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The migmatites, granites and metasediments of Danmark Ø and adjacent areas of Milne Land and Gåseland, East Greenland Caledonian fold belt

by

Kurt Bucher-Nurminen

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Abstract

The mapped area (Danmark Ø, part of south-east Milne Land and eastern Gåseland) consists mainly of migmatites and granitic rocks forming part of a migmatitic zone within the East Greenland Caledonian fold belt. The area can be divided into various granitic and syenitic rocks, strongly migmatized paragneisses, a metasedimentary sequence, garnetiferous augen granite sheets, and a thrust sheet of hornblende quartz diorite. Some rock units may have been formed in Precambrian time, and others during the Caledonian orogeny. Large scale E–W trending folds occur in eastern Gåseland and small scale folds throughout the area. Mineral assemblages suggest several metamorphic events. No indications of economic mineralization were found.

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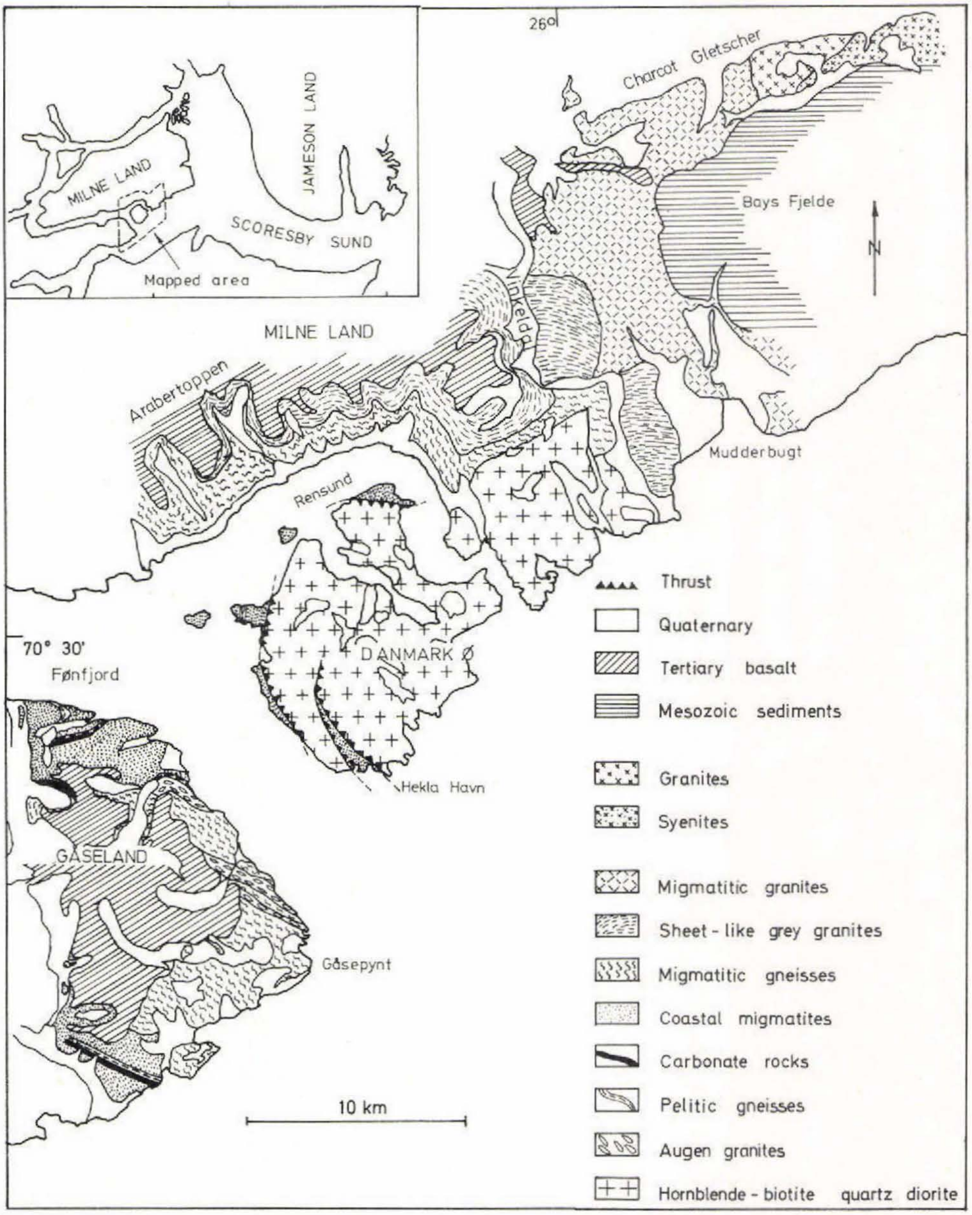

Fig. 1. Geological map of the area described in the inner Scoresby Sund region.

INTRODUCTION

This report describes the geology of Danmark Ø, a part of south-east Milne Land and the eastern peninsular of Gåseland, situated in the inner part of the Scoresby Sund region (fig. 1). The area was mapped during 7 weeks in the summer of 1972, and the field work formed a part of the 5-year mapping programme of the Geological Survey of Greenland.

Much of the area comprises glacially polished hills easily accessible on foot, or by boat along the coasts. Parts of Milne Land and Gåseland have a mountainous topography and helicopters were used to reach distant outcrops.

This study deals only with the crystalline rocks which have partly an Archaean and Proterozoic history, and have partly been involved in the Caledonian orogeny. Mesozoic sediments overlie the crystalline rocks in south-east Milne Land, and are in turn overlain by Tertiary plateau basalts. The pre-basalt topography surface declines from about 1000 m in Milne Land to about 600 m on Gåseland.

GEOLOGY OF THE SCORESBY SUND REGION

The Scoresby Sund region (70°–72°N) includes the southern part of the Caledonian fold belt in East Greenland. Crystalline rocks outcrop in the western half of this region (fig. 2), and in the narrow strip of Liverpool Land in the east; late Palaeozoic and Mesozoic rocks of the Jameson Land basin separate the two crystalline regions.

The western broad region of crystalline rocks is divided into several zones of distinctive character by major thrusts (fig. 2). In the extreme west several windows cut through flat-lying thrust sheets and expose outcrops of presumed foreland in the Paul Stern Land and Charcot Land areas. To the east and partially overlying the windows a zone 40–60 km wide bordered on both sides by thrusts can be traced from Vestfjord to Hinks Land; it comprises two lithostratigraphic units, the Flyverfjord infracrustal complex and the Krummedal supracrustal sequence. Further to the east occurs a very different and distinctive zone about 80 km wide of dominantly migmatitic and granitic rocks, traceable from Gåsefjord through Milne Land and Renland to the Stauning Alper; the area described here occurs in the south-east part of this migmatite and granite zone.

The isotopic ages so far obtained from the Scoresby Sund region are discussed in relation to the regional geology by Henriksen & Higgins (1976) and Higgins (1976). The data suggest that the Flyverfjord infracrustal complex is of essentially Archaean development, and that the overlying Krummedal supracrustal sequence suffered an important metamorphic event about 1150 m.y. ago (Hansen, 1976). The genesis of the zone of migmatitic and

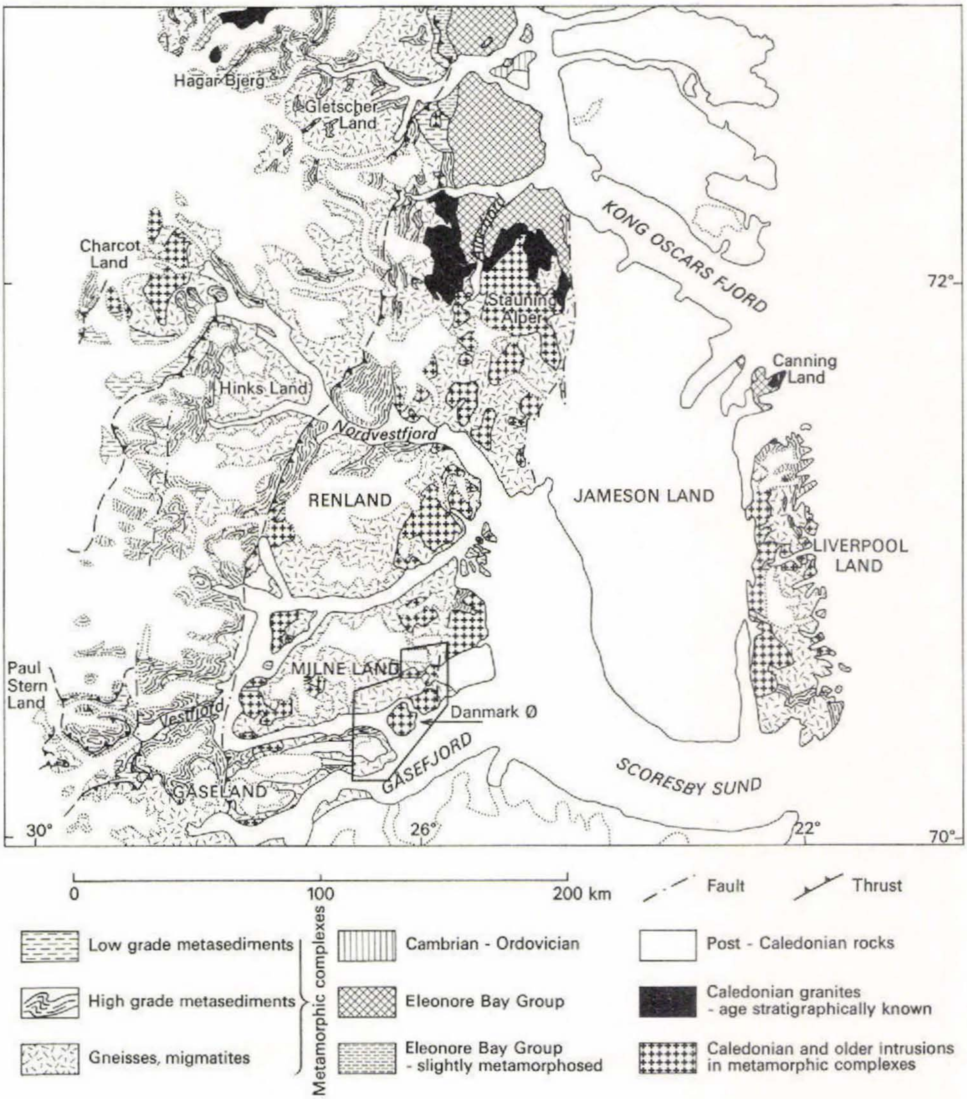

Fig. 2. Geological map of the crystalline rocks of the Scoresby Sund region. The area described is outlined by a frame.

granitic rocks, of which the area described forms a part, is less clearly defined. Zircon ages of c. 950 m.y. on augen granite intrusions emplaced at an early kinematic stage of development of the migmatites suggest middle Proterozoic orogenesis, but Caledonian ages suggest the possibility of Caledonian migmatization superimposed on the earlier events. Some of the problems of interpretation are discussed in the regional descriptions of the Stauning Alper (Henriksen *et al.,* in press), and part of eastern Milne Land (Higgins, in prep.).

GEOLOGICAL DIVISIONS

For descriptive purposes the rocks which occur in the mapped area can be roughly divided, from north-east to south-west, as follows:

Grey-pink granites and reddish syenites
Pink garnetiferous migmatitic granites with gneiss and amphibolite inclusions
Sheet-like grey, garnetiferous granites with plagioclase-rich gneiss layers
Rusty brown migmatitic gneisses
Coastal migmatitic gneisses
Metasedimentary sequence on Gåseland
Grey-pink garnetiferous augen granites
Hornblende-biotite quartz diorite

The distribution of these units is shown on the geological map (fig. 1). On the basis of field investigations the geological events represented can be placed into a relative time scale (Table 1). Since no isotopic work has yet been carried out in the area of study, interpretations of ages of developments are based on extrapolation from other parts of the region.

Grey-pink granites and reddish syenites

These poorly exposed rocks occur in the north-east part of the area, south of Charcot Gletscher. They form patchy weathered outcrops on moraine covered plateaus limited to the south by unconformably overlying Mesozoic sediments. Fresh outcrops occur in the gullies leading down to Charcot Gletscher. The two principal rock types are a grey fine-grained homogeneous granite in the west and a reddish fine to medium-grained garnetiferous syenite in the east. Contacts between the rock types, and with the migmatites further west, are not clear.

