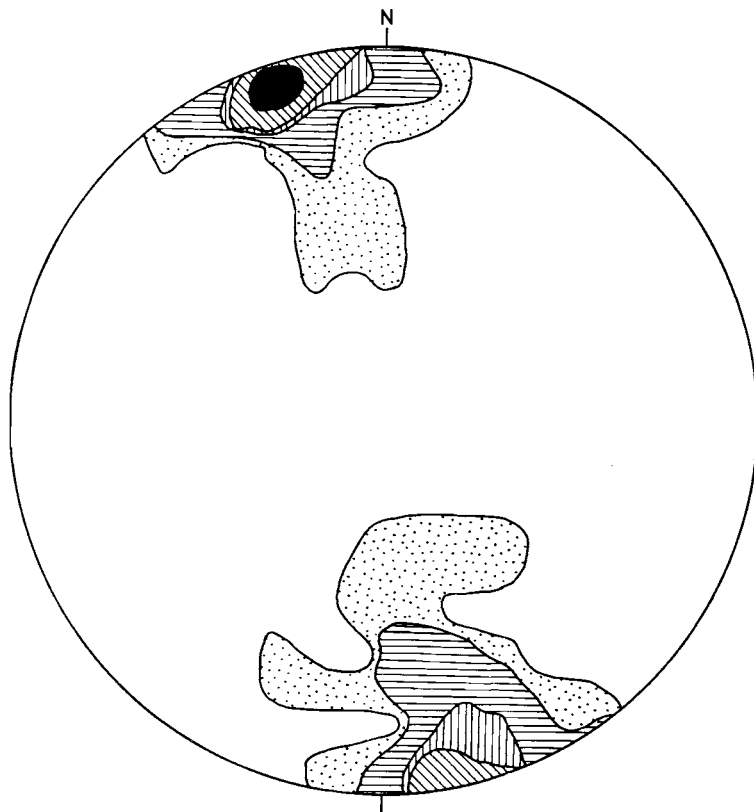


Fig. 7. Stereographic Lower Hemisphere projection of poles of phase I linear structures (fold axes, crenulation lineations and mineral lineations), contoured at 1%, 3%, 6%, 12% and 19% per 1% area.

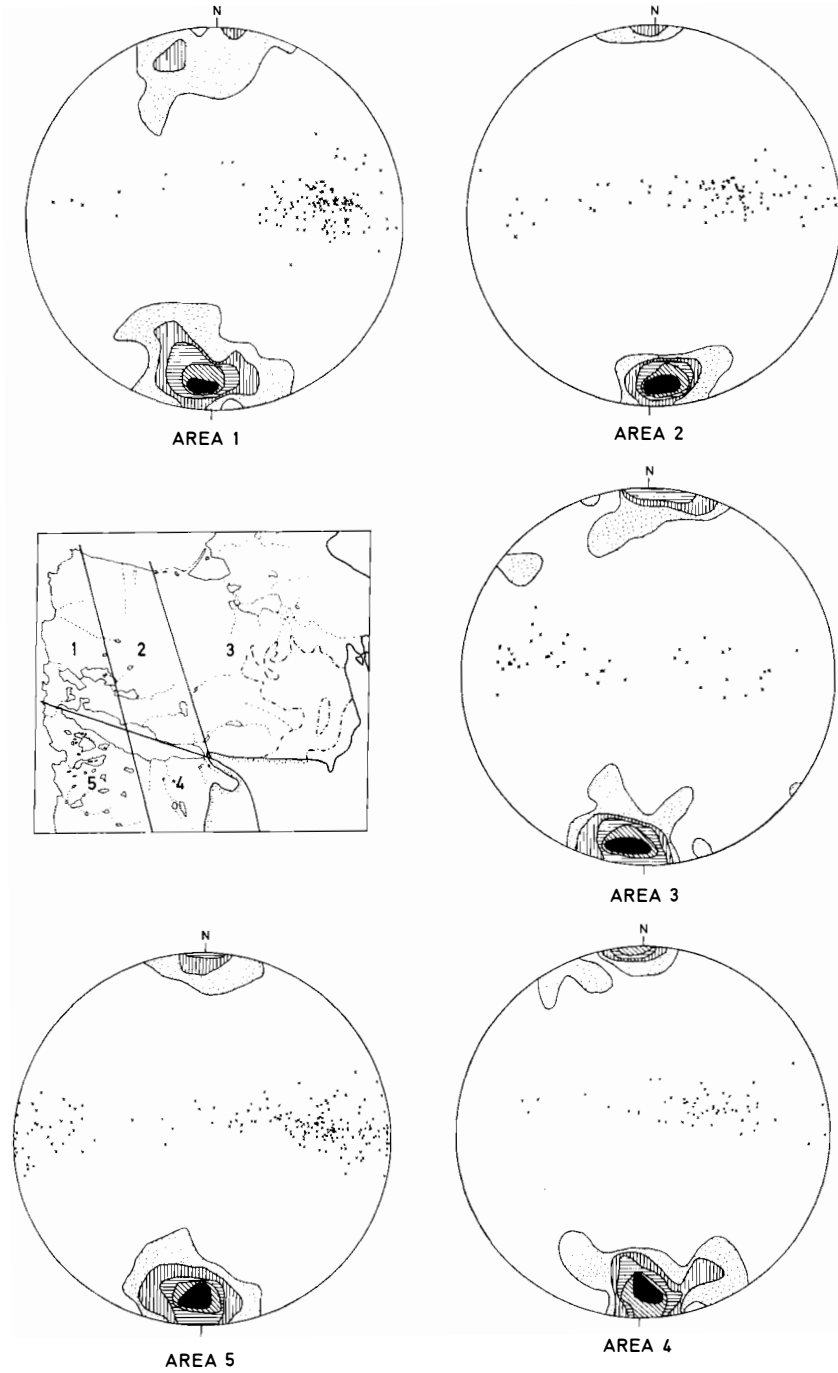


Fig. 8. Stereographic Lower Hemisphere projections of poles of phase II linear structures (fold axes, crenulation lineations and mineral lineations), contoured at 1%, 5%, 10%, 20% and 30% per 1% area, and poles to foliation surfaces (shown as x) from the five areas shown in the inset map of the region.

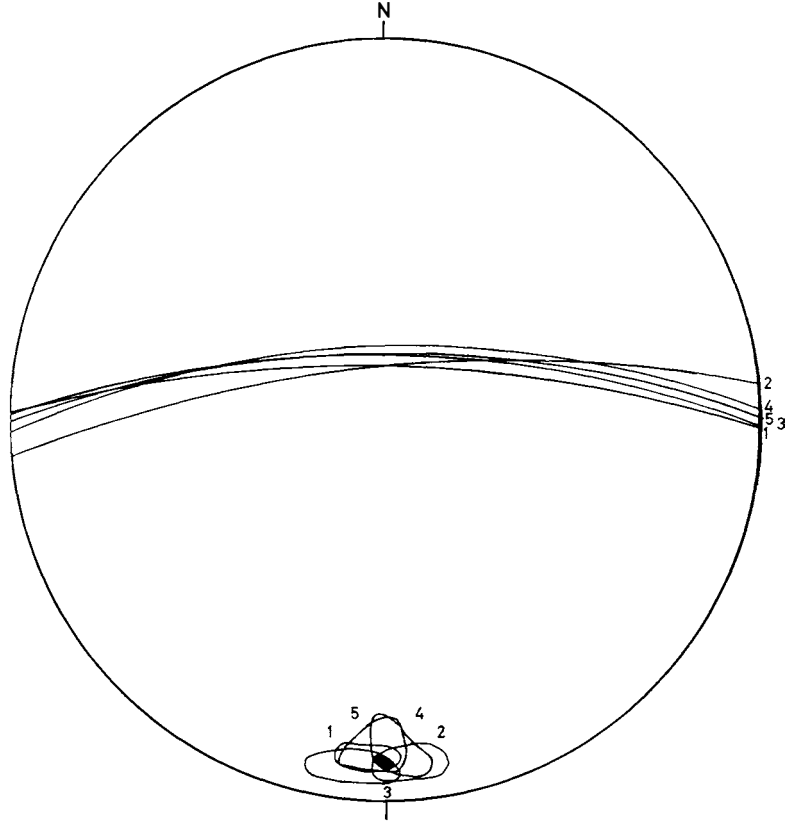


Fig. 9. Composite diagram of the five stereographic Lower Hemisphere projections shown in Fig. 8. The great circles represent best fits to poles to foliation surfaces and the areas indicate the maximum concentrations of poles of linear structures.

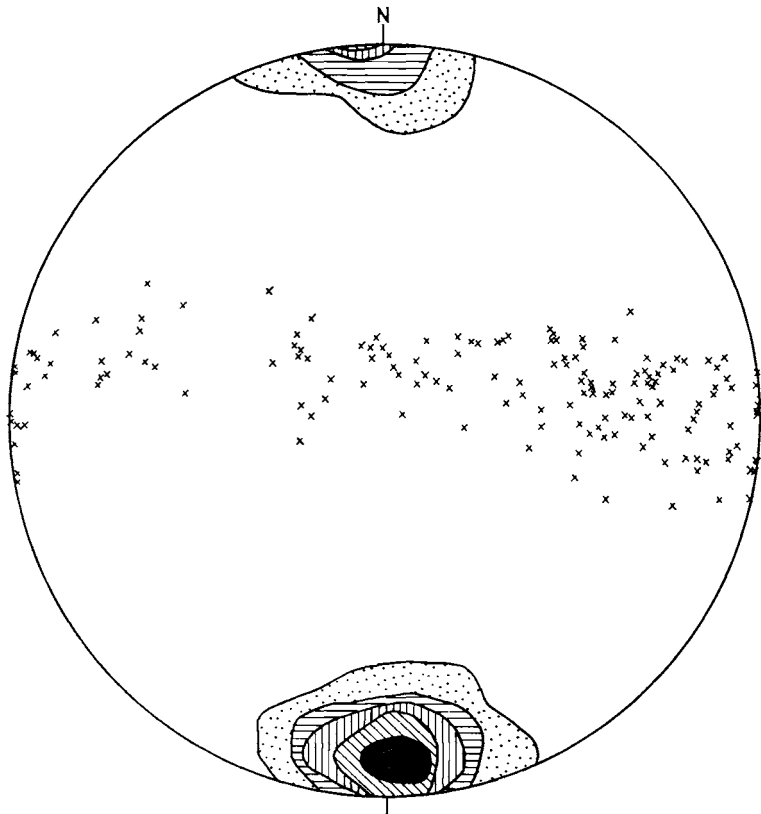


Fig. 10. Stereographic Lower Hemisphere projection of poles of phase III fold axes, contoured at 1%, 5%, 10%, 20% and 30% per 1% area, and poles to phase II fold axial surfaces (shown as 9 x). The maximum concentration of phase III fold axes coincides with the pole to the great circle on which the phase II fold axial surface poles lie.

