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Preliminary account of the geology of south-east Renland, Scoresby Sund, East Greenland

by

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PRELIMINARY ACCOUNT OF THE GEOLOGY OF SOUTH-EAST RENLAND, SCORESBY SUND, EAST GREENLAND

by

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With 5 figures, 3 tables and 1 map

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Abstract

South-east Renland occupies an internal position in the Caledonian orogenic belt of East Greenland. The area comprises migmatised paragneisses of Caledonian supracrustal origin intruded by concordant sheets of garnetiferous augen granite in the west. The gneisses and granites are folded in large-scale, tight to isoclinal folds. Intermediate igneous rocks with charnockitic affinity were intruded after the folding. The principal intrusion is an extensive, concordant sheet delimiting an area of gneisses in the east that have undergone further migmatisation and granite intrusion. Prominent among the many fractures are normal faults with downthrow to the east. No indications of economic mineralisation were observed.

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INTRODUCTION

Area and accessibility

This report describes the geology of about 900 km^2 (approximately 300 sq miles) in south-east Renland that was mapped at a scale of 1:50.000 during six weeks of inclement weather in the summer of 1969. The field work formed part of the second of a five-year series of expeditions by the Geological Survey of Greenland to the Scoresby Sund region (Henriksen & Higgins, 1969, 1970).

South-east Renland lies within the internal part of the Scoresby Sund fjord complex and centres on 26° 15′ W and 71° 8′ N (inset, map 1). The area is included on map sheet 71 Ø 2 of the 1:250.000 series of the Danish Geodetic Institute.

The topography is mountainous and glaciated with summits and ice-covered plateaux at about 2000 m marking a prominent peneplain level. Access is on foot using the large valley glaciers in the interior, by boat along the precipitous cliffs of the shoreline of Øfjord, or by helicopter where topography is most severe. The most difficult terrain is the large massif underlain by granites and migmatites in the north-east where erosion of these granitic rocks has produced sharp peaks, aiguilles and arêtes strongly dissected by steep valley glaciers. Because of the severity of the terrain, the interior of the massif was visited only during helicopter reconnaissance.

Lithological divisions and regional setting

The area comprises various migmatised gneisses, various granites *s.l.* and intermediate intrusive rocks showing complex structural and metamorphic histories. Field mapping revealed eight principal lithological divisions which may be listed in a broad evolutionary sequence as follows:

1. Rusty-brown garnetiferous gneisses and quartzites
2. Grey, garnetiferous augen granites
3. Pink granitic rocks of uncertain affinity
4. Intermediate intrusions
5. Migmatite complex on the Øfjord coast
6. Grey-pink granite with gneissic enclaves
7. Grey-brown granitised gneisses
8. Pegmatites and aplites

Renland lies within the southern extreme of the outcrop of the Caledonian orogenic belt exposed between latitudes 70° and 82° N in East Greenland (Haller, 1961). Comparison with rocks in Nordvestfjord of inner Scoresby Sund (Henriksen &

Higgins, 1969) shows that the migmatised gneisses in the area studied are Caledonian supracrustal paragneisses. The magmitisation and presence of various granites and intrusive intermediate rocks indicate a deep internal position for the area within the orogenic belt itself. Confirmation of Caledonian age has been obtained by Larsen (1969) with a K/Ar date of 435 $\pm$ 12 m.y. for biotite from a migmatised intermediate intrusion in "Skillebugt", a small inlet marking the east of the area. Although all the rocks in the area have been involved, or have evolved, in the Caledonian orogeny, there is tentative evidence in the form of pyribolite inclusions to suggest that parts of the migmatite complex in the Øfjord coast may be reworked infracrustal rocks. Probable Tertiary igneous activity is represented by the very local occurrence of coarse agglomeratic breccias.

Previous work

The earliest geological investigations in the inner part of the Scoresby Sund region were made by E. Bay (in Ryder, 1895) during an expedition in 1891-92. Bay travelled through Øfjord and made an outline geological map. The Øfjord coast was also visited by H. G. Backlund, K. Lupander and E. Wenk during an exploratory journey through the inner fjord region in the summer of 1934 (Backlund, in Koch, 1955, p. 350). They noted "several generations of basites in highly tectonised areas within the micaceous felspar-quartzites," and they were also impressed by the "magnificent, phantastically isolated, high granite pillars in the north." J. Haller made some reconnaissance flights over parts of the Scoresby Sund region in 1958 and he makes brief remarks concerning the intrusions in Renland in his book on the geology of the East Greenland Caledonides (Haller, in press).

A preliminary report on the geology of the Bjørneøer has recently been prepared by Kalsbeek (1969). Many of the Bjørneøer rocks are closely similar to those seen in east Renland and comparisons are made where relevant.

Coarse agglomeratic breccia

A coarse breccia (fig. 1) with very local, widely-scattered occurrence was found in three parts of the western half of the area. In two places it outcrops high on cliffs at 1500-1700 m and the third occurrence is at 650 m on the west of the southern spur of the main valley glacier. The breccia is composed of large, unsorted subangular blocks up to 5 m in diameter of local gneisses contained in a sparse gravelly matrix. Blocks are commonly touching and both blocks and matrix are cut by fractures with orientations similar to those in adjacent gneisses. Similar breccias were seen in south-west Renland in 1970 where they are associated with basic intrusions in pipe-like forms cutting vertically through host gneisses. This association and mode of occurrence suggest the breccias have a Tertiary age.