Table 1. Schematic relative chronology of main events

Migmatite and granite zone	Age
Tertiary dykes and basalts Mesozoic sediments	Post-Caledonian
N-S folds Metamorphism Faults Intrusion of grey pink granite & syenite E-W folds (2nd phase) Augen granites Migmatization Thrusts Emplacement of quartz diorite Recumbent E-W folds Metamorphism Deposition of sediments (Krummedal sequence)	Caledonian 395-480 m.y. and Middle Proterozoic *c.* 900-1150 m.y.
? Older basement	

The grey granite shows no deformation, is almost free of inclusions, and displays only minor variations in grain size and composition. Quartz, microcline, plagioclase, biotite and muscovite occur as an equidimensional mosaic. The quartz is slightly deformed and often contains rutile inclusions. K-feldspar occurs as a fresh microcline perthite. Zoned plagioclase is usually slightly altered in the centre to white mica. The muscovite and biotite occur as fine, sometimes coarse, non-oriented flakes, locally fresh and in other areas strongly chloritised. Intergrowths of green and brown biotite are common. Chlorite may be present as fresh flakes, as well as an alteration product. Rare inclusions in the granite up to a few centimetres in length consist of almost monomineralic biotite.

The garnetiferous syenite comprises up to 80 per cent reddish K-feldspar in grains from one to twenty millimetres in diameter, broken into slightly rotated domaines displaying a coarse microcline lattice. Plagioclase occurs usually as myrmekite. Quartz (about 5 per cent) is strongly deformed. Brown garnets (about 10 per cent) are an unusual constituent of this syenitic rock, developed as corroded, poikilitic individuals.

Higgins (in prep.) has described the area immediately to the north of Charcot Gletscher and also a narrow strip to the south; he suggests that the grey homogeneous granite body mentioned here is one of a suite of small pink or grey-pink granite plutons occurring in eastern Milne Land. One of these plutons has given a Rb-Sr isochron age of 442±8 m.y. (Hansen & Steiger, 1976), and it is suggested that the entire suite of pink granites might be Caledonian in age. The only other syenitic intrusions in the migmatite and granite zone are bodies of hornblende syenite occupying the central parts of some granitic bodies in the Stauning Alper (Henriksen *et al.,* in press).

Pink garnetiferous migmatitic granites with gneiss and amphibolite inclusions

These rock types occur in a zone running from Charcot Gletscher southwards to Mudderbugt, and seem to represent the deepest structural level of the migmatite region. They vary from nearly massive granites to neosome-rich banded gneisses, chiefly depending on the proportion of inclusions (fig. 3). The zone as a whole has a concentric structure about a

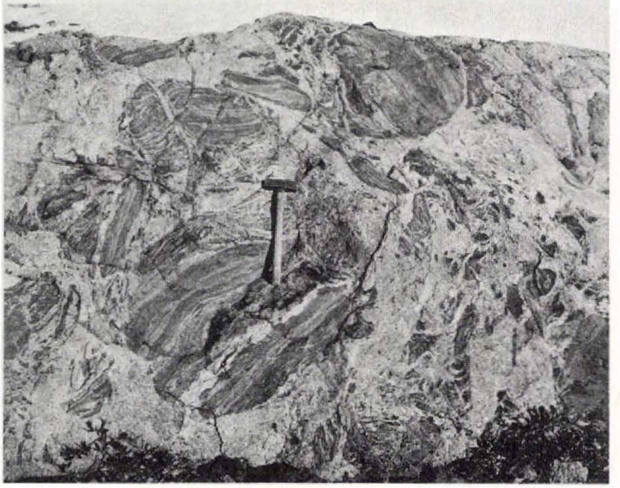

Fig. 3. Migmatite granite south of Charcot Gletscher with numerous schollen of garnet-biotite gneiss.

reddish inclusion-poor granitic mass. Southwards and northwards from this granitic mass the amount of mainly gneissic inclusions steadily increases. In the extreme north around Charcot Gletscher, and extreme south around Mudderbugt, amphibolite inclusions are common. There are no sharp boundaries within the zone but rather a continuous range of rock types due to variations of the neosome-inclusion proportion. There are several generations of pink to reddish leucosome suggesting the formation of the migmatites was a polyphase event.

The pink to reddish granitic leucosome may form thin conformable layers in gneisses, cross-cutting dykes, irregular masses with diffuse boundaries, light coloured ptygmatic veinlets in schollen, extensive masses with wavy gneissic structure or large massive granitic bodies with small inclusions. The rock is rich in K-feldspar with variable amounts of garnet and biotite and a wide range of colour and texture. Grain size varies dramatically, K-feldspar crystals ranging from a few millimetres to ten centimetres in diameter within a short distance. The cross-cutting dykes also have a granitic texture.

Except for quartz the minerals tend to be euhedral. Fresh stringlet perthitic microcline shows almost no deformation. Plagioclase is usually zoned and slightly altered and shows mymerkitic textures; the cores are relatively Ca-rich and the rims Na-rich, the anorthite content being, however, uniformly low at around 14 per cent. Fresh, brown biotite flakes and quartz form with the feldspars an equidimensional magmatic mosaic texture. Rare muscovite occurs as strongly corroded tiny flakes. Locally, coarse euhedral K-feldspars give rise to a fluid-like flow structure while the texture of wavy gneissic rocks is due to orientation of biotite. Retrogressive alteration is very minor and limited to replacement of biotite by muscovite, exsolution of quartz in biotite, and chloritization. Accessories are apatite, rutile and zircon, while poikilitic brown garnet is always present.

The several neosome generations all have more or less the same composition which approximates to the eutectic composition in the quartz – K-feldspar – plagioclase system. Concordant or discordant aplitic or pegmatitic dykes are rare, and differ from the granitic neosome by a higher K-feldspar content.

The most important types of paleosome inclusions are dark brown mica-rich gneissic remnants, forming subparallel gneissic bands, or broken and rotated schollen of various sizes. The rock types vary from garnet-biotite schlieren to garnet-biotite-plagioclase gneisses. Garnet is always present, in crystals up to several centimetres in diameter. Many of the schollen have garnet-rich centres and garnet-free rims. Biotite is a major constituent and forms almost monomineralic masses and schlieren. No cordierite, pyroxene or sillimanite have been observed in these rocks.

Further important types of paleosome inclusions are quart-zrich grey gneisses and quartzites found throughout the zone usually in decimetre size fragments. Biotite and garnet are found in minor amounts. Garnet-bearing, coarse-grained almost pure quartzites have been found.

Amphibolite remnants are significantly frequent in the northern and southern extremes of the unit, occurring always as rounded inclusions up to a metre in size in the granitic neosome. The amphibolite schollen form more or less E–W striking bands concordant to the regional banding in the gneissic remnants, indicating possibly a supracrustal origin. Garnet-bearing amphibolites are most frequent, brown grossularite-andradite garnets up to 10 mm in diameter forming in some places more than 50 per cent of the rock. Hornblende crystals in occasional amphibolites may be several centimetres in length.

Different types of amphibolite remnants strike across the regional lithological layering, suggesting they may originally have been doleritic dykes. They are very dark garnet-free amphibolites, comprising two generations of amphiboles (hornblende and actinolite), plagioclase, biotite, orthopyroxene (hypersthene) and accessories. Amphibole and plagioclase have mutually embayed grain boundaries. Brown mica, locally chloritised, occurs as intergrowths with amphibole or as poikilitic inclusions in the amphiboles. The younger amphibole generation (actinolite) looks extremely fresh, and occurs in the association actinolite, biotite, sodic plagioclase. Small rounded grains of hypersthene are frequent, but textural evidence suggests it belongs to an early mineral generation of hypersthene, hornblende and calcic plagioclase.

Migmatitic granites occur throughout the migmatite and granite zone as small and large bodies up to 5 by 25 km in outcrop (Henriksen & Higgins, 1976). The amphibolite remnants in the paleosome, so common in the area described, are found also in south-west Milne Land and locally in parts of Gåseland and Renland. Henriksen & Higgins (1976) have suggested they are derived from a characteristic level of the migmatised original succession, possible a basement gneiss and amphibolite complex, but the writer suggests that the concordant amphibolites could also have a sedimentary or volcanic origin.

Sheet-like grey, garnetiferous granites with plagioclase-rich gneiss layers

These rocks make up the strikingly banded cliffs north of Rensund, with extensions eastwards across Vinkeldal to the Mudderbugt area where they overlie the migmatitic granites described in the previous section. The grey, homogeneous, garnetiferous granite sheets are 5 to 50 m in thickness, and are separated by layers up to 10 m thick of finely banded plagioclase-rich gneisses (fig. 4). This alternation of rock types produces the typical megascopic banding.

The grey garnet granite sheets are medium-grained, typically with a wavy flow structure outlined by oriented biotite, sometimes curving around up to 3 cm across euhedral K-feldspar, plagioclase, biotite and minor amounts of garnet. Quartz is slightly deformed and shows sutured grain boundaries. String, rod or interpenetrating microcline perthite is often transformed into white mica, which occasionally itself shows chloritization. Subhedral oligoclase is fresh and zoned, and commonly has mymerkitic grain boundaries with K-feldspar. In areas where the K-feldspar is altered, the oligoclase also shows alteration, to mica and calcite.

Biotite and garnet are the principal mafic minerals in the grey granite forming up to 10 per cent of the rock. Biotite occurs as very fresh flakes pleochroic from pale brown to very dark brown or red-brown. It exhibits no signs of deformation or alteration, and the only inclusions are zircons. Garnet forms brown, strongly embayed, occasionally poikilitic individuals up to 2 mm in diameter. Inclusions are mainly quartz. Occasionally epidote rims the garnets or fills cracks of broken individuals. Apatite and zircon are abundant accessories, zircon in relatively high amounts.

The petrography of the granite sheets suggests a relatively simple history for the rock. In spite of the common flow structure, the absence of strongly zoned minerals and the thin concordant gneiss layers imply relatively little transport. The grey granite sheets may represent slightly moved neosome bands. Post-migmatitic tectonic movements caused only minor deformation of the granites. Later alteration affected only feldspars, although the alteration

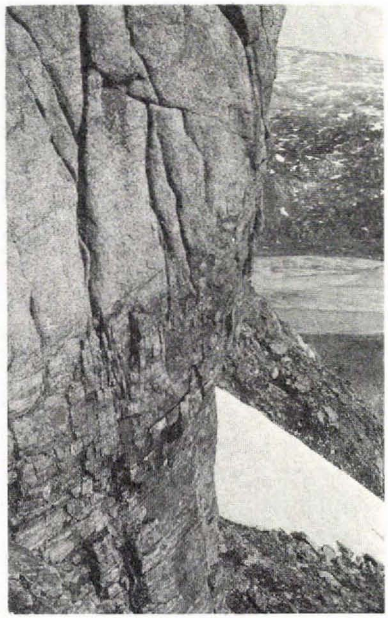

Fig. 4. Sheet-like grey granite in the Vinkeldal area. Garnet bearing granite shows magmatic flow structure due to orientation of euhedral K-feldspar laths; garnet-biotite gneiss below.

products, white mica, calcite and epidote could be interpreted as a younger distinct metamorphic event, which also caused recrystallization of the biotite.

The finely banded gneissic layers between the grey granite sheets consist of dark, brownish weathering, garnet-biotite-plagioclase gneisses. The layers do not exceed 10 m in thickness. Lateral thinning has frequently been observed, the thinning layers being usually increasingly enriched in biotite. Occasionally oriented monomineralic biotite schlieren occur as remnants in the granite. Within the gneiss layers thin concordant bands of leucocratic, granitic neosome are common, as are phenocrysts of K-feldspar developed along distinct surfaces. Cross-cutting granitic neosome veins are very rare and of minor extent. The absence of rotated schlieren and displacements other than parallel to the foliation, strongly suggest there were only slight lateral movements during emplacement.