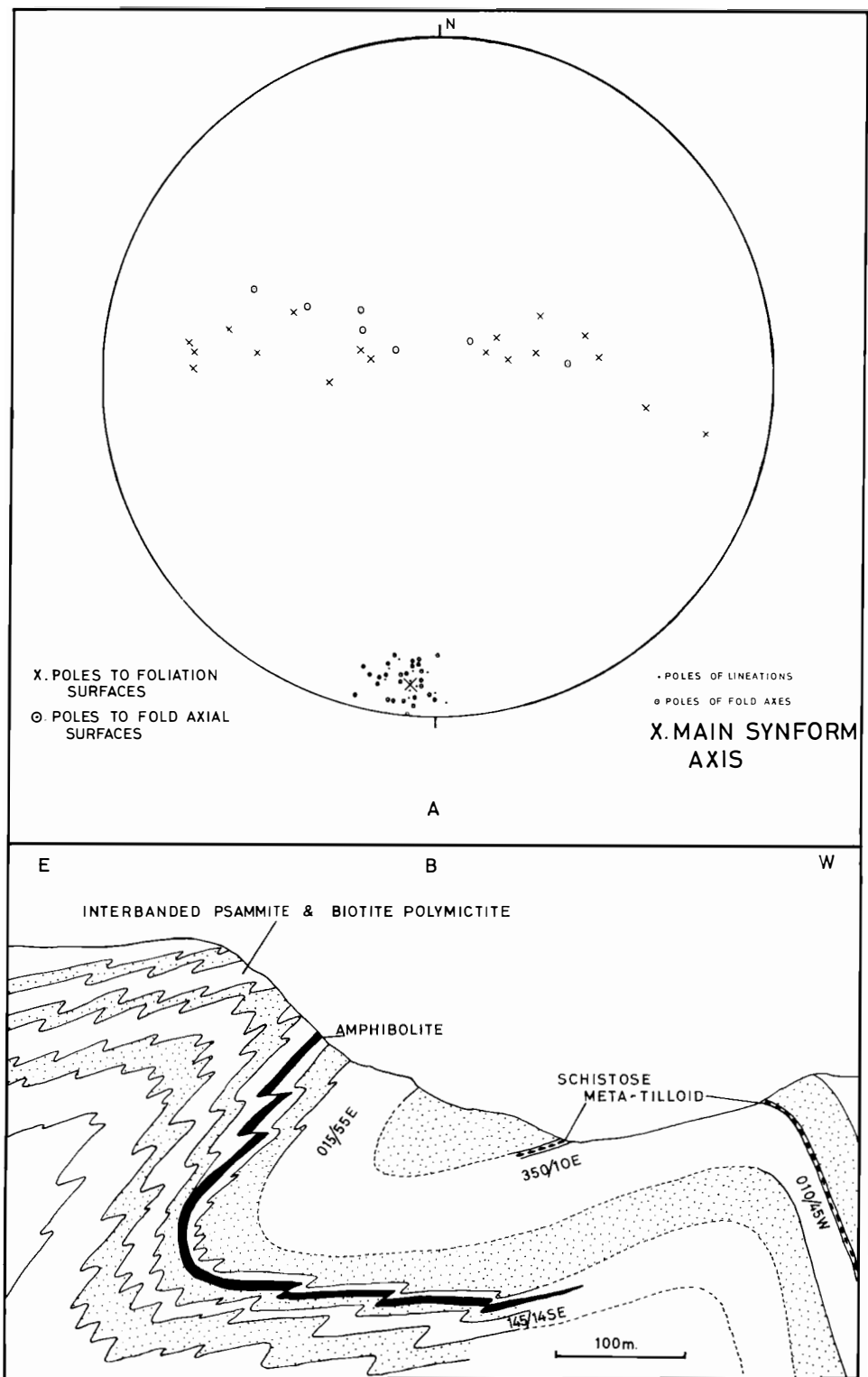


Fig. 11. A - Stereographic Lower Hemisphere projection of foliation surfaces and phase II fold structures shown in section in B). The metasediments belong to the Rittervatnet Formation and the structure is also shown in Plate 7B.

and enables the relationship between different scale structures to be determined. Thirty-eight small scale fold axes and crenulation lineations were measured in the main fold and show a striking parallelism with the main synform axis. The poles to the foliation surfaces measured lie approximately in a plane normal to the fold axis (Fig. 11A). Small scale structures developed in the main fold show a systematic variation around the fold (Fig. 11B).

In the shallow lower limb the banded psammites and polymictites are intensely folded with angular hinges. The amphibolites show only spasmodic folding, the folds generally occurring in pairs, with the outer fold, away from the axial surface of the main synform, facing towards the synform hinge. Many of the folds within the psammites are disharmonic; the amplitude increasing away from an unfolded amphibolite band.

Within the hinge of the main synform many small folds are developed in all lithologies, making a precise location of the synform hinge difficult.

In the steep upper limb of the synform, folds are not so intensely developed and are confined to the psammites and polymictites. These folds are either disharmonic against an unfolded amphibolite band or are represented in the amphibolite by a shear fracture parallel to the axial surfaces of the folds in the psammites, and moving the amphibolite over itself towards the main synform hinge. Numerous boudins within the amphibolite bands extend the rock parallel to the fold axis.

In general the small scale structures are closely related to the main synform, the difference in style being related to the varying competence of the lithology deformed and its position with respect to the hinge of the main fold.

Major folds of phase I generation have not been recorded and there appears to be no suggestion of major stratigraphical repetition in the region which could be attributed to phase I structures. Major folds of both phase II and III generations are present and indeed coincide in their positions. This coincidence is best seen in the superb three dimensional exposures to the north and south of the west end of Femmilsjøen where, due to the southward plunge of both sets of folds, a composite section can be built up from the different levels of exposure in the structure (Fig. 12). The structure is composed of an antiform-synform pair of major phase III folds whose common limb is the site of a vertical dip-slip fault. Many smaller scale open folds occur in the hinge area of the antiform. The antiform deforms a series of tight intermediate phase II folds which together form a major phase II antiform. The overall impression is one of flowage of the earlier formed phase II folds of the antiform crest into the synform trough giving the arching of phase II fold axial surfaces (see WYNNE-EDWARDS 1963). Against this view is the planar nature of the phase III fold axial surfaces which one would have expected to be non-planar on a flowage hypothesis.

The overall shape of the folded surfaces for the region appears to agree rather with the phase III fold formation being due to flow from the crest to the trough of the earlier phase structures and a generalised diagram of the structure illustrating this is given in Fig. 13.

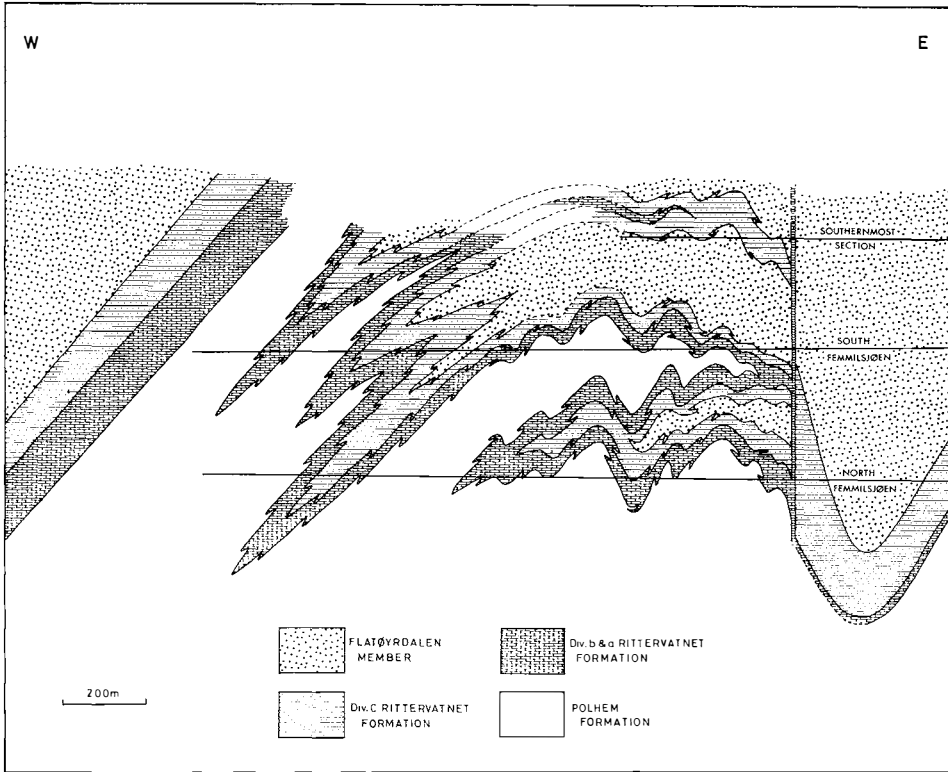


Fig. 12. Diagrammatic horizontal section of complex refolding of phase II structures by phase III folds north and south of the western end of Femmilsjøen. The section is built up from the traverses indicated.

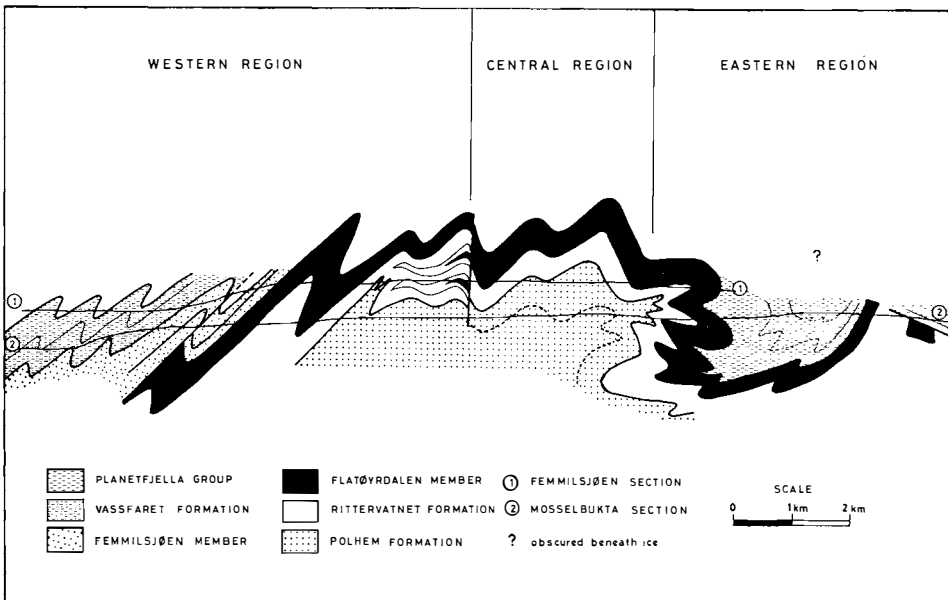


Fig. 13. Generalised section across the region illustrating the inferred overall shape of the fold profile.

FOLIATION

Bedding and compositional banding

In many lithologies compositional banding produces the most noticeable foliation. This banding is sometimes on a large scale with bands up to 50 m thick, representing major changes in lithology, as in divisions a) and b) of the Rittervatnet Formation and in division a) of the Vassfaret Formation. Within these large scale bands and in the polymictites and psammities of the Vassfaret Formation, division c) of the Rittervatnet Formation and the Planetfjella Group, minor changes in composition produce bands from less than 1 cm up to 1 m thick. In the polymictites the banding is caused by changes in the proportion of quartz, mica or hornblende and in the psammities by changes in the proportion of epidote, hornblende or mica. The compositional banding is thought to be a primary sedimentary feature, as, in the Vassfaret Formation, sedimentary structures (current and ripple bedding, mud-cracking etc., GAYER and WALLIS, 1966) involve the smaller scale compositional bands. Deformation and recrystallisation has modified the banding to varying extents. In the Bangenhuk Formation the original banding has been largely obliterated with the development of a gneissose banding.

Early schistosity

In addition to the compositional banding, most lithologies possess a foliated schistose fabric. This schistosity is developed better in the pelitic and amphibolitic lithologies where the micas and hornblende are aligned to give a lepidoblastic fabric, than in the quartz and feldspar rich lithologies, which in some instances show a granulose fabric; the compositional banding being their only foliated element. The schistosity is more or less parallel to the compositional banding and in the subpelitic and polymictic lithologies is usually more pronounced in mica rich lithologies adjacent to more competent quartz or feldspar rich bands.

The relationship between the schistosity and phase I isoclinal folds is not clearly demonstrable. In the limbs of the isoclinal folds the schistosity is sub-parallel to both the banding in the limbs and the axial surfaces of the folds. In the hinges of the folds the schistosity is not so clearly developed and even in thin sections cannot be seen to penetrate the banding. The schistosity is folded by phase II generation folds, following the banding around the hinge and is, therefore, thought to pre-date the phase II folds.

The schistosity within the metadolerite sheets, showing sigmoidal boudinage, was developed at the same time as this early schistosity.

In general the schistosity strikes north-south in the limbs of phase II folds and dips at varying angles both to the east and to the west (Figs. 8 and 9), depending on the position within the folds.