Rusty brown migmatitic gneisses

Rusty brown, very variable, migmatitic gneisses make up the Rensund coast of Milne Land and the steep narrow valleys of the Arabertoppen area, underlying the zone of sheet-like grey granites. They occur at the same tectonic level as the pink garnetiferous migmatitic granites from which they differ by a much lower granite proportion, and the presence of sillimanite. Migmatitic gneisses are also widespread in eastern Gåseland. The degree of migmatization varies over a wide range, and is seen in the development of K-feldspar phenocrysts, thin concordant, leucocratic granitic layers, ptygmatic pegmatitic veinlets, large concordant granitic neosome layers, irregular granitic masses, and cross-cutting granitic and late pegmatitic dykes (fig. 5). Geometric relations suggest at least three

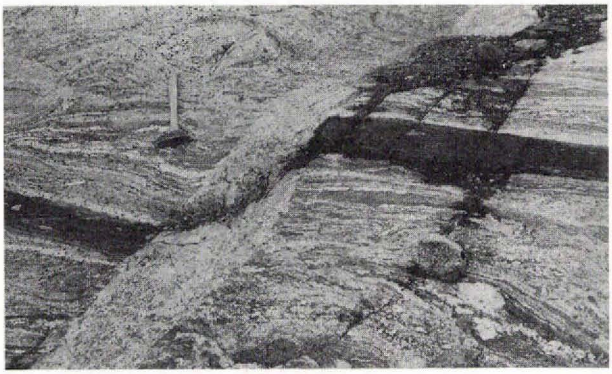

Fig. 5. Garnet amphibolite band in variably migmatized gneisses, displaced by a later discordant granitic sheet.

phases of migmatite development. The paleosome remnants are predominantly gneissic, amphibolite being rare. The proportion of neosome seems to increase towards the north-east. Two different fold types are commonly developed. Rotated schollen, shear zones and displacement zones indicate tectonic movements during migmatization.

The pink medium-grained granitic neosome usually shows no preferred mineral orientation. Occasionally where K-feldspar occurs as large euhedral crystals (up to 30 mm across) a typical fluid-like flow structure can be developed, but even here biotite does not show a parallel orientation. Strong cataclastic deformation is typical. Quartz occurs as deformed, broken and extremely indented individuals. The K-feldspar is microcline, coarsely latticed and strongly deformed with myrmekitic rims at grain boundary contacts with plagioclase. The K-feldspar shows slight alteration to white mica. The plagioclase (oligoclase) is commonly broken, but only slightly altered. Of the mafic minerals, about 10 per cent of the rock, biotite is the most important as subhedral red-brown flakes, many of which show oxide exsolution but no deformation. Broken brown garnets frequently have chlorite-filled cracks. Apatite is a common accessory.

In the granites with flow structure fine-grained shear zones form wavy surfaces made up of needle-shaped sillimanite and fine flaky muscovite. In these rocks biotite is overgrown by muscovite. Large poikilitic, stringlet, orthoclase perthites have inclusions of quartz, zoned plagioclase and biotite. Carlsbad twinning is common. Within the orthoclase small areas of microcline with myrmekite reaction rims are common. The K-feldspar in the matrix is a microcline perthite. Apart from the subhedral, fresh oligoclase in the matrix, an older generation of small zoned plagioclase is present having an anorthite-rich core and an oligoclase rim.

Rusty brown weathering, garnet-biotite-plagioclase gneisses are the principal paleosome rocks, thin leucocratic quartz-feldspar sweats giving the rock its banded appearance. The principal constituents are quartz, K-feldspar, plagioclase, biotite, muscovite, hornblende, sillimanite and garnet. Muscovite occurs as corroded, embayed flakes, and shows a close relation to fine needle-shaped sillimanite. Where amphiboles are present, pleochroic green hornblende is occasionally overgrown by colourless actinolite. Large embayed garnets occur in association with zoistite, calcite and muscovite, calcite being a rather common constituent of some gneisses. Chloritisation of biotite and garnet may occur, but generally retrogressive alteration is not common. Cataclastic deformation is the rule, although some fresh, undeformed biotite-rich granitic gneisses have been found.

Amphibolite remnants are rare in this unit, and occur usually as thin isolated plates or occasional rounded schollen. They comprise pleochroic, fresh green hornblende, with quartz, plagioclase and biotite as matrix minerals; garnet is uncommon. Biotite shows exsolution of iron oxides and quartz along (001) cleavage planes. Generally there is little alteration.

At one outcrop several schollen up to 5 m across of an unusual biotite-garnet rock were found. Garnet forms about 70 per cent and biotite 25 per cent of the rock.

Migmatitic rocks such as those described above as 'rusty brown migmatitic gneisses' and below as 'coastal migmatites' dominate throughout the migmatite and granite zone, a region 80 km from east to west and more than 200 km from south to north. There is great variety in their appearance from area to area (Chadwick, 1971, 1975; Henriksen *et al.*, in press; Henriksen & Higgins, 1970, 1971, 1973), but an overall similarity in their genesis.

Coastal migmatites

Along the west coast of Danmark Ø and on eastern Gåseland banded migmatitic gneisses can be distinguished from the other migmatitic units by the characteristic occurrence of metasedimentary rocks, consisting typically of a sequence of metapelites, amphibolites and marbles. A few augen granite sheets occur exclusively in the coastal migmatite complex. The migmatitic structures are rather heterogenous, but banded and folded types are predominant (figs 6 & 7). The content of granitic leucosome is significantly lower than in the rusty brown migmatitic gneisses, and as a consequence the pre-migmatitic structures are rather well preserved. The leucocratic, occasionally pink neosome occurs as concordant bands from about one centimetre to several metres thick in the gneisses. Biotite granite veins fill cross-cutting displacement planes, and a late generation of mica-poor granitic dykes can be found all over Gåseland. These banded migmatitic gneisses are strongly folded in many parts of Gåseland.

The common migmatitic leucosome in the coastal migmatites is a garnet-biotite granite, though in several places the granite is very poor in biotite. Garnet may be the only mafic mineral present in some white granite leucosome on Gåseland and Danmark Ø. The composition of the granitic material varies considerably. Anorthite content of the plagioclase varies between 9 and 28 per cent. Plagioclase may form 30 to 70 per cent of the rock volume, and alkali-feldspar varies from 11 to 45 per cent. These large compositional variations of the granitic leucosome may be mainly of metasomatic origin. Usually the rocks show little retrogressive alteration. Euhedral or subhedral untwinned microcline as string or rod

Fig. 6. Irregular shaped garnet amphibolite schollen in migmatitic gneisses of the coastal migmatites; island west of Danmark Ø.

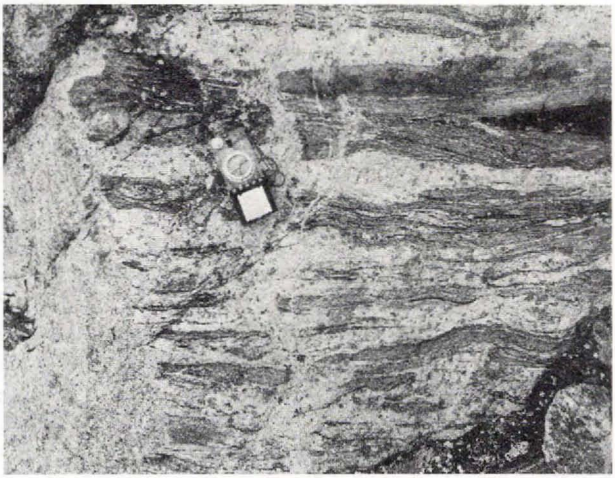

Fig. 7. Banded garnet-biotite-sillimanite gneiss with two generations of migmatitic neosome; coastal migmatites of south-east Gåseland.

perthite, and plagioclase and quartz are the principal minerals. Quartz shows only little deformation, with straight grain boundaries common. Myrmekitic reaction rims are rare, while many of the feldspars show polyphase growth and zonation. Occasionally, chloritized, brown biotite is the principal mafic mineral, and it frequently occurs together with corroded, embayed white mica. Unbroken poikilitic garnet with inclusions of quartz is invariably present in small amounts. Zircon occurs as an accessory.

The zones of marbles, amphibolites, metapelites and various semipelitic paragneisses interlayered with the coastal migmatite complex imply a general metasedimentary character for the migmatite host. The principal paleosome rock type is a garnet-biotite-plagioclase gneiss with frequently interlayered amphibolites. The structures in the gneisses indicate a complex polyphase deformation history. The composition of the gneisses and their close relation to the interlayered concordant amphibolites suggest a sedimentary origin. Unzoned plagioclase, quartz and biotite are the principal minerals; a little microcline perthite is present in most sections. Commonly two generations of biotite are present, an older generation transformed into chlorite and a younger one very fresh and showing a considerably brighter pleochroism than the biotites in the neosome. Muscovite is rare or absent. Needle-shaped fresh sillimanite occurs as inclusions in feldspars or along feldspar grain boundaries but most frequently is found in close relation to fresh biotite. In one section the sillimanite needles were barb-like and overgrown by young biotite. Poikilitic almandine-rich embayed garnet is commonly present. Layers of slightly lenticular garnets, fresh biotite and sillimanite are characteristic for these gneisses. Barbs of biotite can be found in the pressure shadows of the garnets. The typical metamorphic mineral assemblage is quartz–alkali feldspar–plagioclase–garnet–sillimanite–biotite–magnetite. Accessories are sphene and zircon.

Metasedimentary sequences on Gåseland

On eastern Gåseland metasedimentary sequences are interlayered with the weakly migmatised gneisses of the coastal migmatite complex. The thickness of the sequences does not exceed 200 m. These sequences form the only good marker horizon in the mapped area and allow some conclusions to be made on local tectonics. The characteristic members of the sequence are garnet-sillimanite gneisses, amphibolites and various carbonate rocks (figs 9 & 10). Concordant layers of leucocratic granite sheets and rare cross-cutting granitic dykes

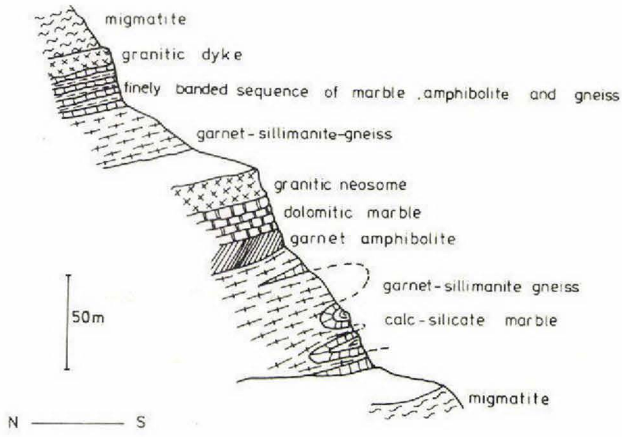

Fig. 8. Profile through the metasedimentary sequence in eastern Gåseland.

demonstrate the relationship to the migmatites above and below the metasediments. The common occurrence of the different rock types in one characteristic stratigraphic sequence all over eastern Gåseland strongly suggests the existence of only one metasedimentary horizon within the migmatites of the mapped area (fig. 8).

Garnet-sillimanite gneisses

These are finely banded biotite and garnet-rich gneisses (fig. 9). Thin leucocratic bands of alkali feldspar, quartz and garnet alternate with dark, very biotite-rich sillimanite-bearing

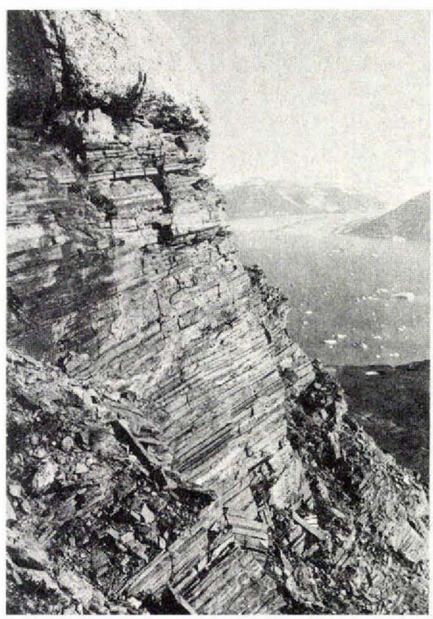

Fig. 9. Well banded sequence consisting of amphibolite, calc-silicate marbles and garnet-sillimanite-biotite gneiss of the metasedimentary unit in south-west Gåseland, capped by a late, undeformed granite sheet.

layers. The gneisses occur at various levels within the metasedimentary sequence. Probably some of the horizons are tectonic repetitions due to isoclinal folding.

The principal minerals are quartz, K-feldspar, plagioclase, biotite, garnet and sillimanite. Plagioclase and quartz form the bulk of the rock and are only little deformed. Fresh untwinned K-feldspar is closely related texturally to biotite, sillimanite and garnet. The mafic minerals are usually fresh. Minor retrogressive alteration of biotite (exolution of opaque minerals) and K-feldspar (formation of white mica) may occur. Sillimanite is most probably formed from the breakdown of muscovite and quartz, as rare relicts of corroded muscovite texturally related to sillimanite, biotite and K-feldspar suggest. Thin sweats of K-feldspar and quartz and a tendency for K-feldspar blastesis prove a slight migmatitic affinity even for these aluminous gneisses. The gneisses contain a considerable amount of zircon.