Late foliation

In the megacrystic calcite, hornblende, garnet, biotite polymictites of division b) of the Vassfaret Formation, the pelites of division c) of the Rittervatnet Formation and the psammitic-feldspathites of the Bangenhuk Formation, a later

foliation is developed parallel to the axial surfaces of the phase II generation folds, partially destroying the earlier foliations. In the pelitic lithologies this takes the form of a schistosity with lepidoblastic growth of the micas, the earlier schistosity being only preserved in the garnet and hornblende megacrysts (Figs. 14 and 15). In the psammitic-feldspathites the micas and potash-feldspar are realigned into new surfaces forming definite bands a few centimetres thick truncating the folded earlier schistosity of the bands in between. The metadolerites showing straight necked boudinage invariably have a schistosity developed in the necks of the boudins, but the margins of the boudins are either unfoliated or possess only a thin foliated rim. This foliation is correlated with the later period of foliation development. Concretion pegmatites are also developed in the psammitic-feldspathites of the Bangenhuk Formation, forming lenses parallel to the phase II fold axial surfaces and rods parallel to their axes (Plate 8B). These later foliation surfaces have strikes similar to those of the earlier schistosity but differing dips, generally between 45°–60° west in the western region and 10°–60° east in the eastern region.

Correlation between foliation, folding and dolerite intrusion

Time	2nd Schistosity and Foliation	Phase II folds
↑	2nd Dolerite Sheets	
	1st Schistosity	Phase I folds
	1st Dolerite Sheets	
	Bedding and compositional banding.	

LINEATION

Both mineral lineations and crenulations are widely developed throughout the region. Although it is not unusual to find both types of lineation in one lithology, mineral lineations are characteristic of the psammitic and feldspathitic lithologies, whilst crenulations are more commonly developed in pelitic and polymictic lithologies. Amphibolitic horizons frequently show both types of lineation with prismatic hornblende developing the mineral lineation and tabular hornblende and micas forming the crenulated foliation (Plate 9A).

Mineral lineations and crenulations are always associated with schistosity surfaces. The mineral lineations form an integral part of the schistosity and were developed at the same time as the formation of the schistosity whilst the crenulations deform the earlier schistosity surfaces and are presumably of later date.

Two sets of crenulation lineations are developed in those lithologies possessing an earlier schistosity; one set being parallel to adjacent phase II fold axes and deforming the other set which lie in a plane parallel to that in which the phase I isocline axes lie (Figs. 7 and 8).

In those lithologies possessing only the later schistosity, crenulations belonging to the set parallel to phase II fold axes are developed to the exclusion of the earlier set. However, the megacrystic calcite, hornblende, garnet, biotite subpelites of

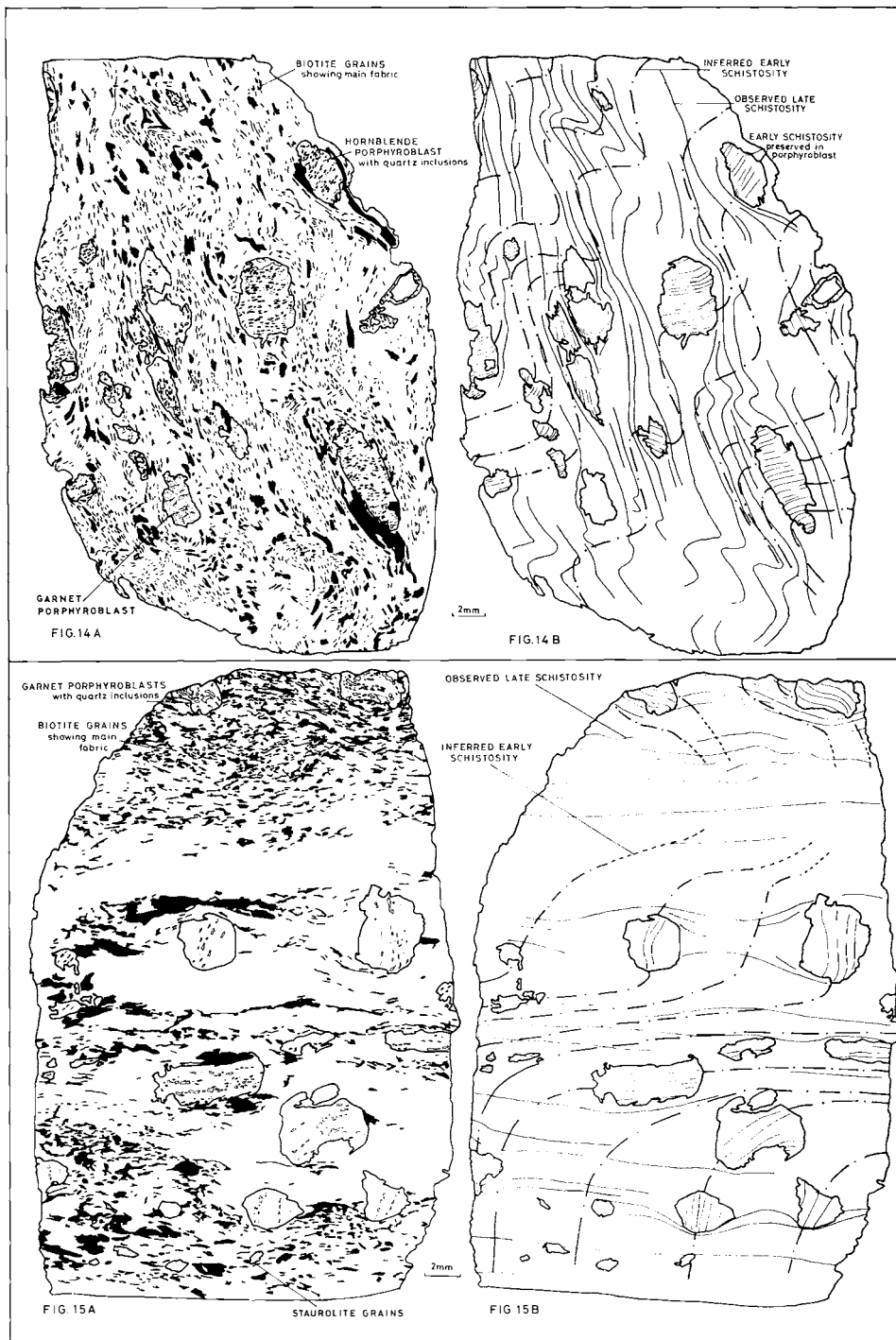


Fig. 14. *A* – Fabric diagram of megacrystic garnet-hornblende-biotite subpelite from division b) of the Vassfaret Formation drawn with aid of an industrial projection apparatus.

B – Diagram of the thin-section illustrated in *A*, showing the relationship between the trace of the late schistosity and an earlier schistosity inferred from the inclusions within the hornblende megacrysts.

Fig. 15 *A* and *B* as in Fig. 14, but illustrating a thin-section of megacrystic garnet-staurolite-biotite-muscovite subpelite from the Planetfjella Group. The earlier schistosity is inferred from the inclusions within the garnet megacrysts.

Figs. 14 and 15 illustrate the static growth of hornblende and garnet between two periods of kinematic metamorphic recrystallisation.

division b) of the Vassfaret Formation contain relics of an earlier crenulated schistosity within the megacrysts and, although the attitude of these crenulations has not been determined accurately, it appears to have been more or less parallel to the later crenulations seen in the ground-mass (Figs. 14 and 15). In this rock the later schistosity appears to have developed from the earlier schistosity by reorientation of the fabric parallel to the long limbs of the first crenulations. However, the growth of the megacrysts has occurred after the formation of the first crenulations but before the complete reorientation of the fabric into the later schistosity as is evidenced by the helicitic inclusions in the megacrysts and the later schistosity which envelops the megacrysts. The preservation of the first crenulations within the megacrysts, without evidence of the reorientation of the fabric during the growth of the megacrysts (snowball inclusions, see e. g. RAST 1958, ZWART 1960, and RAMSAY 1962b) indicates that the megacrysts grew during a period of relaxation of compressive stress that divided into two stages the process of reorientation of the fabric of the earlier schistosity into the later schistosity. The first of these stages was associated with the development of phase I isoclinal axes as the first crenulation lineations are parallel to the isoclinal axes. The second stage was associated with the development of phase II folds as the schistosity is more or less parallel to the axial surfaces of the folds. The second crenulations deforming the later schistosity are parallel to the axes of phase II folds and are therefore also thought to be associated with the development of phase II folds, presumably after the formation of the schistosity.

<i>Folding</i>	<i>Lineation</i>	<i>Foliation</i>
Phase II folds	{ 2nd crenulations Late schistosity

Period of relaxation of compressive stress with megacryst growth

Phase I folds	{ 1st crenulations Early schistosity
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BOUDINAGE

Boudinage is of common occurrence in all the formations within the area, particularly in those lithologies with interbanding of rocks with varying competence.

Orientation

The boudins take the form of cylindroids with elliptical or rectangular cross-sections; the major axis of such a cylindroid, which parallels the line of separation of adjacent boudins, is here referred to as the *boudin axis*. The boudin axes invariably lie within the surface of the compositional banding and, where present, within the schistosity and are commonly perpendicular to the mineral lineations, crenulations and fold axes in the surrounding rocks. Less frequently the boudin axes are parallel to the linear fabric of the enclosing rock. The boudinage has thus

resulted in extension of the boudined rock both parallel to the fold axes, 'B', and to a lesser extent in a direction perpendicular to the fold axes, varying between 'A' and 'C', depending on the position of the boudin within the fold.

Time relationships

The spacial relationship between the boudins and the other linear and foliated fabrics of the rocks is unambiguous. However, the relationship between the time of formation of the boudins and the development of the other fabrics is not so apparent. Normally there is no indication of the relationship between folding and boudinage as the boudins typically occur only in the limbs of the folds. Even when a boudined band is folded (e.g. Plate 9B), the relationship is ambiguous; the boudinage could have occurred either before or during the formation of the fold, but not after the formation of the fold as the neck of the boudin is itself folded. In one instance an antiform and synform pair of phase II folds is boudined where an amphibolite band occurs in the hinges of the folds (Plate 10A and Fig. 16) demonstrating that boudinage occurred after the formation of at least these particular folds.

Similar ambiguities arise when the relationship between the boudinage and schistosity is considered. The boudins commonly possess a foliated schistosity

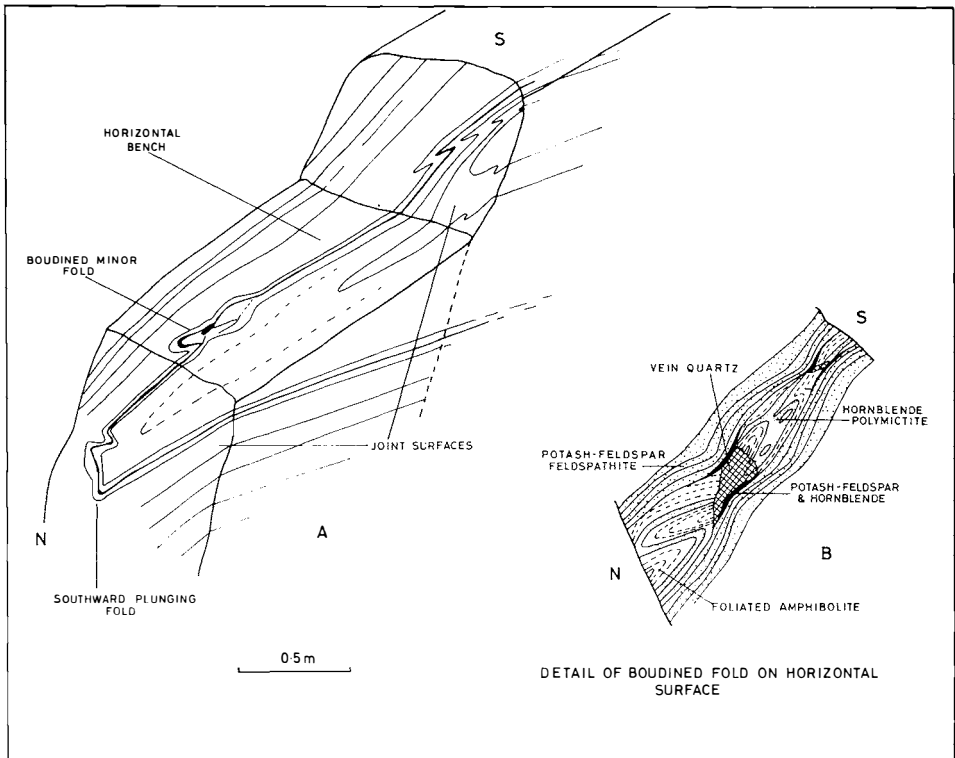


Fig. 16. A - Diagram illustrating the boudinage of a pair of small scale phase II folds shown in detail in B). See also Plate 10A.

which in many cases is parallel to the margins of the boudin, following the margins into the boudin neck. This suggests that the foliation was present at the time of boudinage or developed contemporaneously with the boudinage. Unless the production of the schistosity is very closely associated with variations in the competency of the lithologies, the schistosity cannot have been developed after the formation of the boudins.

It is concluded that the boudinage occurred in some cases either before or contemporaneously with phase II folding and in one case definitely after phase II folding and was either contemporaneous with or later than the early schistosity. There is no evidence relating the times of formation of boudinage and phase I folding.

Style

The style of boudinage varies considerably, and most of the varieties described by RAMBERG (1955) have been recorded.

The most common variety, shown principally in the foliated amphibolites enclosed in any of the other lithologies and in some of the metadolerite intrusions, is a straight necking of the band to produce a continuous thickening and thinning of the horizon both along the strike and down dip (Plates 10B and 11A). The foliation in the enclosing lithology is folded into the neck, conforming with the shape of the boudin. In many instances, where the boudins are completely separated, the neck is occupied by newly grown minerals; mainly vein quartz but in some cases also biotite, hornblende and potash-feldspar, largely dependent on the composition of the enclosing lithology.

An unusual type of straight necked boudin found in one band only has a continuous rim of vein quartz enclosing a core of tremolite, biotite subpelite with sigmoidally curved foliation surfaces (Fig. 17). These boudins appear to have been formed by a combination of straight necking with marginal shear parallel to the banding, producing the sigmoidally shaped foliation, of a band of subpelite bordered by vein quartz.

Very common in the outcrops of hornblende polymictite enclosed in biotite polymictites of the Vassfaret Formation and in bands of vein quartz enclosed in banded polymictites and psammites of division c) of the Rittervatnet Formation, is a type of boudinage involving both necking down of the band and a shear fracture of the neck. The shear fracture has a strike slip displacement producing a rotation of the boudin out of alignment with the foliation of the surrounding lithology (Plate 12A). The boudins are in some cases separated by a thin band of secondary quartz and these bands are incorporated in intense small scale shear folds developed in the enclosing rock in the neck of the boudins (Plate 11B). These folds plunge steeply parallel to the line of separation of the boudins. The necking of the band appears to have occurred prior to the rotational shear although the whole process was continuous and connected as the deflection or intense folding of the foliation in the enclosing rocks is restricted to the immediate neighbourhood of the boudin.

A variety of boudinage showing no necking is found mainly in vein quartz and aplite bands enclosed in biotite polymictites or thick, poorly foliated marbles.

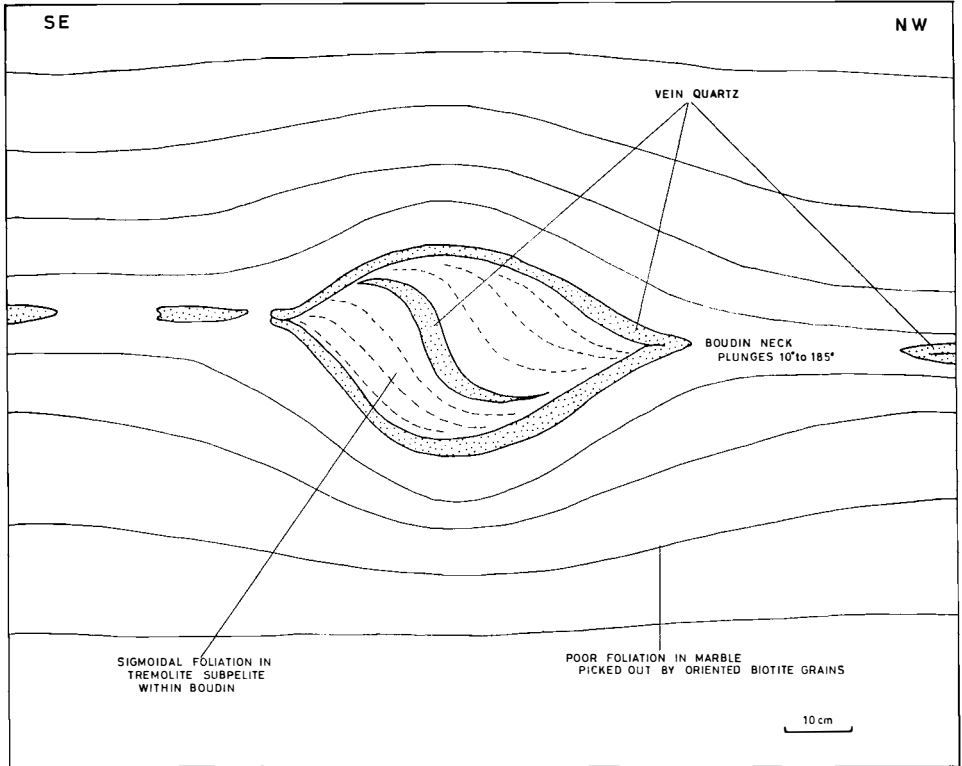


Fig. 17. *Diagram of necking boudinage of a subpelite band rimmed with vein quartz in a biotite marble with marginal shear producing sigmoidally curved foliation surfaces within the boudin, from division a) of the Rittervatnet Formation.*

This type of boudinage involves only fracture of the boudined horizon. The fracture may be a shear with a strike slip component, oblique to the banding. In this case there is no separation of the boudins within the foliation surface. The fracture is restricted to the boudined lithology; the enclosing rock shows a deflection of the foliation around the boudin which dies out rapidly away from the boudin. In other cases the fracture has no shear component and gives rise to a separation of the boudins in the foliation surface only, the boudins being separated by secondary vein quartz and by the enclosing lithology. Both types of fracture boudinage may occur in the same set of boudins (see e.g. Plate 12B).

Boudinage of metadolerites

Many of the metadolerite sheets are boudined to produce a sigmoidally shaped boudin in horizontal sections, with the central portion of the sigmoid striking about 40° west of the regional north-south foliation and the necks parallel to the regional foliation (Fig. 18). The foliation in the enclosing rocks adjacent to the boudin conforms to the sigmoidal outline of the boudin but away from the boudin the sigmoidal deflection grows weaker until some distance away no deflection of

the regional foliation is apparent. The necks of the boudins are commonly occupied by vein quartz and potash-feldspar.

The metadolerites showing sigmoidally shaped boudins would appear to belong exclusively to the earlier set of intrusions, whilst the boudinage of the later set of dolerites is by straight necking. There would appear to be two alternative explanations for this relationship:

1) The sigmoidally shaped boudins were produced by a rotational plastic shear followed by necking down of the metadolerite sheet prior to the intrusion of the second dolerite. Subsequently both were boudined, further separating the sigmoidal boudins and producing necked boudins in the second dolerite. (Fig. 19.)

2) The sigmoidal shape of the one set of boudins is a result of an original discordance of the dolerite sheet. The conformity of the foliation around the boudin in the surrounding feldspathites could be explained as a result of recrystallisation in a local stress field influenced by the presence of the competent discordant dolerite. In this case the straight necked boudins represent boudinage of a dolerite intruded parallel to the gneissosity.

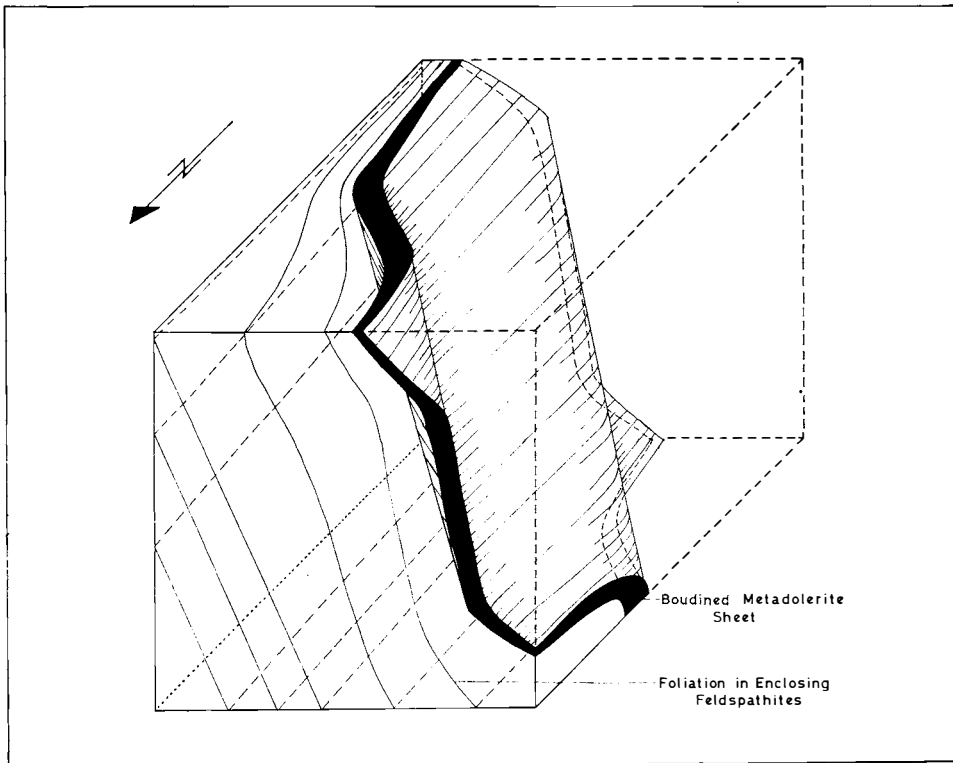


Fig. 18. Block diagram of typical metadolerite boudinage illustrating the sigmoidal outline of the boudins on both horizontal and vertical surfaces. The boudin axis is perpendicular to the fold axes in enclosing lithologies.

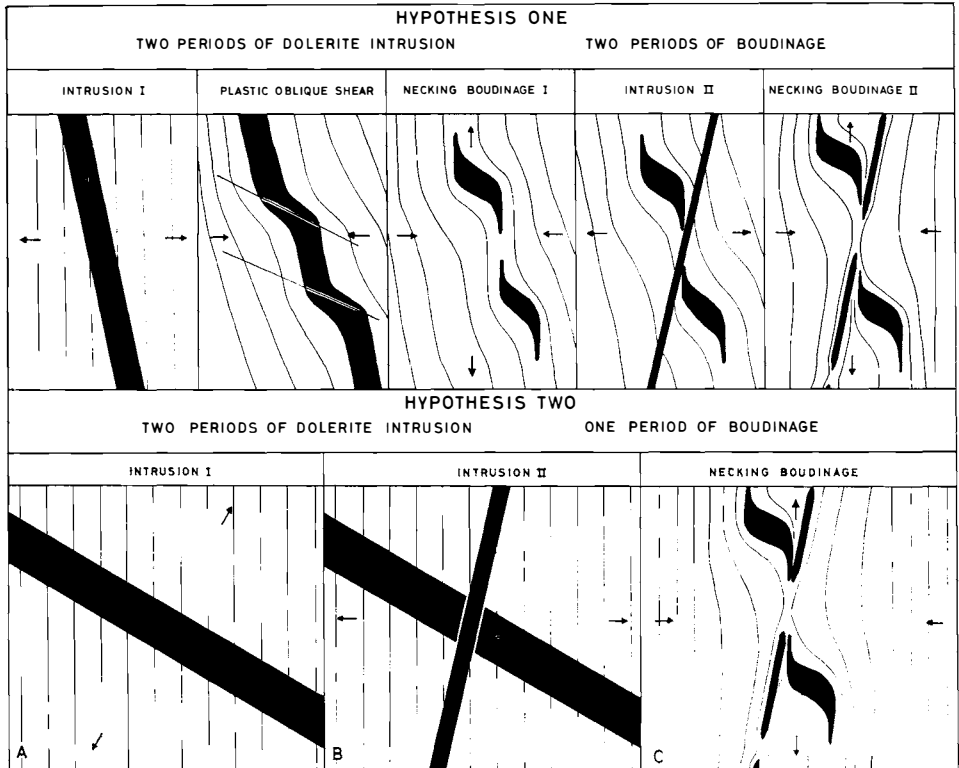


Fig. 19. Diagrammatic representation of the two hypotheses for the formation of two sets of meta-dolerite boudins. For explanation see text.