Amphibolites and related rocks

The basic members of the metasedimentary sequence vary from the most common garnet-amphibolites to clinopyroxene-bearing amphibolites and clinopyroxenites. The thicknesses of a single layer varies from about 10 cm up to 8 m. Laterally thinning amphibolite bands are common and rapid vertical compositional fluctuations cause variable mineralogies within a given band. A dark green garnet-rich banded amphibolite is the most frequent; biotite and hornblende are well oriented and give the rock its gneissic habit.

Large violet garnets are extremely poikilitic. Brown-green pleochroic hornblendes constitute about 20 to 40 per cent of the rock. Brown biotite occurs together with hornblende as euhedral crystals. Calcic-plagioclase with embayed grain-boundaries represents about 10 to 20 per cent of the rock by volume and is commonly slightly altered. Hornblende and biotite may be slightly chloritized. The characteristic assemblage is hornblende–biotite–garnet–plagioclase–quartz–magnetite. Opaque minerals (probably magnetite) are usually associated with hornblende and biotite.

Many of the amphibolites contain diopsidic clinopyroxene usually in mosaic textures with green amphibole and biotite. The relative proportions of biotite, hornblende and pyroxene may vary markedly across the layering and up to as much as 40 per cent of the rock may be formed by clinopyroxene. Overgrowths of green amphibole on pyroxene suggest hornblende to be later relative to pyroxene. A remarkable feature in the clinopyroxene-bearing amphibolites is the frequent occurrence of small amounts of carbonate. The characteristic assemblage is hornblende–diopside–biotite–garnet–plagioclase–opaques (magnetite)–calcite±quartz±K-feldspar. The occurrence of banded layers of amphibolite of strongly variable composition in close relation to marbles and metapelites suggests a sedimentary or pyroclastic origin of these metabasites.

Carbonate rocks

Marbles and calc-silicates are distinguished. The marbles may be divided into two groups. The first group comprises very coarse-grained almost pure dolomitic marbles usually in bands of up to 10 m thickness (fig. 10), in which the size of the crystals reaches 2 cm. The bands are very homogeneous and uniform in composition. At least four bands of dolomitic marbles occur in the sequence, the thickest of them interlayered with garnet-amphibolite. The second group consists of a repeated series of banded aluminous-siliceous calcite-dolomite marbles. These are banded on a decimetre scale, and the changes in composition are usually gradual and reflect most probably an original sedimentary layering of marly lime-

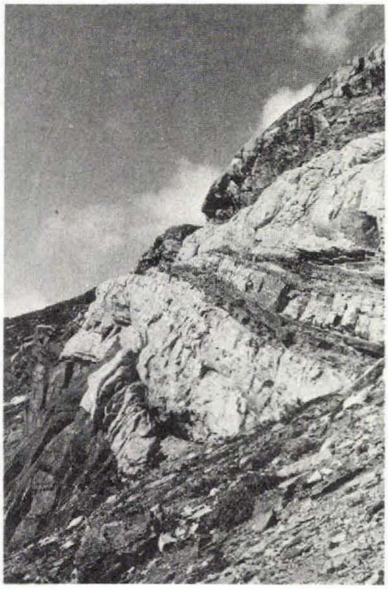

Fig. 10. Metasedimentary sequence on south-east Gåseland. From bottom to top: garnet amphibolite, dolomitic marble, garnet-sillimanite-biotite gneiss.

stones and argillaceous dolomites. In spite of the common gradual changes it is useful to describe the rocks separately. The great advantage of these rocks is that their mineral assemblages are very sensitive to variations in metamorphic grade. These marbles are in fact the only rock types within the mapped area which allow some interpretation of the metamorphic history, and provide limits for the metamorphic conditions. Unfortunately the silicious marbles occur exclusively on Gåseland.

The mineralogy of the siliceous marbles is summarized in Table 2. The textural relationships between the minerals suggests several generations of mineral assemblages reflecting a polymetamorphic history

Table 2. Mineral content of east Gåseland siliceous marbles and calc-silicates

GGU sample number	Cc	Do	Ol	Chu	Am	Di	Hed	Chl	Phl	Sp	Se	Pla	Other	Remarks
196575	×	×	×	×	×	×		×		×	×			
570	×	×	×	×	×			×	×	×				
710	×	×	×	×	×			×	×	×				
574*	×	×	×	?				×	×	×				
574*	×	×	×	?	×						×			
547*	×	×	×		×	×		×	×					Do retrograde
534	×	×			×				×		×			
577*	×							×	×			×		
577*	×				×		×					×	Sphene	
545	×				×		×		×			×	Scapolite	Phl Fe-rich
547*	×				×	×	×		×			×	Sphene	Phl Fe-rich

Abbreviations: Cc = calcite, Do = dolomite, Ol = olivine, Chu = clinohumite, Am = pargasitic amphibole, Di = diopsidic clinopyroxene, Hed = Fe-rich clinopyroxene, Chl = clinochlore, Phl = phlogopite, Sp = spinel, Se = serpentine (always retrograde), Pla = plagioclase.

Samples denoted with an asterisk represent inhomogeneous bulk chemistry within the scale of hand samples (finely banded marbles).

for the rock. Coarse-grained dolomite with straight boundaries contains small, colourless, euhedral Mg-Al-spinel. In extremely silicate-rich samples all dolomite was consumed by decarbonatization reactions to form magnesian silicates. However, small amounts of irregularly shaped dolomite are present even in these rocks, formed by retrogressive exolution of dolomite from magnesian calcite. Olivine occurs as somewhat broken crystals, occasionally elongated along (010) planes. In some samples olivine shows various degrees of serpentinization, from crack-fillings to serpentine pseudomorphs after olivine. The serpentine minerals have not been examined by X-ray methods, but antigorite and greenalite are probably present. Dark reddish-brown and twinned monoclinic humite group minerals up to several millimetres in size are typical. The humites belong to the chondrodite and clinohumite group and are rich in titanium and therefore poor in fluorine (Bucher-Nurminen, 1977). The shape of the humite minerals is similar to that of olivine; the embayed crystals are slightly broken but less serpentinized than olivine. Diopside was found in one sample only, as corroded individuals together with amphibole, calcite and dolomite. Needle-shaped tremolite is developed at the expense of olivine and calcite which is clearly a retrograde reaction. A very unusual feature can be observed in amphiboles found in association with spinel, chlorite, olivine and carbonate; very sharply zoned and perfectly euhedral amphiboles consist of a pargasitic core with a rim of tremolite. A representative pargasite analysis is given in Table 3. This feature and the metamorphic history and conditions of these marbles is discussed below in the metamorphic section. Serpentinization of amphibole occurs in retrograde rocks.

Colourless or very bright greenish euhedral spinel is of about the same size as the other minerals. Its iron content is certainly below 10 per cent judging by the colour, and therefore the iron content can be expected to be even very low in all the other phases (Bucher-Nurminen, 1977). The spinel may be slightly chloritized, but occurs usually as very fresh individuals. Chlorite on the other hand occurs as an alteration product of spinel but is more important as euhedral, colourless, coarse flakes. This magnesian chlorite, probably of the clinochlore-pennine series, forms mosaic textures with spinel, carbonates, olivine, humite and amphibole. The mentioned assemblage represents one critical mineral paragenesis of these rocks. The textures suggest that another assemblage involving diopside and amphibole preceeds it. Phlogopite is the only potash-bearing mineral in the marbles and forms colourless to slightly brownish euhedral flakes. Occasionally kinking can be observed in both phlogopite and chlorite. Frequently phlogopite-chlorite intergrowths have been observed as well as direct phase contacts with all other marble minerals. For the discussion on conditions of metamorphism in a later section two critical assemblages have to be considered:

Table 3. Microprobe analyses of pargasitic amphibole in dolomitic marble

		Atomic proportions normalized to 24 oxygens	
SiO_2	43.52	Si	6.17
TiO_2	1.00	Al^{IV}	1.83
Al_2O_3	15.25		
FeO*	1.65	Al^{VI}	0.70
MnO	0.07	Fe	0.19
MgO	19.03	Mn	0.01
CaO	13.48	Ti	0.11
Na_2O	1.73	Mg	3.99
K_2O	1.39	ΣAl^{VI} to Mg	5.00
F	0.69		
H_2O^+	1.90	Ca	2.03
OH=F	0.40	Na	0.47
	99.72	K	0.25
		ΣCa to K	2.75

Sample GGU 169575, east Gåseland.
*Total Fe expressed as FeO, + stoichiometric H_2O.
Analyst: K. Bucher-Nurminen.

(1) calcite–dolomite–olivine–amphibole–chlorite–spinel
(2) calcite–dolomite–amphibole–diopside–forsterite.

Associated calc-silicates comprise commonly clinopyroxene (hedenbergite), green amphibole, plagioclase, scapolite, calcite and biotite; K-feldspar and sphene are present in minor amounts (table 2). The clinopyroxene is coarse-grained, broken, embayed and corroded, and is frequently overgrown by younger Fe-poor pyroxene of diopsidic composition. In close relation to the diopside a fresh needle-shaped actinolite (tremolite) can be found. Plagioclase in association with calcite contains 70 to 84 per cent anorthite component. In one section scapolite occurs as large euhedral crystals in rather large amounts. Where green hornblende and biotite are present these phases are always fresh and undeformed. In the transition zones to the dolomitic marbles biotite changes into phlogopite, green hornblende into actinolite (pargasite), feldspars and scapolite disappear and chlorite becomes an important phase. The very minor importance of metasomatic features in the transition zone is surprising, i.e. there are no monomineralic zones, or zones with a significant decrease in the number of involved phases, or symmetrically zoned bands.

The metasedimentary sequence in Gåseland, with its banded rocks of enormous variability as regards chemical composition and therefore mineralogy, has sharp boundaries to the migmatitic, rather uniform gneisses on both sides. It is not unlikely that the described metasediments are closely related genetically to the migmatitic gneisses of the coastal migmatites, in that both are common members of the same sedimentary sequence. The metasedimentary sequence provides as a marker horizon insight into the style of the regional tectonics, described in the structural section below.

In the migmatite and granite zone as a whole the abundant metasedimentary paleosome relics in the migmatites and the occasional area of well preserved sedimentary sequences are assumed to have once formed a single sequence, provisionally correlated with the Krummedal supracrustal sequence. The best preserved metasedimentary successions occur at the west margin of the zone on both sides of Nordvestfjord (Henriksen *et al.*, in press; Higgins, 1974) and in eastern Milne Land (Higgins, in prep.). Discontinuous strips and lenses of marbles can be traced for long distances in the migmatites of the Stauning Alper and northern Milne Land presumably representing a partially consumed specific horizon within the original sedimentary succession; they may be compared with the similar units of eastern Gåseland described above.

Grey-pink garnetiferous augen-granites

Along the northern coast of Gåseland and on Danmark Ø several augen granite sheets occur within the coastal migmatitic complex. The thickness of the sheets varies between about 10 m and several hundred metres. The contacts with the coastal migmatites are generally sharp and slightly discordant to the layering of the migmatites. Many sheets can be traced over several kilometres. The thickness of the individual sheets is remarkably constant, but the structural and compositional homogeneity of these rocks makes it impossible to correlate individual sheets across detritus and moraine covered areas, and therefore they cannot be used as marker horizons.

Fig. 11. Gneissic variety of late kinematic augen granite on north coast of east Gåseland.

The common rock type is a grey-pink garnetiferous granite gneiss with well developed planar orientation, and strings and lenses of quartzo-feldspathic material (fig. 11). The micas are perfectly parallel. Microcline megacrysts up to 8 cm diameter show a typical lenticular augen texture. The lenticular shape of the K-feldspar and the parallel orientation of mica is less pronounced in the direction of the regional fold axes. Characteristic for most of the augen granite sheets is a network of thin slightly discordant aplitic veins.

Perthitic K-feldspar (25 per cent vol) occurs both as microcline and orthoclase, the former mainly in the groundmass, and the latter in the augen. The large lenticular K-feldspar megacrysts include small grains and flakes of quartz, plagioclase and biotite. Usually slightly altered plagioclase (35 per cent of the rock) contains about 18 per cent anorthite component. In contact to K-feldspar, plagioclase very frequently exhibits myrmekitic textures. Quartz (about 30 per cent) is present in the groundmass but also occurs in the augen. Fresh biotite flakes and small embayed grains of garnet (free of inclusions) are the major mafic minerals. Partial retrograde alteration of biotite to chlorite is common in some sections. White mica is less abundant than biotite but occurs as well developed individuals; textural evidence suggests that white mica is in equilibrium with the other minerals of the rock. Apatite and zircon are the principal accessories.