FAULTS AND JOINTING

Faulting

The faults occurring in the area fall into two classes. The more abundant are a series of small strike slip oblique faults with movements rarely exceeding a few metres. These are developed in two complementary sets; one striking 100° – 130° with sinistral movement, and the other striking 040° – 060° with dextral movement, both with more or less vertical fault surfaces. A zone of brecciation commonly accompanies the faults and is often up to 0.5 m wide. Occasionally calcite and galena mineralisation is found in association with the fault breccias. The more prominent of these faults can be traced for up to 2 km along their strike, when they die out in a flexure with a steeply plunging axis. The faults usually produce a clean break of the foliation with little or no drag. The effect of the two sets of faults is to extend the rocks in a north-south direction as a result of east-west compression.

Less common are a set of near vertical dip-slip faults with downthrows of up to 200 m both to the north and the south. These faults strike between 090° and 110° and, in those occurring to the north of the area, can be followed along their strike for several kilometres. Zones of brecciation with mineralisation accompany the faults and these zones are up to 1 m wide.

The fault running along Mosseldalen and Tåbreen is nowhere exposed, being

covered by ice, moraine and fluvio-glacial material. The swing of the foliation in the outcrops along the southern edge of the valley from the regional north-south attitude to about 300° suggests that it is an example of the sinistral strike-slip oblique fault set.

Apart from the swing in strike of the foliation, the nature and amount of the movement on the fault cannot be determined directly from observations in the Lower Hecla Hoek rocks of the area.

Only one example of a dip-slip strike fault has been found in the area. This fault strikes north-south and dips steeply to the east. It is associated with a large scale synform/antiform pair of folds of phase III generation. The fault surface is occupied by a belt of foliated graphite pelite representing the coalesced hinges of earlier phase II folds in division b) of the Rittervatnet Formation. This horizon, being far less competent than the neighbouring lithologies, acted as a lubricant for the fault which was located where the horizon was thickened in the hinges of the earlier folds. The fault has a downthrow to the east, bringing the feldspathites of the Bangenhuk Formation in the synform to the east down against various members of the Rittervatnet Formation in the antiform to the west.

With the exception of the dip-slip strike fault all the faulting occurred after the formation of the folds and the foliation. However, the attitudes and the nature of the movements on the faults suggests an east-west compression which was presumably a continuation of that which produced the earlier structures. Isolated patches of conglomerates and sandstones, thought to be of Carboniferous age, do not appear to be affected by the strike-slip faulting.

Jointing

Joints are of widespread occurrence and are developed in three principal sets. All three sets are more or less vertical, one striking east-west perpendicular to the fold axes, and the other two symmetrically arranged about the fold axes striking 040° – 050° and 100° – 110° . Insufficient data have been obtained to enable an analysis of these joints to be made. The sets symmetrically arranged about the fold axes grade into small strike-slip faults with occasional surfaces showing slight strike-slip movement.

Joint drags are also occasionally developed. These are pairs of close set joints striking 040° – 050° with a rotation of the foliation between the joint surfaces out of alignment with the regional foliation. In all cases the sense of movement on the joint drags is sinistral. The formation of these structures occurred after the development of the foliation and the lineation.

STRAINED PEBBLES

Throughout the area the original sediments have undergone considerable deformation, with flattening in the direction of maximum stress and extension in the plane perpendicular to the maximum stress. This strain is shown in the presence of geometrically similar folds and the boudinage of horizons of greater competence. In most lithologies it is impossible to gain an accurate estimate of the amount of this strain. However, an approximate value of the strain is given by the deformed pebbles in the Rittervatnet Formation conglomerates, where the

original shape and size of the pebbles can be estimated. Although an attempt was made to evaluate the deformation of the calcareous concretions in division a) of the Vassfaret Formation, it was found that the original shape of the concretions was too variable to allow a quantitative study.

The deformation of pebbles in the Rittervatnet Formation conglomerates

In order to determine the amount of deformation of the pebbles in any one direction it is necessary to compare the dimensions of the pebbles in that direction before and after deformation. As there is no area where the pebbles remain undeformed, only the dimensions of the pebbles after deformation can be measured and the dimensions before deformation must be estimated.

The simplest estimate is given by assuming all the pebbles were spherical before deformation. If it is assumed that the volume of a pebble does not change during deformation, the original diameter of the pebble would be given by calculating the diameter of the sphere having the same volume as that of the deformed pebble, derived from its measured dimensions.

In fact it is most unlikely that all the pebbles were originally spherical. Depending on the degree of orientation in the original sedimentary fabric, the long axes of the pebbles which were not spherical would have tended to lie in one direction. This sedimentary fabric cannot now be ascertained and if the calculations are based on a random sedimentary orientation, the values for the dimensions in any one direction would sometimes be more and sometimes less than the value calculated by assuming the pebbles were originally spherical. Those values which were higher should be more or less compensated by those which were lower. Clearly this estimate is likely to give an exaggerated value for the deformation if the long axes of the pebbles in the sedimentary fabric coincided with the direction of maximum stretching of the tectonic fabric. If the long axes of the pebbles in the sedimentary fabric coincided with the direction of maximum shortening of the tectonic fabric, the estimates of the deformation will be too small. Thus estimates based on a random orientation of pebbles in a sedimentary fabric are likely to have a certain error. As the deformation is so intense in the tectonic fabric 'b' and 'c' directions, the percentage error in these values is only likely to be small. The error in 'a', however, may be much greater due to the small deformation in this direction.

The shape of the deformed pebbles agrees closely with the form of a triaxial ellipsoid, the major (Z), intermediate (Y), and minor (X) axes lying in 'b', 'a' and 'c' tectonic fabric directions respectively.

$$\begin{aligned} \text{The volume of a triaxial ellipsoid } V_e &= \frac{1}{6} XYZ \\ \text{and the volume of a sphere } V_s &= \frac{1}{6} d^3 \\ \text{as } V_e &= V_s, \\ XYZ &= d^3 \\ d &= \sqrt[3]{XYZ} \end{aligned}$$

Hence the ratios of the dimensions before and after deformation are:

$$\frac{X}{\sqrt[3]{XYZ}} : 1; \quad \frac{Y}{\sqrt[3]{XYZ}} : 1; \quad \frac{Z}{\sqrt[3]{XYZ}} : 1.$$

The average dimensions of the ellipsoids representing deformed spheres of unit diameter for the three main composition classes of pebbles are given in Table 1.

Table 1

Pebble type	'X' axis	'Y' axis	'Z' axis	Sample size
Granite	0.7	1.0	1.5	16
Gneiss	0.35	0.9	3.4	28
Quartzite	0.25	0.9	4.5	31

All pebble types show little deformation along their 'Y' axes, which corresponds to the 'a' tectonic fabric direction. The 'X' axis is in all cases shortened, the effect being more marked in the gneiss and quartzite pebbles than in the granite pebbles. This is thought to be due to the greater competence of the granite. The 'Z' axis is in all cases elongated, again more markedly in the quartzite and gneiss pebbles. The effect of the deformation has been a shortening in the 'c' fabric direction compensated for by an elongation in the 'b' fabric direction.

The varying amounts of strain shown by the various pebble types reflects the different competencies of the rocks.

The strain in the matrix must be greater than that shown by the weakest pebble; in this area an elongation of greater than 4.5 : 1.

It is difficult to partition the observed overall strain between the compressional phases as the axes of all three phases of folding are homoaxial. The evidence of rock extension from boudinage structures is different from the observed pebble deformation, as extension has occurred in the fold limbs both parallel and perpendicular to the fold axes. Admittedly boudinage demonstrating extension parallel to the fold axes is more extensive than that perpendicular to the fold axes and it is possible that the strain in the pebble matrix may have had an appreciable component in the 'a' tectonic fabric direction not obviously reflected in the strain of the more competent pebble lithologies.

From a theoretical viewpoint it is difficult to reconcile the formation of shear folds by extension purely parallel to the fold axes, but with other mechanisms of fold production, such as the flow folds discussed by FLINN (1962), such a strain presents no difficulties. There is little, if any, evidence for the existence of a 'shear' mechanism in any of the fold phases of the region; a schistose foliation being developed parallel to the fold axial surfaces in only the pelitic lithologies. The majority of the folding appears to have arisen from some form of flow mechanism.

Metamorphism

The dominant effect of the regional metamorphism of the Lower Hecla Hoek rocks of the region was to produce well oriented fabrics of mineral assemblages in the almandine amphibolite facies (TURNER and VERHOOGEN, 1960). In many

cases these fabrics can be shown to be associated both with the late schistosity and the lineations parallel to phase II fold axes and were thus formed during the second episode of east-west compression. Garnet and hornblende megacrysts containing 's' shaped strings of inclusions, continuous with the groundmass fabric, confirm the syn-tectonic conditions of metamorphism.

Far less obvious is the evidence for two earlier stages in the metamorphism of these rocks. Garnet and hornblende megacrysts in some of the pelites, subpelites and biotite-polymictites preserve an earlier crenulated, foliated fabric in their helicitic inclusions (Figs. 14 and 15). These megacrysts have overgrown an earlier syn-tectonic fabric and thus their growth pre-dates the development of the late schistosity. Furthermore, the relationship between the inclusions in adjacent megacrysts is consistent with static growth of the megacrysts. The cores of some of the amphibolite boudins contain clusters of granular diopside imperfectly recrystallised into oriented hornblende grains. The granular diopside is thought to have originated during the static metamorphic recrystallisation period predating the syn-tectonic recrystallisation which produced the late schistosity. It seems probable therefore that the metamorphism can be divided into three stages; two periods of syn-tectonic recrystallisation separated by a period of static growth.

Recrystallisation accompanying phase I folding

There is very little evidence to indicate the facies or facies distribution during this period. Megacrysts developed during the later period of static recrystallisation preserve, as helicitic inclusions, quartz-oligoclase-epidote-biotite assemblages.

K₂O metasomatism occurred locally within the feldspathites of the Bangenhuk Formation.

Recrystallisation between phase I and II folding

Widespread static recrystallisation occurred within the almandine amphibolite facies with the formation of garnet and hornblende megacrysts and, in the lithologies free of potash-feldspar, kyanite and staurolite were developed locally. Generally the earlier foliated and crenulated fabrics were partially preserved.

Recrystallisation accompanying phase II folding

Much of the earlier fabric in the pelitic lithologies was obliterated and new assemblages with a foliated fabric in the lower almandine amphibolite facies were developed. Typical assemblages developed during this period are:

<i>Amphibolites</i>	Hornblende-oligoclase-epidote-quartz-sphene (± garnet ± biotite).
<i>Pelites</i>	Biotite-muscovite-garnet-quartz-oligoclase (± staurolite ± kyanite).
<i>Psammites</i>	Quartz-oligoclase-epidote-hornblende (± biotite ± muscovite).
<i>Feldspathites</i>	Oligoclase-potash-feldspar-quartz-hornblende-biotite-sphene.
<i>Polymictites</i>	Quartz-oligoclase-biotite-epidote (± hornblende ± garnet).
<i>Marbles</i>	Calcite-quartz (± oligoclase ± biotite ± tremolite).