The genesis and origin of the augen granites is difficult to interprete. The remarkable homogeneity and the sharp boundaries to the country rock suggest an injection of granitic material into the surrounding gneisses supplied by an unknown but distant source. In some respects the augen granites are similar to those described by Henriksen & Higgins (1969) and Chadwick (1971, 1975), but there are differences in chemical composition, mineralogy and metamorphic and structural history.

Hornblende-biotite quartz diorite

Most of Danmark Ø and parts of south-east Milne Land comprise an extensive mass of homogeneous hornblende-biotite quartz diorite. In the central parts of the mass minerals have no preferred orientation, whereas in the border zones, especially on Milne Land, the rock developes a clearly gneissic schistosity parallel to the contacts. The quartz diorite body forms a major open syncline with east dipping regional axes. The contacts to the underlying

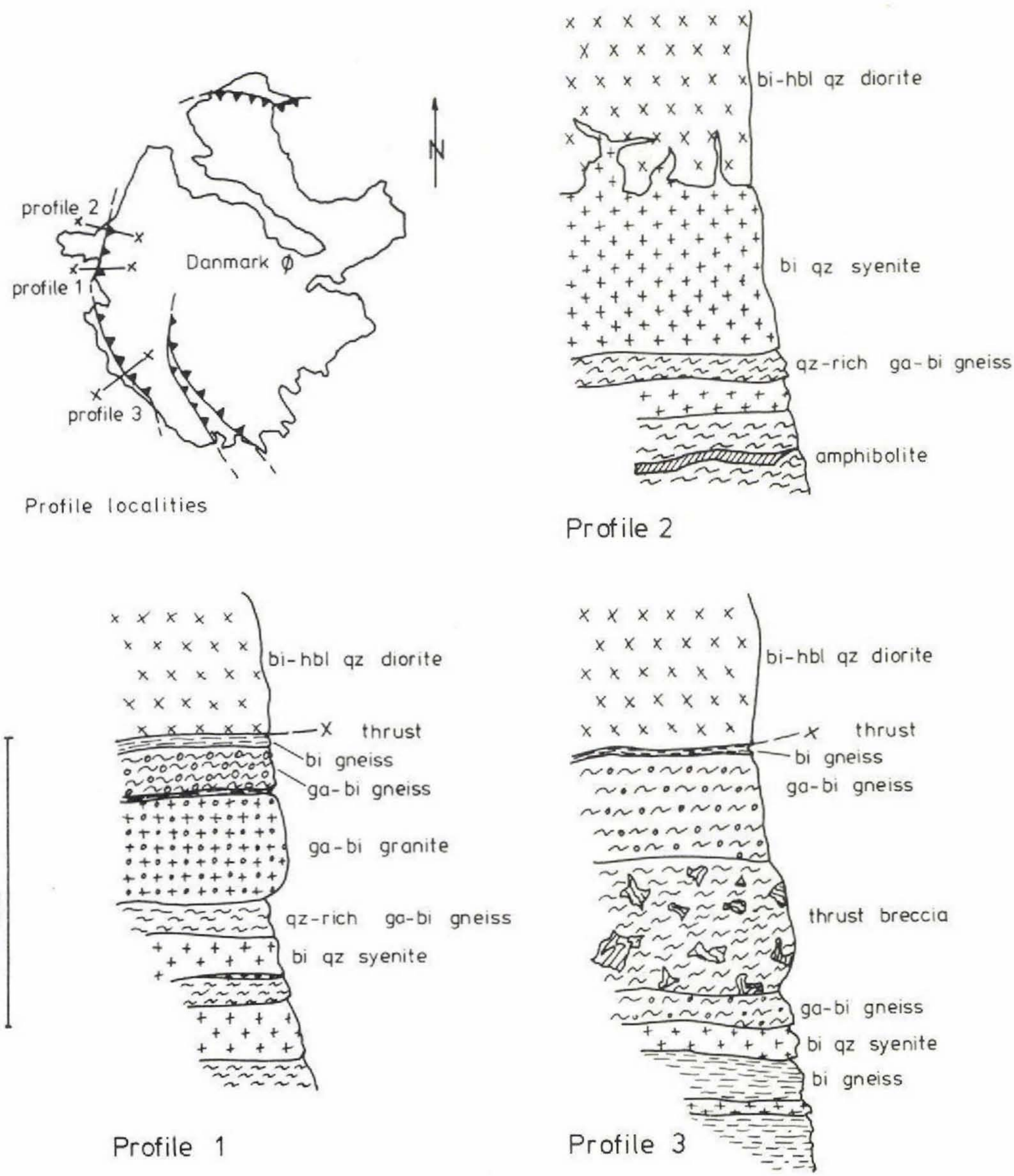

Fig. 12. Profile through the quartz diorite contact on Danmark Ø.

migmatites are clearly tectonic in the south and south-west (fig. 12). The quartz diorite body has been thrust over the coastal migmatite complex. On Milne Land and northern Danmark Ø magmatic contacts are dominant. The quartz diorite has been intruded by pink granitic neosome from the migmatites, and agmatitic structures are common on Milne Land especially where granitic neosome has broken through the quartz diorite and dissolved the massive quartz diorite into schollen of various size. Within the body several shear zones have been observed, one of which has been traced over several kilometres, and terminates in the 'schuppen' zone around Hekla Havn. All these recrystallized shear zones are parallel to the main contacts. Rounded, usually elongated, mafic inclusions have a widespread occurrence in the quartz diorite, and in a number of localities form pronounced accumulations; the ratio of mafic inclusions to quartz diorite matrix may exceed two to one.

Two generations of leucocratic dykes can be distinguished. An early generation of white aplitic and pegmatitic rocks cuts sharply through the diorite, while a second dyke system of large numbers of striking red syenitic to quartz syenitic irregularly shaped pegmatites is more or less parallel to the mineral orientation. The red pegmatites cut sharply through the primary dyke generation. In many places the syenitic dykes coalesce to form extensive masses of irregular shape.

In a profile across Danmark Ø the quartz diorite becomes increasingly less deformed and shows less preferred orientation from west to east, that is from close to the thrust surface towards higher tectonic levels. A continuous decrease of contamination by red syenitic dykes from the migmatites beneath the diorite is also observed in the same direction.

Plagioclase, quartz, biotite and hornblende are the dominant constituents in the fresh rock. The fabric of the undeformed quartz diorite is a rather coarse mosaic and typical for a magmatic rock. Fresh, twinned, coarse-grained plagioclase has a high anorthite content, generally andesine; zoning is rare but has been observed. Frequently calcite is present in small amounts between large plagioclase crystals. Quartz occurs as large, always deformed (slightly biaxial) crystals with embayed grain boundaries. The modal ratio of plagioclase and quartz is in the order of two to one. The rock is of quartz-dioritic composition and together with the mafic minerals biotite and hornblende it fullfills all requirements of a tonalite (*sensu stricto*). A dark brown biotite is the major mafic mineral forming about 10–15 per cent of the total rock. Alteration and exsolution of plagioclase and biotite are rare and may be absent in some sections. Hornblende constitutes less than 5 per cent of the rock, is commonly associated with biotite, and forms together with plagioclase, quartz and biotite magmatic mosaic textures. None of the major minerals shows euhedral crystals. This feature suggests simultaneous crystallization of all minerals. Accessory, perfectly euhedral and slightly zoned orthite, is always rimmed by epidote. Minerals of the epidote group occur frequently as small irregular grains, and except for orthite are believed to be of retrogressive origin. Alteration of plagioclase to mica, epidote and carbonate, and of biotite to chlorite, is very minor. Zircon is very rare, and alkali feldspar has not been observed.

The irregular masses and dykes of red syenitic pegmatites which are a characteristic feature of the quartz diorite body are very rich in alkali feldspar and generally mica-poor. The alkali feldspar is a coarse untwinned perthite; coarse string and band shaped perthitic exsolution can be observed in most feldspar grains. Quartz is strongly deformed. Less than 5 per cent of the pegmatites are made up of plagioclase which is always strongly altered, though the alteration products are fine grained and difficult to identify. Small amounts of chlorite occur (less than 5 per cent) accompanied by tiny flakes of white mica.

A wedge of garnetiferous migmatitic gneisses of the coastal migmatite complex is found in the quartz diorites around Hekla Havn. The migmatitic gneisses are enveloped by hornblende-bearing, garnet-free gneisses displaying migmatitic structures. Finally a gradual change into the quartz diorites can be recognized, and the zone after being wedged out can be traced for several kilometres laterally as a recrystallized mylonite horizon. The very distinct gneissic zones inside the quartz diorite mass have a lenticular texture with quartz and feldspar forming small lenses.

The quartz diorite is doubtless of magmatic origin but is allochthonous. It is difficult to demonstrate directly the direction of transport. The geometry of the schuppen zone around Hekla Havn with its east facing wedge of migmatites suggests thrusting roughly from west to east. All geological observations demonstrate that thrusting preceded the migmatization event.

The quartz diorite is a very distinctive intrusion, and within the migmatite and granite zone there are three other similar bodies. One occurs in southern Gåseland west of the area described here, and is a sheet about 500 m thick; most of the body is foliated and lensoid mafic inclusions are common (Henriksen & Higgins, 1973). In eastern Milne Land north of Charcot Gletscher an extensive body has been described by Higgins (in prep.) as the Korridoren granodiorite; the central parts are granodiorite, the wide marginal zones quartz diorite, and mafic inclusions are common throughout. The third body of comparable composition is the 'grey granite' of the Bjørneøer which has quartz dioritic to granodioritic composition and many inclusions (Kalsbeek, 1969). B. T. Hansen (personal communication, 1977) has obtained a preliminary Rb-Sr isochron age on the Korridoren granodiorite suggesting a Caledonian age of intrusion. If the quartz diorite of Danmark Ø is also Caledonian, it follows that the veins and pegmatites cutting the body are Caledonian as is presumably at least part of the migmatite formation in the surrounding region.

STRUCTURAL GEOLOGY

Folds

Regional fold axes in general strike in E–W directions (fig. 13), and therefore the deep N–S trendings valleys could be expected to give the best insight into the tectonics of the area. However, the only area where large scale folds have been observed was Gåseland. A low degree of migmatization in this part of the working area seems to have favoured the preservation of pre-migmatization structures, and pronounced lithological units illustrate the folds and fractures clearly.

The most striking large scale folds are isoclinal folds with amplitudes in the range of hundreds to thousands of metres, only seen in Gåseland. The east dipping axes show remarkable constant orientation. Small scale and superimposed folds are conformable with the axes of the isoclinal folds. The flat lying axial planes dip to the east. A sillimanite lineation coincides with the orientation of the fold axes. Orientations of measured planar and linear structures are plotted in fig. 14. A commonly observed feature in sequences with distinct viscosity differences is a very strong boudinage also parallel to the fold axes (fig. 15). Frequent cross-cutting granitic neosome and granitic dykes together with boudinaged migmatitic layers in banded gneisses suggest a syn-migmatitic to pre-migmatitic folding. Late migmatitic activity outlasted the isoclinal folding.

Throughout the mapped area a distinct tectonic event produced open synforms and antiforms having axial planes striking E–W and fold axes which are conformable with the axes of the isoclinal folds. These folds deform the axial planes of the isoclinal folds. In the Charcot Gletscher area and along the north coast of Gåseland a number of E–W striking fold structures in the range of tens to hundreds of metres wave length form outstanding

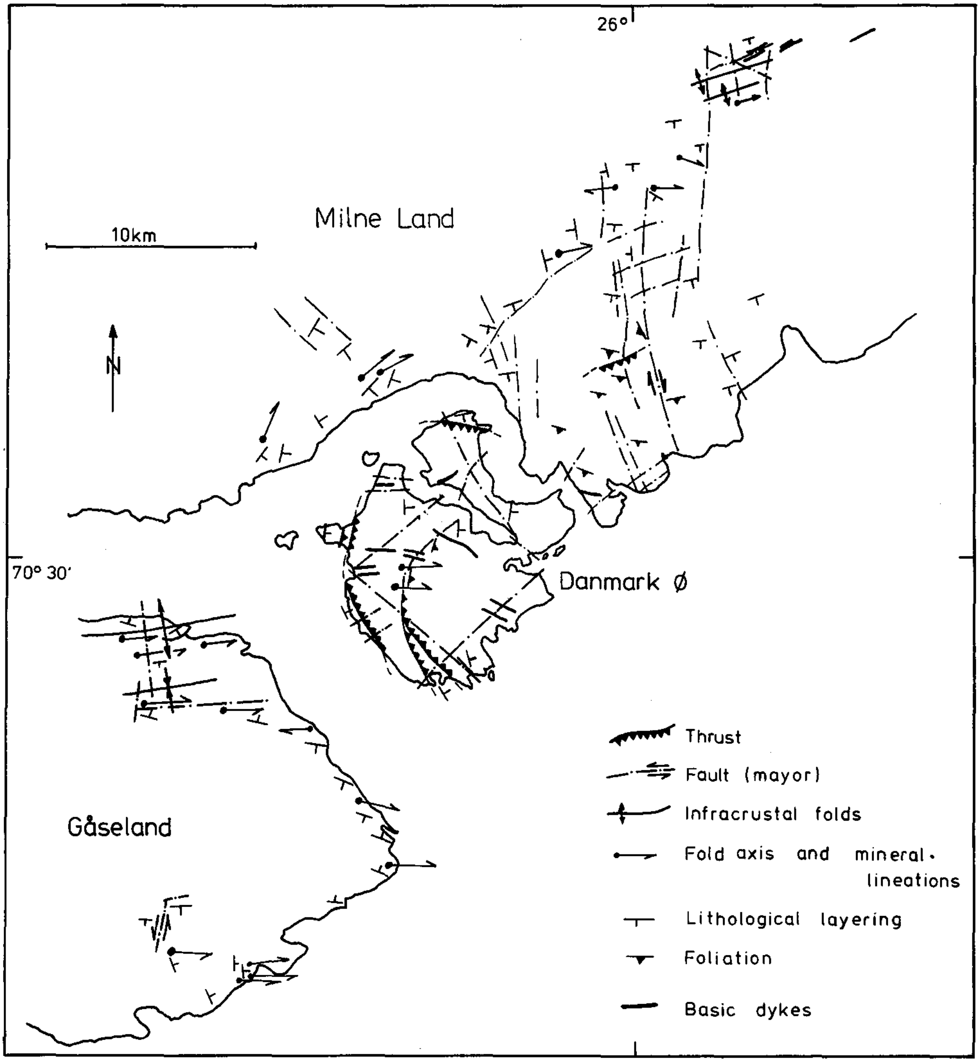

Fig. 13. Structural map showing the traces of faults, thrusts and the principal folds.

morphological features. Augen granites have been deformed by this event, but have not been affected by the isoclinal folding.

Parasitic small scale folds with conformable axes and steep axial planes can be found in many rock types, and especially in banded gneisses and marbles. Many of the small scale folds show an assymmetric geometry with axial planes dipping south and a northerly vergence. On Milne Land these small scale folds are the fold structures which can be seen most clearly. They have usually a very local occurrence but are very similar as regards geometry and orientation to those of Gåseland, and have undoubtably been produced by the same

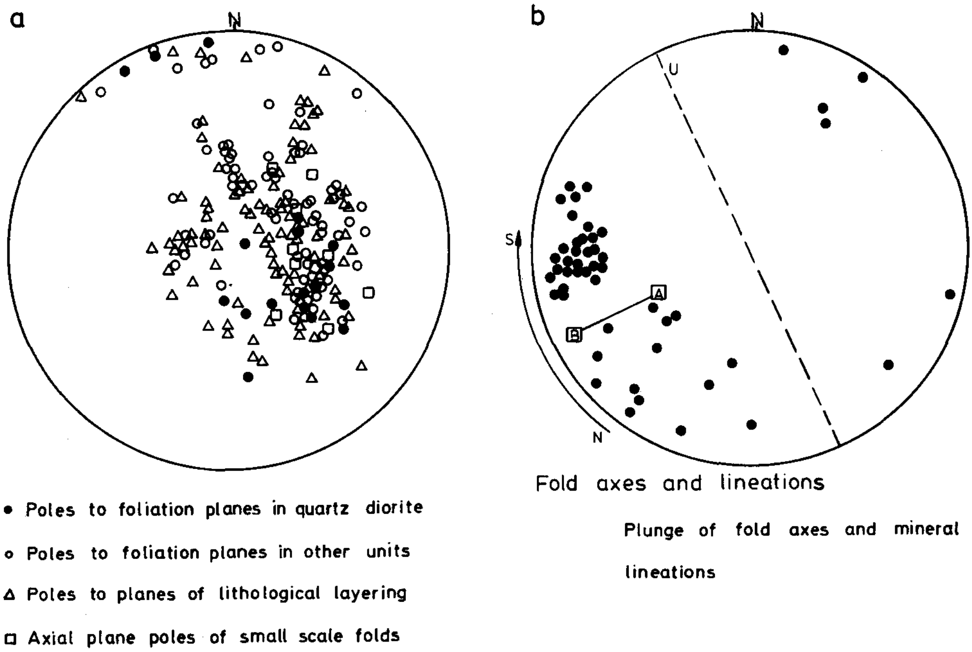

Fig. 14. *a.* Upper hemisphere plot of planar structures. *b.* Upper hemisphere plot of linear structures. A and B represent the extremes in dip of the fold axis of the east dipping regional folds. The rotation of the fold axes between northern and southern parts of the mapped area is indicated by the arrow at the left. The general trends of the late open folds are given by the dashed line; their influence on planar structures is seen in *a*.

event of deformation. In the northern parts of the mapped area the small scale folds and the mineral lineation seem to be folded by wide, late, open folds with roughly N–S trending axes; no sign of this fold type has been seen on Gåseland.

On Milne Land deformation features such as folds, boudinage, flexures and other structures are generally of minor importance. Although the lithology is rather uniform and there is a high proportion of migmatitic granites, it is possible to exclude the occurrence of large scale folds, both isoclinal and superimposed steep open synforms or antiforms. The only exceptions are the folds parallel to the Charcot Gletscher valley.

The overthrust hornblende-biotite quartz diorite sheet of Danmark Ø and the bordering zone of Milne Land is folded as a whole in a very wide and open syncline with an eastwards dipping axis. Field evidence suggests that the superimposed E–W trending folds are younger than the thrust development.

The pattern of deformation can be fitted reasonably well into the regional deformation history established for the migmatite and granite zone as a whole, though few detailed structural studies of other areas have been published. Henriksen & Higgins (1976) report that there were at least two phases of recumbent, often isoclinal folding: these presumably are equivalent to the large scale isoclinal folds of Gåseland. A later phase of ENE-trending

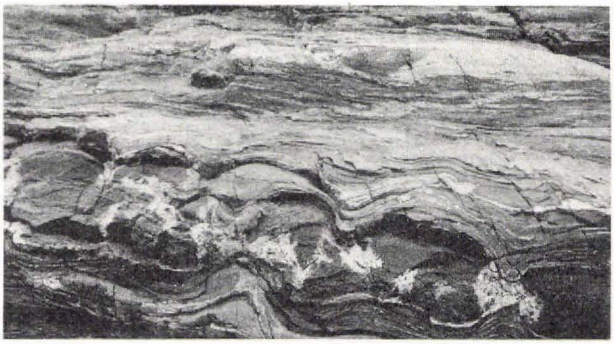

Fig. 15. Boudinaged garnet amphibolite in coastal migmatites of the north coast of Gåseland.

structures prominent in northern Milne Land may be equivalent to the E–W folds of Gåseland (fig. 2). The major N–S folds of the Stauning Alper and Renland seem to be represented by late open folds in southern Milne Land, but are not seen at all in Gåseland.

Fractures

Two fracture systems can be distinguished. The first type are N–S trending and can be interpreted as fractures normal to the regional fold axes (*a-c* fractures). Displacements can be demonstrated on Milne Land where the quartz diorite body has been displaced by at least 1.5 km. The major movement was probably in a vertical direction. At a number of localities vertical displacements in the range of tens to hundreds of metres can be directly observed along N–S trending fractures. The sense of vertical movements is always a relative uplift of the western part.

The second fracture system shows great variation in its orientation, but roughly strikes east–west. It may possibly be related to a younger phase of tectonic activity accompanied by the extrusion of the Tertiary plateau basalts. The Tertiary basalt dyke system has the same general orientation as this fracture system. Vertical displacements were found along a fracture linking Vinkeldal with Rensund, the northern part having been uplifted relative to the southern part. The very frequent E–W striking basalt dykes on Danmark Ø, which is situated in the mouth of Fønfjord, suggests the possibility of major fracture zones along this morphological structure. The same reasoning applies to the dyke system in the Charcot Gletscher valley. The pronounced geological differences between eastern Gåseland, and the Milne Land and Danmark Ø area, make large scale (vertical?) displacements along this E–W fracture zone very likely.

In other parts of the migmatite and granite zone N–S major faults and thrusts are conspicuous (fig. 2) but significant displacements on many less spectacular fractures have also been noted in Renland (Chadwick, 1975 p. 54–55), where a cumulative displacement of 1000–1500 m has been recorded with consistent relative uplift of the western side.

METAMORPHISM

Migmatization

The occurrence of migmatized rocks over the entire area demonstrates that conditions of partial anatexis were reached during regional metamorphism. It appears that migmatization and synmetamorphic isoclinal folding proceeded in one continuous episode, presumed to be mainly middle Proterozoic in age, but it cannot be excluded that some migmatitic phenomena are Caledonian (cf. Chadwick, 1971, 1975). Growth of alkali-feldspar phenocrysts in thin concordant layers and formation of thin banded gneisses with layers of granitic neosome may represent the initial steps of migmatization. With the production of extensive amounts of granitic melt, cross-cutting neosome in banded gneisses and finally schollen textures became dominant. Large quantities of neosome seem to have migrated from the place of formation and accumulated to form irregular shaped masses or conformable sheets (garnetiferous grey granites). Leucocratic pegmatitic and aplitic dykes terminated the climax of regional metamorphism. From the south-west (Gåseland) to north-east (Charcot Gletscher) a significant increase in proportion of granitic neosome can be observed. On Gåseland the typical migmatite contains clearly less than 50 per cent neosome, banded gneisses with thin conformable neosome layers being the typical migmatitic structure, whereas in the vicinity of Charcot Gletscher the neosome content of the rock is in excess of 50 per cent, migmatitic granites with schollen textures being dominant. This may reflect a metamorphic gradient increasing from south-west to north-east.

Pelitic and semipelitic rocks

In pelitic gneisses a systematic decrease of sillimanite and an increase of K-feldspar from south-west to north-east may be related to a metamorphic gradient in this direction. On Gåseland the critical mineral assemblage is found to be quartz-plagioclase –K-feldspar–biotite–garnet–sillimanite. Small corroded muscovites are texturally related to sillimanite and the later mineral may have formed at the expense of muscovite. Biotite-garnet-plagioclase gneisses lacking K-feldspar do not contain sillimanite. The assumption of pre- or syntectonic formation of sillimanite is supported by the perfect sillimanite lineation concordant to the regional fold axes over the entire area. On Milne Land sillimanite is rare. Around Charcot Gletscher pelitic rocks are characterized by the assemblage quartz–plagioclase–K-feldspar–biotite–garnet. This significant change in mineralogy of the pelites is presumably caused by an increase in grade from south-west to north-east. The schematic mineral reaction:

$$\text{biotite}_{ss}{}^{*} + \text{sillimanite} + \text{quartz} = \text{garnet}_{ss} + \text{K-feldspar} + \text{water}$$

may serve as a model for the metapelitic gneisses (Kretz, 1964). The observation that the disappearance of sillimanite is not a sharp mappable isograde in the field is easily explained by the continuous reaction noted above. This reaction depends not only on temperature and total pressure, but as a consequence of the extensive solid solution in biotite and garnet, on

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* ss denotes solid solution

the composition of biotite and garnet in the rock. This dehydration reaction is also dependent on the composition of the metamorphic fluid. Detailed knowledge of the compositions of the minerals is therefore necessary for a quantitative treatment of the observed mineralogical changes in the pelitic rocks. Cordierite could be expected under the given metamorphic conditions but was absent in all sections examined.

Muscovite occurs as corroded relicts or as a late retrogressive mineral almost exclusively. Only in the augen granites is muscovite present as large fresh flakes, and forms together with biotite microtextures which point to equlibrium relations. This observation, together with the fact that the augen granites are never cut by any pegmatitic dykes related to the migmatization event, strongly suggests an emplacement of the augen granites significantly later than the climax of regional metamorphism. It should be remembered here that the augen granites on Gåseland also post-date the isoclinal folding.