Only minor movements of K_2O occurred in those rocks already containing potash-feldspar, represented by the concentration of potash-feldspar in concretion pegmatites.

Recrystallisation after phase II folding

A static recrystallisation within the green schist facies of regional metamorphism followed the cessation of the east-west compression. Widespread mimetic recrystallisation of the biotite fabrics occurred in the west of the region, with in places a development of biotite porphyroblasts obliterating the earlier fabric. Retrogression of the amphibolite facies assemblages occurred patchily over the entire area, but principally in the west of the region.

The main changes were:

biotite	→	chlorite and prehnite
garnet	→	chlorite
hornblende	→	tremolite
oligoclase	→	epidote and albite

The second set of dolerite sheets were intruded after the development of the early schistosity but before the formation of the late schistosity. Their intrusion therefore can be correlated broadly with the period of static recrystallisation and, as has been argued above (see p. 00–00), the evidence from the metadolerite sheets is consistent with their emplacement into hot, unstressed country rock. There is thus no argument for waxing and waning metamorphic conditions but rather of a continuous period of metamorphism in amphibolite facies conditions, at times accompanied by compressive stress, with a final period of waning metamorphism in the green schist facies.

Conclusions – tectonic synthesis

The analysis of the structures developed in the Lower Hecla Hoek rocks of the area suggests a fairly simple process of deformation under a prolonged period of east-west compression (Fig. 20).

In its early stages the compression gave rise to intermediate and small scale cylindrical geometrically similar folds of a near isoclinal style about NNW–SSE axes. A foliated schistosity more or less parallel to both the compositional banding and the axial surfaces of the folds was developed at about the same time. This schistosity was better developed in the pelitic and amphibolitic lithologies than in the quartz- and feldspar-rich rocks, reflecting the difference in crystalline form of the constituent minerals rather than differences in competency of the various lithologies, as the folds maintain their characteristic style throughout the differing rock types. Boudinage cannot be associated definitely with this period of deformation and, indeed, if the competence difference between the various lithologies was only slight under the physical conditions accompanying the deformation, the strain may have been entirely plastic with no boudinage. In the

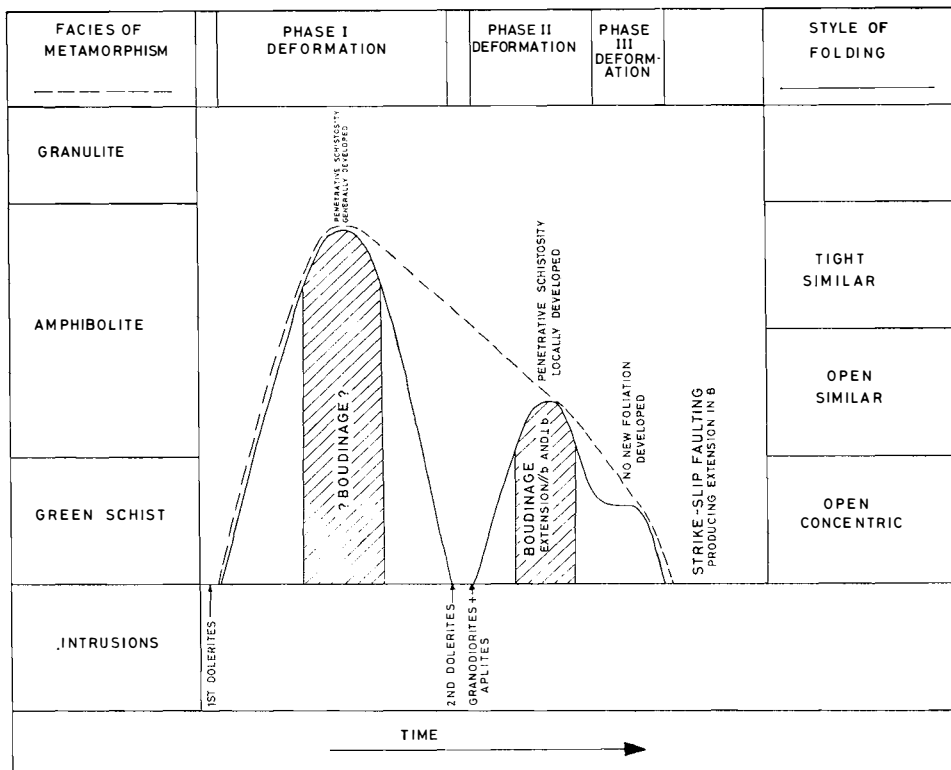


Fig. 20. Schematic representation of the inferred relationships between: time – metamorphic intensity – deformation and intrusion within the region.

later stages of this period, the east-west compression crenulated the foliated fabric about similarly oriented axes to those of the isoclinal folding.

Although the original attitude of the axial surfaces of the isoclinal folds cannot now be determined, due to later re-folding, it is thought that the deformation resulted in east-west shortening and upward extension of the sedimentary pile – a *primary thrust regime* (HARLAND and BAYLY, 1958).

The east-west compression was interrupted by a period of static conditions, and even of actual relaxation. During this period a set of dolerite sheets was intruded into the folded succession, forming a belt running north-south in the western half of the area. Acidic rocks were also intruded into the Bangenhuk Formation feldspathites forming a series of north-south striking aplite sheets associated with a small boss of granodiorite. The metamorphic recrystallisation which accompanied the early period of compression continued during this period with porphyroblastic growth of garnet and hornblende indicating amphibolite facies conditions of metamorphism. It is probable that many of the textural characters of the metadolerites can be attributed to the effects of metamorphism during intrusion.

Following this quiescent period, the east-west compression was renewed with the formation of tight geometrically similar folds with axes oriented more nearly north-south than those of the earlier isoclines and with differently inclined axial

surfaces. Where the folds of the two generations are superimposed, the folds of this period refold the earlier isoclines. The style of folding varies with the lithology folded and reflects the competency variation during this period of the deformation. The folding occurred on a variety of scales; the largest causing major repetitions of the sedimentary sequence.

A new foliated fabric was developed in rocks of only some compositions. The metadolerite sheets, intruded during the preceding quiescent period, together with their rheomorphosed granulose margins, in part received a schistose fabric parallel to the metadolerite margins. In the pelitic lithologies, the early foliated schistosity was entirely reoriented and a schistosity was developed approximately parallel to the long limb surfaces of the crenulations associated with the first period of compression (Figs. 14 and 15). In the gneissose potash-feldspar feldspathites of the Bangenhuk Formation, the early foliated fabric was partly obliterated by the development of bands possessing a gneissosity parallel to the axial surfaces of the folds of this period.

The foliated fabrics, whether newly formed or surviving from the earlier period of compression, were crenulated about axes parallel to those of the folds formed during the period. In the pelitic lithologies this crenulation produced a poor strain slip cleavage.

Boudinage appears to have occurred in part before, in part during and, in one case, definitely after the folding. The style of boudinage varies considerably, reflecting in some cases straight extension of the boudined band and in other cases extension by oblique shearing or by localised strike slip oblique faulting. In either case the extension occurred in two directions both within the surface of banding; one parallel to 'B' and the other between 'A' and 'C'.

Metamorphism of amphibolite facies accompanied the deformation producing, in the pelitic lithologies free of potash-feldspar of the Planetfjella Group, porphyroblasts of kyanite and staurolite in addition to ubiquitous garnet, hornblende and biotite.

The deformation during this period produced renewed east-west shortening which was compensated for by both upwards and north-south extension — a *primary radial regime*.

Following this second period of compression, and possibly continuous with it, was a further period of east-west compression producing renewed folding about north-south axes parallel to those of the previous period but with planar, more or less vertical axial surfaces. The main antiform structure of the region and associated synform (Fig. 13) are in part folds of this generation, but are also coincident with a major antiform and synform produced during the preceding primary radial regime. No evidence has been found to decide whether these phases of folding developed consecutively or contemporaneously. The coincidence of the superposition of the main anticlines and synclines suggests a close connection with continued compression forcing the crests of early formed anticlines into the troughs of early formed synclines. These folds are approximately concentric in style and reflect different stress conditions, although the orientation of the principal stress 'A' must have been very similar to that of the earlier period. A foliated fabric was locally developed in dip-slip strike fault zones associated with the

folding. No crenulations appear to have occurred with the folds which are of varying scales up to the major antiform which folds all the previous structures, producing west dipping surfaces in the western half of the area and east dipping surfaces in the east. Where the folds of this period coincide with earlier formed folds, the axial surfaces of the earlier generation are folded. Boudinage does not appear to have occurred during this period. It is difficult to relate the metamorphic effects to this period but the widespread retrogression from amphibolite facies assemblages to chlorite, prehnite, tremolite assemblages of the green schist facies may have occurred during this period.

The deformation during this period resulted in a continuation of the east-west shortening, although the amount was less than in the previous periods. The release of this compression seems to have been mainly by upward extension as no boudinage reflecting north-south extension has been observed.

Potassium-Argon ages obtained from four specimens in the area date the last metamorphic episode to have affected the rocks at 429 ± 15 million years (GAYER *et al.* 1966), and it is thought that this date marks the close of the period.

The widespread occurrence of oblique joints and small strike-slip oblique faults indicates a further period of weak east-west compression with north-south extension only – a *primary wrench regime* – and this period forms the final episode of the Ny Friesland Orogeny.

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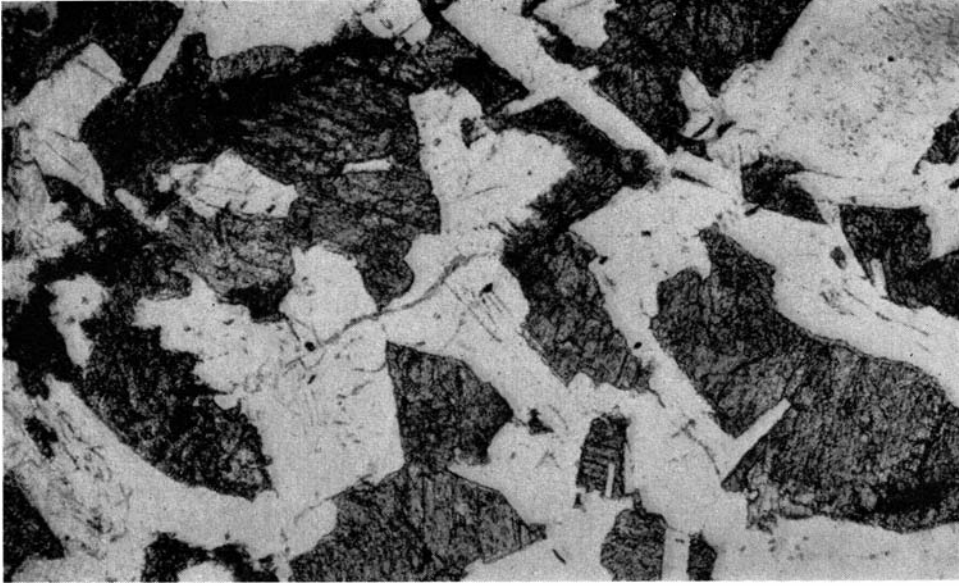
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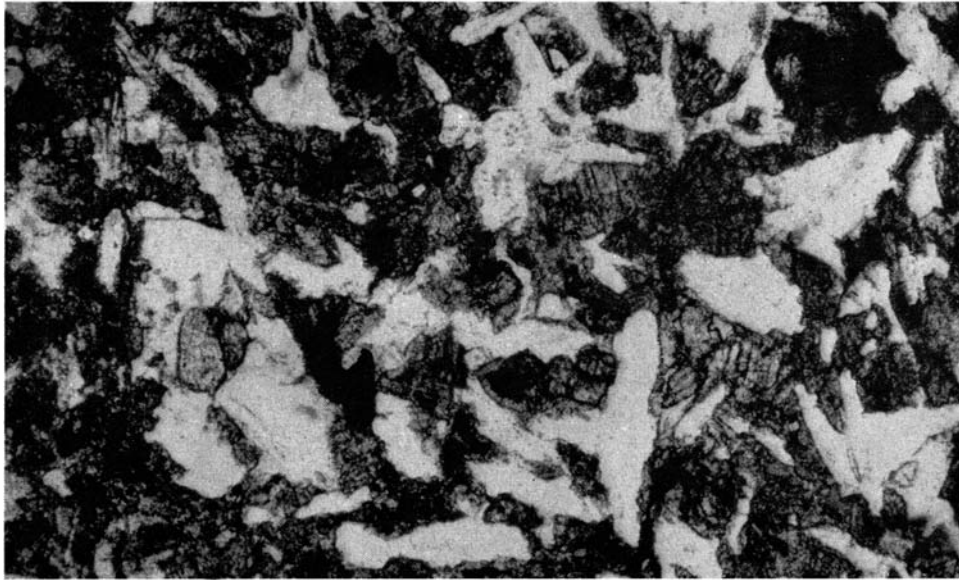
Author's address:

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A

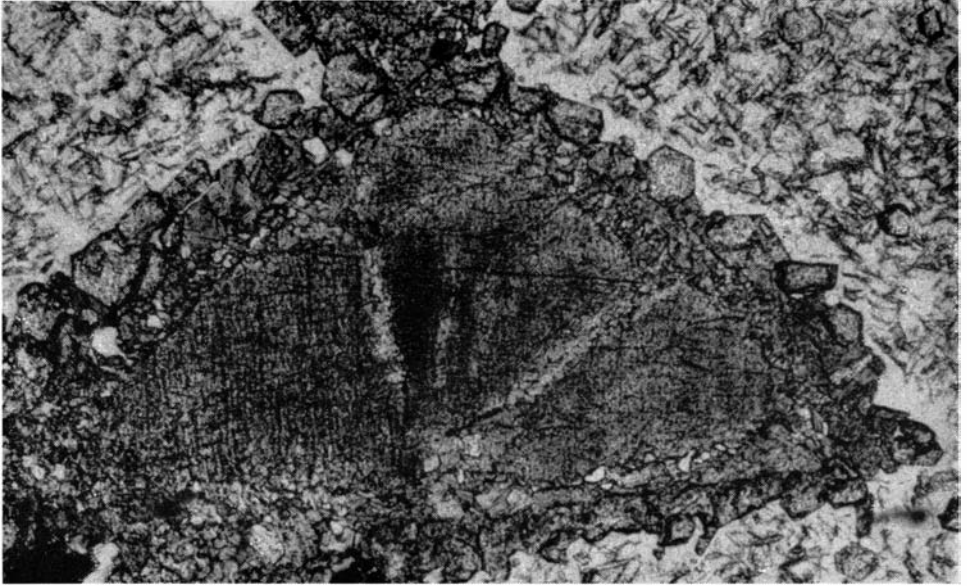
Photomicrograph of metadolerite in zone 1 with igneous mineralogy and texture preserved: colourless – Labradorite; high relief – Augite and Hypersthene; opaque – Iron Ore. Specimen 2 m from the margin of intrusion at (U223). Plane polarised light, $\times 55$.



B

Photomicrograph of metadolerite in zone 2 with igneous texture preserved and igneous mineralogy partly preserved: colourless – Andesine; high relief – Augite and Hypersthene with thin Hornblende rims; opaque – Iron Ore with Sphene rims. Specimen 0.6 m from the margin of intrusion at (U223).

Plane polarised light, $\times 55$. (See also Plates 3B and 4 for other specimens nearer the margin of same intrusion.)



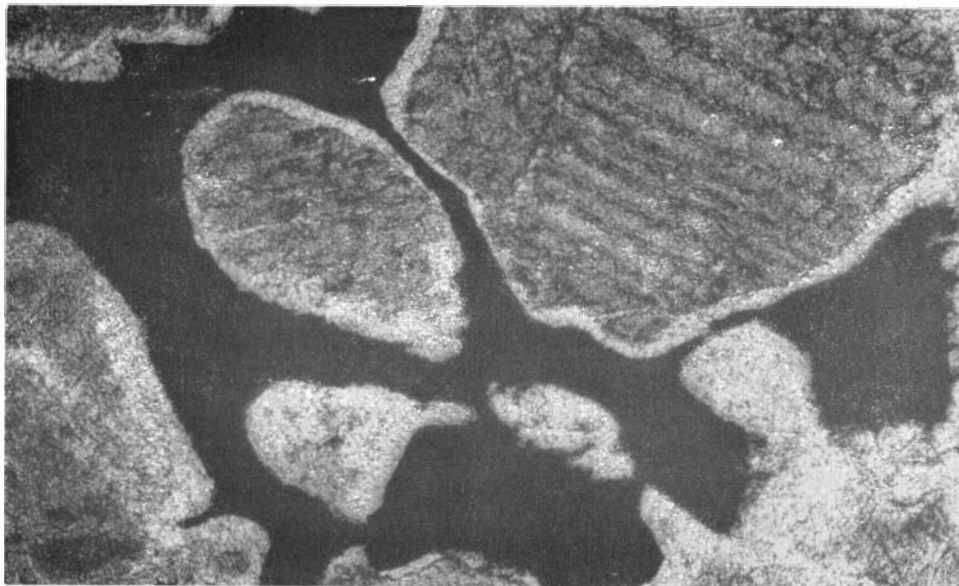
A

Photomicrograph of metadolerite in zone 2 showing a large crystal of Augite rimmed and penetrated by a granulose aggregate of Quartz and Hornblende. An outer rim of euhedral Garnet and Hornblende separates the grain from the enclosing Andesine which has oriented inclusions of Epidote and euhedral Garnet. Plane polarised light, $\times 55$.



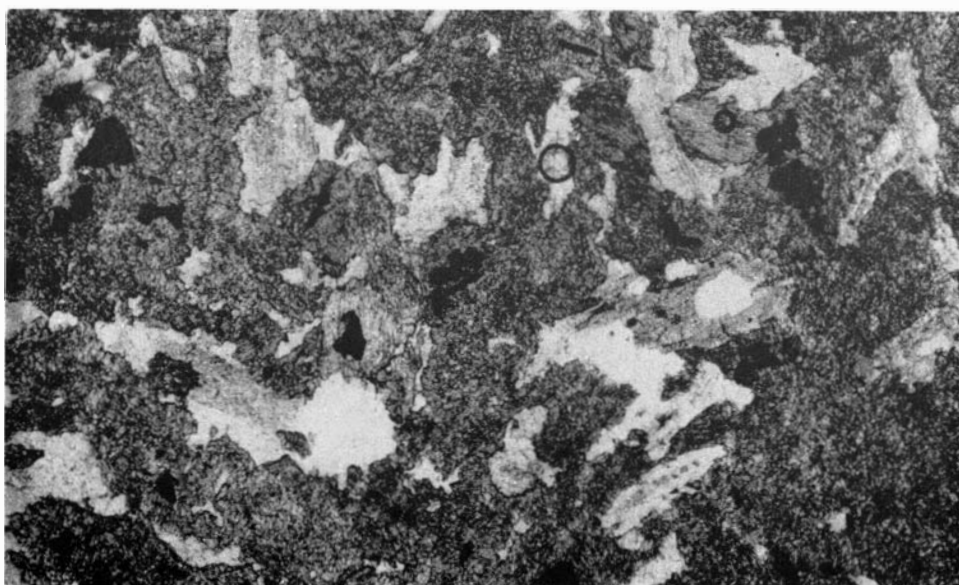
B

Photomicrograph of metadolerite in zone 2 showing a large grain of Andesine with grains of Epidote oriented along the feldspar cleavages. Opaque Iron Ore to the left of the plate is rimmed with Garnet and Augite at the foot of the plate is rimmed with Garnet and Hornblende. Plane polarised light, $\times 55$.



A

*Photomicrograph of metadolerite in zone 2 showing large grains of Hypersthene enclosed by opaque Iron Ore with a narrow rim of Hornblende separating the two.
Plane polarised light, $\times 55$.*



B

*Photomicrograph of metadolerite in zone 3, with granulo-se Quartz/Hornblende intergrowth pseudo-morphing original Augite and with clouded Andesine laths. Opaque Iron Ore is rimmed with sphene.
Specimen 0.3 m from the margin of intrusion at (U223). Plane polarised light, $\times 55$.*

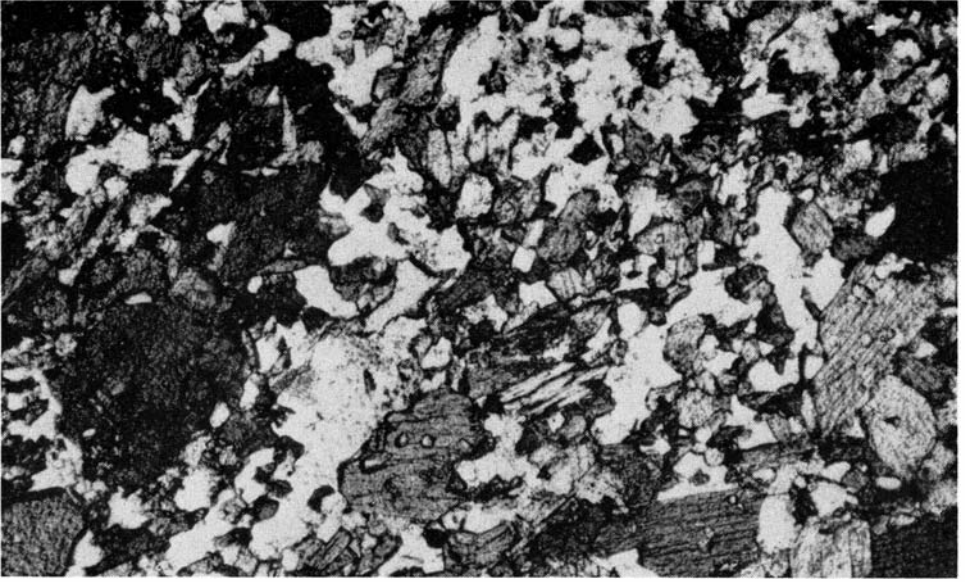


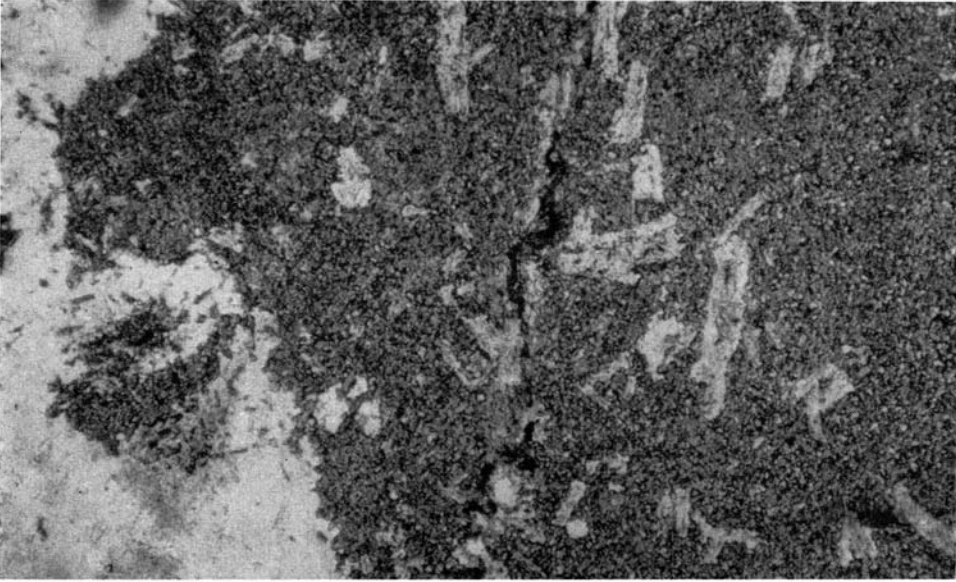
Plate 4A

*Photomicrograph of metadolerite in zone 4 – granulose amphibolite. The original igneous mineralogy and texture are destroyed. Specimen 0.1 m from the margin of intrusion at (U223).
Plane polarised light, $\times 55$.*