Basic rocks

The metabasites can be divided into those of magmatic and those of sedimentary origin. Rocks containing the assemblage orthopyroxene–clinopyroxene–amphibole–plagioclase–olivine are assumed to be of magmatic origin from field evidence. The observed mineral assemblage is interpreted as relict magmatic, and essentially non-metamorphic. Metabasites of possibly sedimentary origin contain the assemblage hornblende–biotite–garnet–plagioclase–(quartz–clinopyroxene). This assemblage is found invariably in all concordant amphibolite layers over the entire area.

Carbonates

Since in many carbonate rocks only a small number of chemical components are present, carbonates are very critical and important for the discussion of metamorphism of a given area. Unfortunately, carbonates occur only on Gåseland.

The assemblage clinopyroxene–hornblende–biotite–scapolite–plagioclase–calcite is typical for high grade metamorphism of calc-silicate rocks. The overgrowth of diopside on ferro-aluminous clinopyroxene and of actinolite (tremolite) on hornblende represent a younger assemblage (calcite–diopside–tremolite). This isobaric divariant assemblage in the system CaO–MgO–SiO_2–H_2O–CO_2 could either be a product of retrogressive metamorphism during cooling history, or of a younger distinctly lower grade metamorphic event.

Silicious dolomites are characterized by the assemblage calcite–dolomite–olivine–tremolite–diopside–clinohumite. This is an isobaric invariant assemblage in the system which can be described by the components CaO–MgO–SiO_2–H_2O–CO_2–HF. At a given total pressure these six phases can coexist at a unique temperature and unique composition of the solids and the metamorphic fluid. Table 4 gives some microprobe analyses of magnesian calcites coexisting with dolomite. These compositions of the carbonates are determined by the calcite-dolomite miscibility gap. The minimum equilibration temperatures derived from the calcite compositions fall in the range $620 \pm 40°C$ and correspond to a satisfactory degree with the temperatures indicated by the mineral assemblages (see below). Excluding the humite

Table 4. Microprobe analyses of calcite coexisting with dolomite from dolomitic marbles (east Gåseland)

Calcite number	1a	1b	2a	2b	2c	3a	3b
$CaCO_3$	90.71	93.18	90.55	92.52	90.80	91.91	90.19
$MnCO_3$	0.15	0.17	0.18	0.17	0.16	0.21	0.19
$FeCO_3$	0.56	0.56	0.55	0.49	0.49	0.59	0.77
$MgCO_3$	5.70	6.67	7.45	5.57	6.27	6.48	8.25
	97.13	100.57	98.72	98.76	97.72	99.19	99.40
mol.% $MgCO_3$	6.69	7.82	8.72	6.54	7.36	7.60	9.64
Temperature °C*	585	616	638	581	603	610	660

*Minimum equilibration temperature given by the calcite-dolomite miscibility gap (equation from Rice, 1977).

All analyses from sample GGU 169575.

minerals and therefore the HF-component in the following considerations, then for an assumed total pressure of 4 to 5 kilobars the coordinates in the temperature-X_{CO_2}-space of the assemblage calcite–dolomite–tremolite–forsterite–diopside can be expected to be 620–640°C for the temperature and 90–95 mole % CO_2 for the fluid composition. In the sections where diopside is absent the isobaric univariant assemblage calcite–dolomite–forsterite–tremolite indicates that the tremolite-dolomite isograd was not passed during the last metamorphic event.

In aluminous-silicious dolomites (represented by the components $CaO–MgO–SiO_2–Al_2O_3–H_2O–CO_2$) the observed assemblage of calcite–dolomite–amphibole$_{ss}$–olivine–chlorite$_{ss}$–spinel is isobarically invariant. Under a given total pressure the six minerals can coexist only at a unique temperature and gas composition and fixed compositions of the solid-solution phases (Bucher-Nurminen, 1977). The assemblage involving these six phases may be related to the univariant equilibrium dolomite+tremolite = forsterite+calcite+H_2O+CO_2 in an isobaric temperature-gas composition diagram (Metz, 1976) and to the equilibrium Chl+Do = Sp+Fo+Cc+CO_2+H_2O. These two equilibria must hold simultaneously (Rice, 1977; Bucher-Nurminen, 1977). Under medium total pressure of 4 to 5 kb and taking the solid solution in the amphibolites into account, the conditions of coexistence of Do+Cc+Fo+Chl+Sp+Am according to such a diagram is close to the invariant point calcite–dolomite–tremolite–forsterite–diopside of the alumina-free silicious dolomite system and hence indicates temperatures of 620–640°C. The occurrence of Mg-spinel in dolomitic marbles is typically confined to low to medium pressure terrains (Bucher-Nurminen, 1977). The conditions indicated by the assemblage in the aluminous silicious dolomites is therefore consistent with those indicated by the pure silicious dolomites. The frequent occurrence of low variant assemblages suggests internal control (buffering) of the metamorphic fluid.

Metamorphic conditions reflected by the assemblages in dolomitic marbles are hence significantly below the conditions required for the pervasive formation of granitic melt. Mosaic equilibrium textures in the marbles do not support the interpretation of simple retrogressive formation of the observed assemblages. The assumption of a metamorphic event under conditions of middle amphibolite facies after an earlier regional migmatization seems to be most realistic. This metamorphic event can be chronologically correlated with the superimposed folding and the emplacement of the augen granites but is rather hypothetical. The period of time separating the two high grade metamorphic events and the conditions between the two peaks is not so far known.

The metamorphic conditions which are reflected by the carbonate rock assemblages were not sufficiently low grade to transform the assemblages in pelitic and basic rocks. The assemblages may have been adjusted to lower grade conditions by exchange reactions between solid-solution phases.

Dolomitic marbles have identical assemblages in both the northern and southern parts of Gåseland. No metamorphic gradient could therefore be demonstrated within Gåseland.

Retrogressive metamorphism

Retrogressive metamorphism affected rocks of all units but is restricted to relatively limited portions of a given rock volume. Most commonly alteration of feldspar and mafic minerals has been observed, and in some sections biotite appears to be chloritized to a large extent. In general, retrogressive metamorphism is of rather subordinate importance over the whole area.

Comparisons

Metamorphic conditions of high amphibolite facies are widespread over most of the migmatite and granite zone, sillimanite being recorded throughout. In the north-west sillimanite coexists with kyanite in the sediments around Nordvestfjord (Higgins, 1974), while in the eastern Stauning Alper and eastern Milne Land cordierite has been recorded (Henriksen *et al.*, in press; Higgins in prep.). Granulite facies conditions may have been reached in parts of eastern Renland and the Bjørneøer (Chadwick, 1971; Kalsbeek, 1969). Nearly all workers in the zone report a late, slight, retrogressive metamorphism.

CHEMISTRY

Fifteen samples were chemically analysed, three augen granites and twelve samples of granitic neosome (Table 5). They were selected in order to examine the possibility of significant chemical differences in a N–S profile, and to trace differences between granitic rocks of distinct setting or characteristic fabric (figs 16, 17, & 18). Only one sample (196694 from locality 9) plots clearly outside the granite field (fig. 17) and has monzodioritic chemistry, the plagioclase being oligoclase (28 % An); it is most probably not of migmatitic neosome origin. A further sample (196697 from locality 8) is a leucogranite with very high albite/anorthite ratio (36.7), plotting into the K-feldspar field close to the 750°C isotherm (Shaw, 1963) and clearly off eutectic composition. The remaining thirteen samples fall into three groups.

Four samples are of the neosome of migmatitic granites on Milne Land (from localities 1, 2, 3 & 5; squares in fig. 18). They are of closely similar composition and on a quartz–K-feldspar–plagioclase plot fall in the granodiorite field (fig. 17). Assuming 4–5 kb total pressure (P_{H_2O}) they are very close to the eutectic composition. The normative al-

Table 5. Chemistry of granitic rocks

Locality No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	16
GGU No.	169628	-633	-642	-671	-666	-692	-690	-697	-694	-507	-511	-519	-583	-598	-561
SiO_2	71.04	69.82	69.06	68.07	70.76	70.90	70.43	70.18	64.60	71.63	72.30	71.96	68.45	75.06	72.77
TiO_2	0.59	0.71	0.81	0.35	0.67	0.47	0.66	0.48	0.67	0.39	0.25	0.36	0.62	0.15	0.47
Al_2O_3	13.82	13.67	14.03	14.53	13.69	14.32	13.62	14.55	18.53	14.39	14.62	14.39	15.10	13.37	13.84
Fe_2O_3	0.58	1.06	1.02	3.58	1.00	0.65	0.56	0.59	0.80	0.57	0.46	0.67	0.44	0.08	0.45
FeO	2.89	3.59	3.68	2.27	3.26	1.36	3.73	2.63	2.00	1.49	1.21	1.39	3.55	1.07	1.96
MnO	0.08	0.12	0.09	0.17	0.10	0.04	0.08	0.07	0.06	0.06	0.06	0.07	0.10	0.07	0.06
MgO	0.40	0.50	0.80	1.50	0.60	0.70	1.40	0.90	0.90	0.50	0.60	0.50	0.90	0.40	0.50
CaO	2.17	2.36	2.26	0.77	2.22	0.59	1.28	0.28	3.87	1.07	1.01	1.36	1.29	0.73	1.20
Na_2O	3.32	2.99	3.28	2.70	3.04	2.59	2.83	3.01	5.36	3.39	3.76	3.57	2.72	2.88	2.91
K_2O	3.38	3.64	3.42	4.36	3.65	6.81	4.04	5.48	1.79	5.49	4.74	4.50	5.35	5.66	5.00
P_2O_5	0.15	0.17	0.17	0.14	0.14	0.09	0.13	0.10	0.09	0.09	0.09	0.07	0.11	0.10	0.10
H_2O+	0.49	0.67	0.62	0.79	0.70	0.83	0.87	1.38	0.57	0.64	0.33	0.67	0.54	0.26	0.30
H_2O-	0.07	0.11	0.14	0.09	0.06	0.13	0.11	0.10	0.07	0.08	0.09	0.07	0.07	0.06	0.05
	98.98	99.41	99.38	99.32	99.89	99.48	99.74	99.75	99.31	99.79	99.41	99.58	99.24	99.89	99.60
Coordinates in the system K-feldspar-quartz-albite															
Quartz	37	37	35	37	38	28	37	31	21	29	30	32	30	35	33
Albite	38	35	38	31	35	26	32	31	65	34	38	37	30	28	37
K-feldspar	25	28	27	32	27	46	31	38	14	37	32	31	40	37	30
ab/an	3.0	2.5	2.9	8.3	2.7	9.9	4.6	36.7	2.6	6.4	7.6	5.0	4.3	8.7	6.0
Coordinates in the system K-feldspar-quartz-plagioclase															
Quartz	33	33	31	36	34	28	35	30	16	27	29	30	28	33	31
K-feldspar	44	43	46	33	42	28	37	32	72	38	41	41	35	31	41
Plagioclase	23	24	23	31	24	44	28	38	12	35	30	29	37	36	28
% anorthite	24.7	28.3	25.6	10.7	27.0	9.1	17.8	2.7	27.9	13.4	11.6	16.4	18.9	10.3	14.3
Mafic minerals present (relative amounts)															
Amphibole			xxx				xxx								
Biotite	xx	xx	xxx	xxx	xx	xx	x	xxx	xx	x	x	x	xxx	x	x

Sample localities shown on fig.16.

bite-anorthite ratio is 2.7, the normative anorthite content of the plagioclases varying between 26 and 29 %. These rocks represent typical eutectic granites (Carmichael *et al.*, 1974).

Six samples represent the neosome component of banded migmatites (from localities 4, 6, 10, 11, 12 & 14; solid circles on fig. 18). They are all of granitic composition, with plagioclases relatively low in anorthite component (10–16 %). These samples show considerable variation in chemical composition. The trend clearly points away from eutectic composition into the K-feldspar field (e.g. samples from locality 10 and most pronounced from locality 6). Since these samples typically are from thin banded neosome layers in migmatitic gneisses, local parameters such as P_{H_2O}, P_{HF}, P_{HCl} (for example) are most likely responsible for this chemical pattern. It should be noted that the chemical variation in these neosome granites does not correlate with their distribution in the field and therefore significant *PT*-gradients within the working area are not supported by the chemistry of granitic rocks.

Three augen granite samples were analysed (from localities 7, 13 & 16; triangles in fig. 18). These show variations in composition, but have a uniform Ab/An ratio (4.3–6.0) and similar plagioclase compositions (An 17–19 %). Quartz–K-feldspar–plagioclase plots are not significantly different from other granitic rocks analysed.

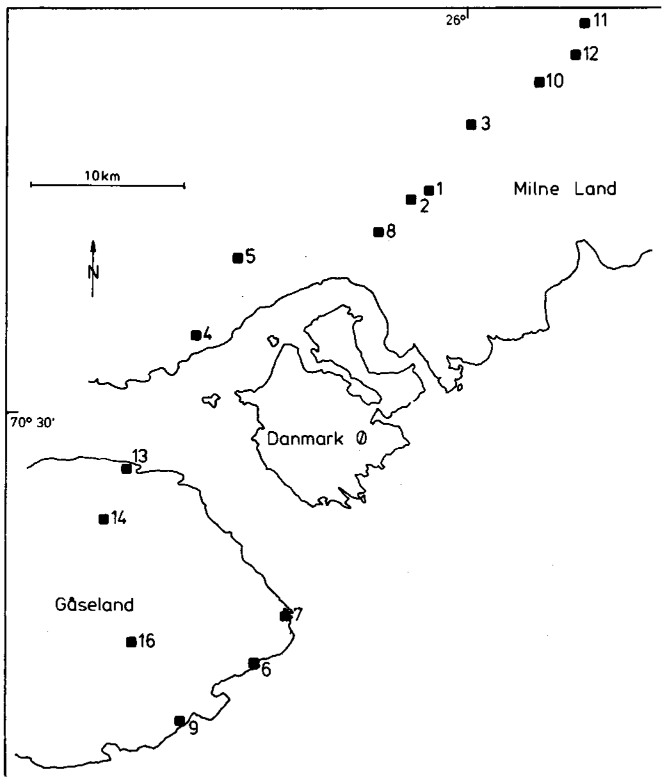


Fig. 16. Sample localities of analysed granitic rocks.

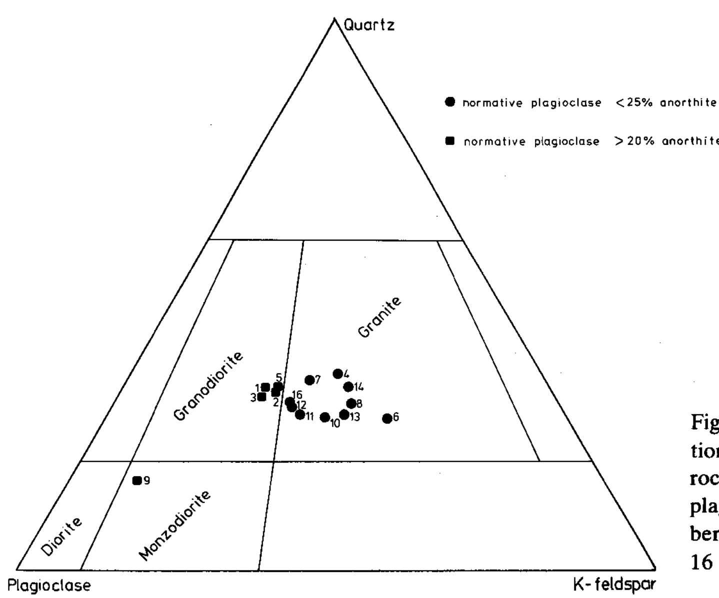


Fig. 17. Normative compositions of analysed granitic rocks on a quartz–K-feldspar–plagioclase diagram. Numbers refer to localities on fig. 16 and Table 5.

DISCUSSION

The oldest rock units represented in the mapped area are the variety of inclusions and paleosome remnants within the migmatitic and granitic rocks. Semipelitic gneisses, quartzites and amphibolites are most common, and in Gåseland interbedded metasedimentary sequences including dolomites occur. It is considered most likely that these rock types are derived from a thick sedimentary succession such as the Krummedal supracrustal sequence, in line with similar interpretations of other parts of the migmatite and granite zone (Higgins, 1974, in prep.; Henriksen *et al.,* in press; Chadwick, 1971, 1975). The common occurrence of amphibolite inclusions in the migmatites of southern Milne Land has previously been considered a possible indicator of involvement of basement gneiss and amphibolite complexes (Henriksen & Higgins, 1976) but those of the mapped area are regarded as of largely metasedimentary origin. Amphibolites are rare in the Krummedal supracrustal sequence where best preserved in the inner part of the Scoresby Sund region further west, but have been recorded especially near the base (Phillips *et al.,* 1973). The indication of cross-cutting basic dykes in the Krummedal supracrustal sequence preceeding the migmatization event is unusual, being recorded elsewhere only at an isolated locality in western Charcot Land (Higgins, 1974, fig. 2).

Migmatization, metamorphism and deformation are considered to relate mainly to an orogenic episode dated from evidence elsewhere to about 900–1150 m.y. (Henriksen & Higgins, 1976, p. 225–6; Higgins 1976, p. 299). Metamorphism reached high amphibolite facies, and a sillimanite mineral lineation was developed parallel to the axes of recumbent folds; the latter are rarely visible due to the masking effect of the migmatization processes. A later Caledonian migmatization event is also possible, as recorded in parts of Renland (Chadwick, 1975).

The migmatization episode could be subdivided into a number of distinct phases, though such a division would have only local significance in a long term process of partial melting

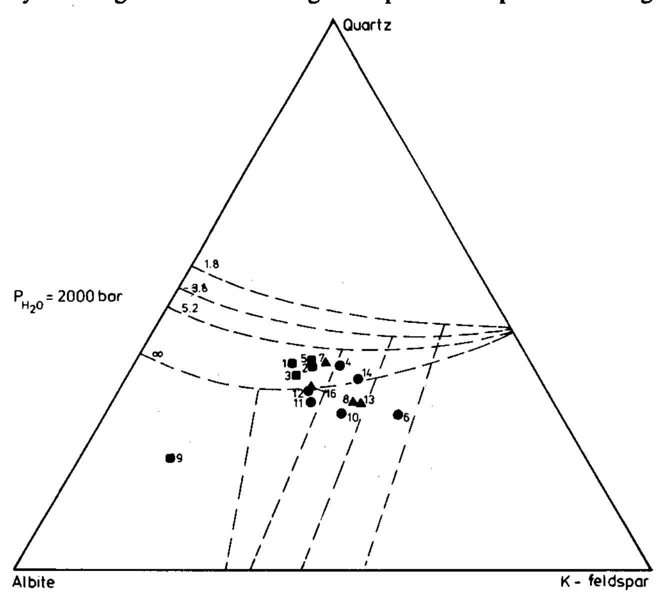


Fig. 18. Normative compositions of analysed granitic rocks plotted on a quartz–K-feldspar–albite diagram. Cotectic curves are taken from von Platen (1965), and are given for four different Ab/An ratios. Numbers refer to localities on fig. 16 and Table 5. Squares: neosome of migmatitic granites; circles: neosome component of banded migmatites; triangles: augen granites.

and simultaneous deformation. The migmatic granites seem to be more or less *in situ* granites created by partial melting of the semipelitic gneiss paleosome. However, the sheet-like, grey, garnetiferous granite of Milne Land frequently shows magmatic flow structure and may be considered parautochthonous or allochthonous. The pressure regime is difficult to estimate because no andalusite or kyanite has been recorded from the mapped area, though they are known in areas further north. A south to north increase in degree of migmatization has been observed, and could be related to a general change of composition of the metasedimentary host closer to the eutectic composition of granite melts. However, it might also reflect variation in temperature–pressure conditions from an assumed medium pressure (4–5 kb) and temperature for Gåseland towards relatively low pressure – high temperature conditions for the vicinity of Renland (Chadwick, 1975), the Bjørneøer (Kalsbeek, 1969) and eastern Milne Land (Higgins, in prep.) as shown by the presence there of granulite facies rocks and of widespread cordierite and andalusite; it is possible that the last named minerals formed during a later Caledonian metamorphic overprint.

The quartz diorite has tectonic contacts at the south and west margin. Along the northern margin it is intruded by veins of migmatitic granite, and neosome veins inside the body can be matched with veins in the migmatites. This suggests that emplacement preceded at least some of the migmatization. A preliminary isochron age on a different but comparable intrusion farther north in Milne Land suggests a possible Caledonian age of intrusion, and implies that some migmatite development may also be Caledonian.

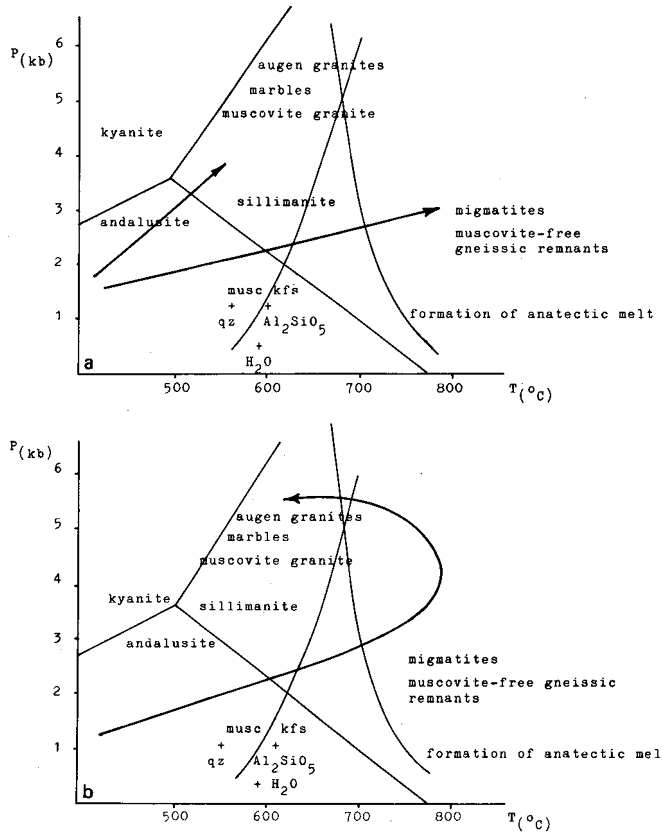
Emplacement of the garnetiferous augen granite sheets must be viewed as clearly distinct from the migmatization process. They are remarkably homogeneous rocks with sharp contacts slightly discordant to the foliation in the surrounding migmatites, and cutting all phases of granitic neosome in the migmatites. The mineral pair muscovite-quartz, which does not occur in stable association in the migmatites implies that migmatization took place along the path drawn in fig. 19, at pressures less than 5 kb. The presence of muscovite and quartz in the augen granites suggests significantly higher pressures.

The formation of the critical assemblages in the impure dolomites on Gåseland is incompatible with regional migmatization under relatively low pressure, i.e. below the muscovite–quartz breakdown curve and minimum granite melt curve intersection (fig. 19). Stability of the pair amphibole-dolomite requires significantly lower temperatures or alternatively higher pressures (7–8 kb). The temperature maximum for the mineral pair tremolite-dolomite was determined as 580°C at 3kb (Skippen, 1974). If amphibole solid solution is taken into account together with an estimated migmatization pressure of 4 kb, dolomite and amphibole should still break down before extensive migmatization of semipelitic sediments occurs (see earlier). The augen granites indicate that the area passed the medium temperature–pressure field (fig. 19) following migmatization under low pressure, high temperature conditions. The assemblages of the impure dolomites seem therefore to have become largely stabilised during the later conditions, whereas in other rock types adjustments are shown, for example, by exsolution of quartz, magnetite and ilmenite from biotite or by overgrowth of diopside on augite.

Post-dating migmatization and the augen granites are two fold phases, one with E–W trending axes and the other N–S trending axes. Retrograde metamorphism is of local significance. Tertiary dolerite dykes were emplaced mainly along the planes of late fracture systems.

Fig. 19. Two alternative interpretations of the metamorphic history of the area. *a.* Proterozoic migmatite formation under low *P*, high *T* conditions. Caledonian metamorphism produces augen granites, muscovite granite (Charcot Gletscher) and mineral assemblages of the marbles under medium pressure (~ 5kb) and medium temperature conditions. Two distinct metamorphic events.
b. Metamorphic evolution along a single path (either Proterozoic or Caledonian).

System Al_2SiO_5 after Holdaway (1971), mus+qz = kfs+Al_2SiO_5+H_2O after Evans (1965), formation of anatectic melt after von Platen & Hoeller (1966).



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