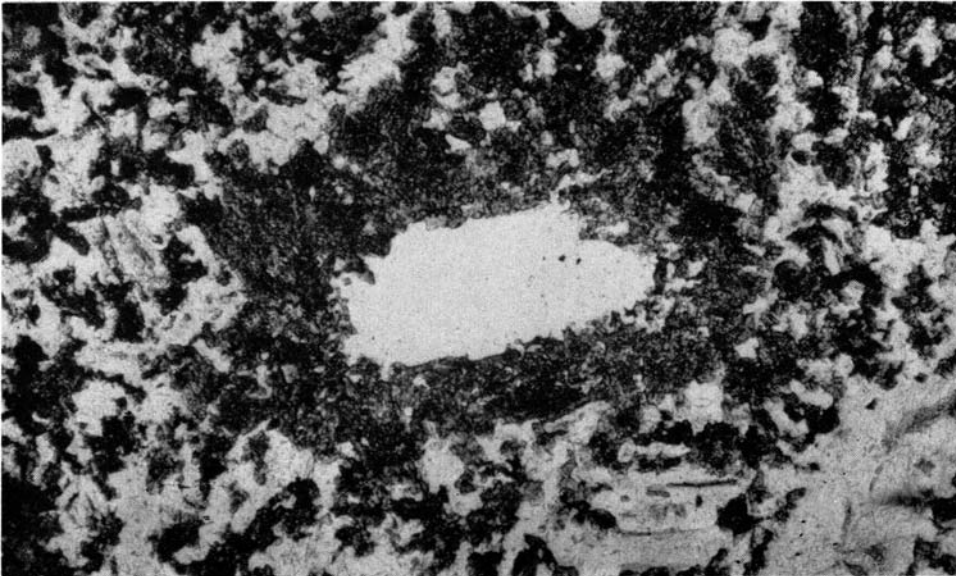
Plate 4B

Photomicrograph of metadolerite in zone 5 – foliated schistose amphibolite. Specimen at margin of intrusion at (U223). Plane polarised light, $\times 55$.



A

*Photomicrograph of metadolerite with fine grained margin in zone 3. Igneous ophitic texture preserved.
Plane polarised light, $\times 55$.*

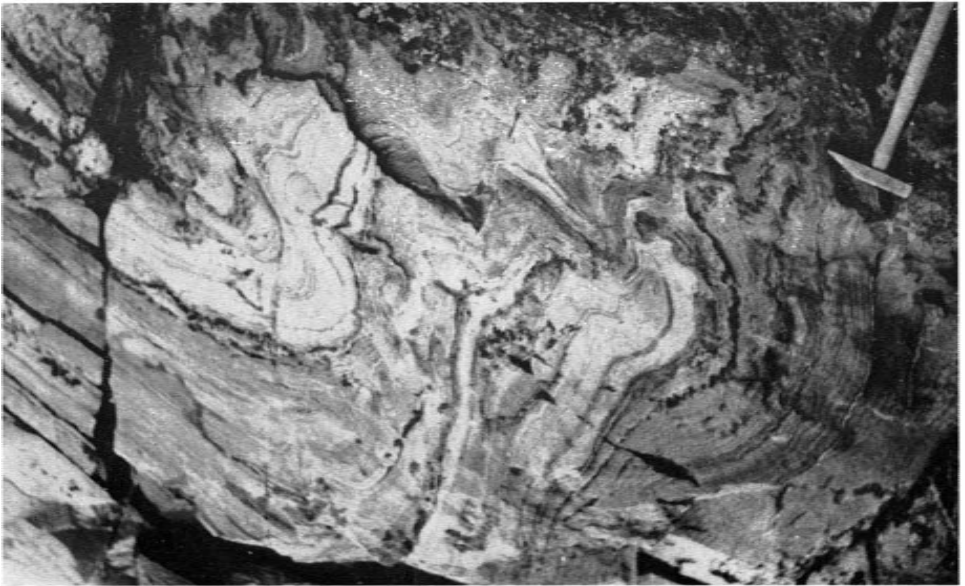


B

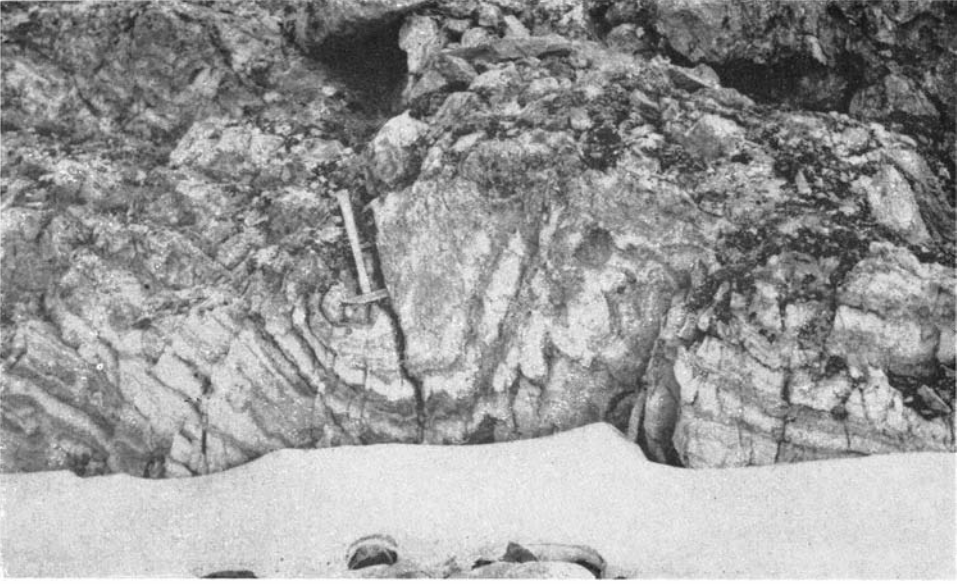
*Photomicrograph of metadolerite in zone 3 near the margin of intrusion, showing a Quartz xenocryst
with granulose Hornblende rim. Plane polarised light, $\times 55$.*



A →
*Vertical joint face in division
c) of the Rittervatnet Forma-
tion showing phase I isocline
refolded by phase II folds
producing a closed outcrop
pattern. The scale is shown
by the 1 krone piece.*



← B
*Vertical joint face in division
c) of the Rittervatnet
Formation showing phase I
isoclines refolded by phase II
folds producing an open
outcrop pattern.*



A

Small scale phase II folds in division c) of the Vassfaret Formation.



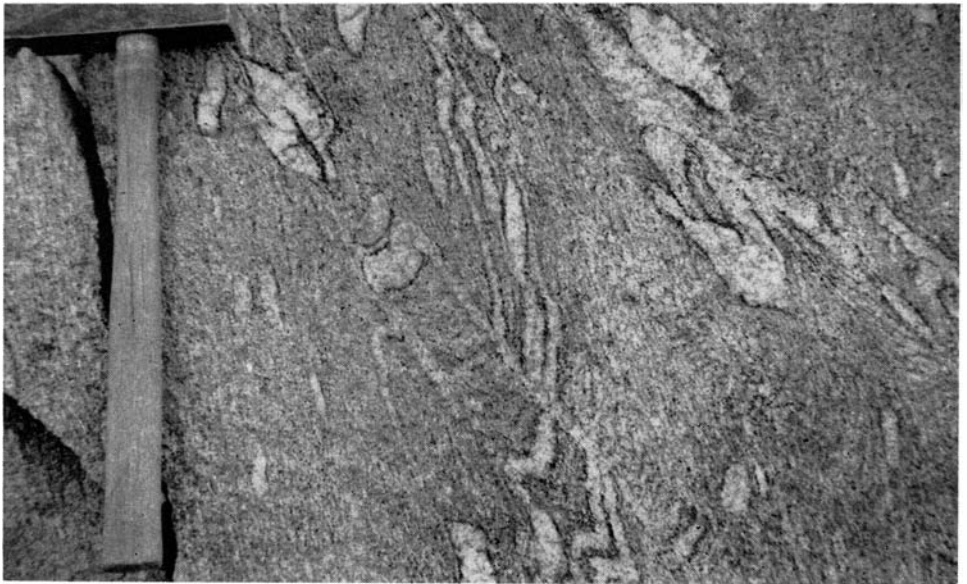
B

Intermediate scale phase II synform in the Rittervatnet Formation. For explanation see Fig. 11B.



A

Flattened small scale phase II folds in division c) of the Vassfaret Formation.



B

Concretion pegmatites of Quartz and Potash-Feldspar rimmed with Biotite within the psammitic-feldspathites of the Flatøyrdalen Member. Note also the early schistosity deformed by phase II folds and crosscutting later schistosity formed parallel to the phase II fold axial surfaces.



A ↑
*Crenulated foliation in a foliated
amphibolite within the Polhem
Formation.*

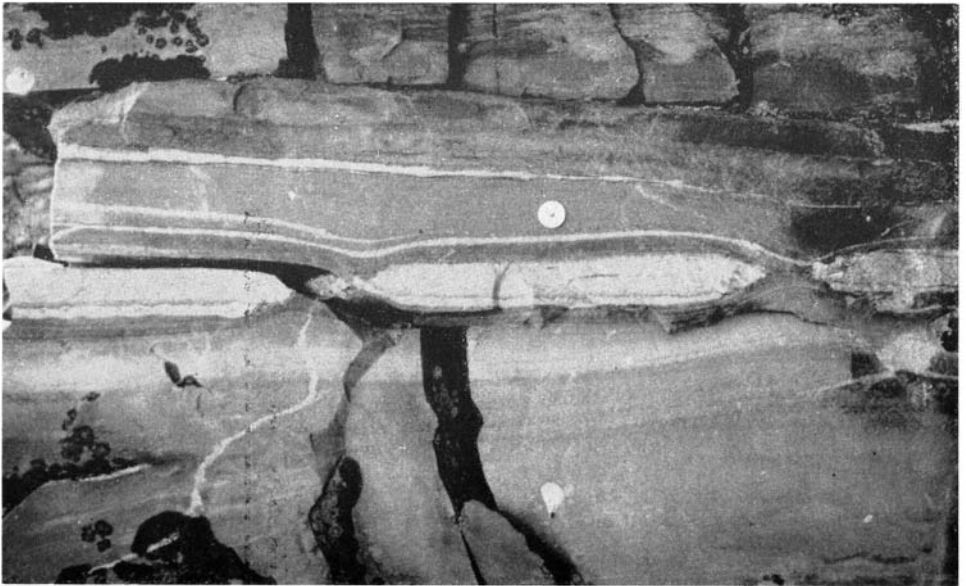


B ←
*Horizontal surface in the Polhem
Formation showing a thin boudined
amphibolite band within foliated
psammites folded by a small scale
phase II fold.*



A

*A pair of small scale phase II folds in an amphibolite band subsequently boudined.
For explanation see Fig. 16.*



B

*Straight necking boudinage in a thin band of Potash-feldspar feldspathite in banded polymictites of
the Femmilsjoen Member. The scale is shown by the 1 krone piece.*



Plate 11A

Straight necking boudinage of a foliated amphibolite in banded polymictites of the Polhem Formation.



Plate 11B

A vein quartz boudin enclosed in banded polymictites of division c) of the Rittervatnet Formation showing small scale folding into the neck of the boudin.



A

Shear fracture boudinage with slight necking of foliated amphibolite and hornblende-polymictite bands enclosed in subpelites of division a) of the Vassfaret Formation.



B

Straight fracture and shear fracture boudinage of vein quartz band in biotite-marble of division a) of the Rittervatnet Formation.

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Enclosed: Geological map of the Femmilsjøen region (Fig. 21).

A.W. BRØGGERS BOKTRYKKERI A/S - OSLO

Norsk Polarinstitutt Skrifter Nr. 145. Rodney A. Gayer: The geology of the Femmilsjøen region of north-west Ny Friesland, Spitsbergen