Fig. 1. Coarse agglomeratic breccia west side of southern spur of main valley glacier.

RUSTY-BROWN GARNETIFEROUS GNEISSES AND QUARTZITES

This group is best seen in the mainly flat-lying or gently-dipping recumbent structures in the western half of the area where it contrasts with conformably interlayered sheets of grey, garnetiferous augen granite. The rusty colour is derived from weathering of garnets and micas; quartzitic members of the group contain less garnet and are consequently paler brown or grey. Apart from bedding, no other sedimentary structures such as cross-bedding or grading were seen. Comparisons with similar rocks in inner Nordvestfjord described by Henriksen and Higgins (1969, p. 13) show that this group in Renland is probably part of the Krummedal supracrustal sequence.

The group is invariably migmatitic with abundant garnetiferous, quartzo-feldspathic neosome parallel to mica- or quartz-rich paleosome. In many instances the neosome is graphitic. Thicknesses of paleosome are very variable, but in the scale of an outcrop paleosome tends to be 5-10 cm thick with concordant neosome 1-2 cm thick. These alternations give rise to the predominant lithological layering (foliation) which is generally accompanied by a parallel mineral fabric of platy micas and sometimes a linear fabric of sillimanite fibres. Neosome is commonly slightly discordant and in some parts, notably at the head and south of the large ice-dammed lake 610 m in Catalinadal where migmatisation seems to have been more intense, randomly oriented, isolated blocks or rafts of paleosome occur within a sugary, aplitic to granitic neosome matrix, and in the steep valleys south of this lake neosome veins radiate irregularly from large leucocratic "clots" that must replace parts of the paleosome.

Work on the petrography of the gneisses is far from complete but in addition to ubiquitous garnet the presence of sillimanite and cordierite has been recorded. Sillimanite occurs over most of the area. Cordierite has been seen commonly in blocks on the moraines of the main valley glacier (map 1) but so far it has been noted in situ only in the south-west. Kyanite has been reported from Krummedal supracrustal rocks in north-west Renland (Henriksen & Higgins, 1970) and hypersthene has been recorded in the gneisses of Bjørneøer (Kalsbeek, 1969), but so far neither mineral has been seen in the gneisses of south-east Renland.

Quartzitic formations are pale grey and may vary from a few cm to 5 m thick, for example in the extreme south-west. Quartzites generally appear to be subordinate to the rusty garnetiferous gneisses. Helicopter reconnaissance suggested that thicker, more extensive quartzitic formations may occur in the extreme north but no confirmatory landings could be made.

Although marble horizons have been reported from adjacent areas in outer Nordvestfjord (Henriksen & Higgins, 1970) and on Bjørneøer (Kalsbeek, 1969), no marble was found in situ or in moraine detritus in the present area. Very rare pieces of weathered, dark green amphibolite were seen in the moraines but amphibolite was not seen in place within the paragneiss sequence.

GREY, GARNETIFEROUS AUGEN GRANITES

Occurrence and petrography

This group is confined to the western half of the area. It forms concordant sheets within the rusty-brown paragneisses and both groups are folded together in tight folds and recumbent isoclines. Thickness of sheets varies between 50 m and 500 m and on a regional scale the sheets are lenticular reaching greatest thicknesses of about 1000 m in the south. Individual sheets may be traced for up to 30 km but correlation of particular sheets across valleys is made difficult by lithological homogeneity, rapid

Fig. 2. Garnetiferous augen granite. Fallen block from outcrop north-west of the main valley glacier. Note deformation of augen fabric by small-scale folds related to large-scale isoclinal structures.

variations of thickness in smaller sheets and thickening of sheets where they tend to overwhelm and incorporate paragneisses, for example in the main valley glacier. The sheets are equivalent to the "syn-kinematic garnetiferous augen granites [that] are conspicuous in parts of Nordvestfjord" (Henriksen & Higgins, 1969, p. 14).

Apart from local variations in grain size, the granites (fig. 2) are remarkably homogeneous in structure and composition. Lithological layering is generally absent apart from occasional late aplitic or pegmatitic veins with diffuse boundaries cutting at low angles across the principal fabric. The dominant fabric is schistose and formed by parallel planar orientation of micas, stringlets and lenticles of quartz-feldspar and abundant microcline augen up to 5 cm in length. Red-brown, globular garnets up to 1 cm in diameter are very common. In common geological usage the rock might be described as a gneissic augen granite in spite of the fact that the fabric is schistose and megascopic layering is absent. The group is probably best described as garnetiferous augen granite, the word augen indicating crystallisation under stress.

Preliminary chemical analyses have been made of four samples of augen granite and the results are given in Table 1.

Compositional homogeneity is of course reflected in thin sections. Microcline perthite occurring as granular aggregates in augen is the dominant feldspar, but some orthoclase in initial stages of inversion to microcline may also occur. The larger microcline grains are generally sieved with droplet quartz and plagioclase and commonly show albitic reaction rims. Myrmekite is common in plagioclase adjacent to microcline. Plagioclase generally forms up to 10% of the total minerals; grains may be large, up to 5 mm, but most are small groundmass components. A Carlsbad-Albite twin determination gave An_{30} composition. Quartz is abundant mainly as a groundmass mineral but it may occur within augen aggregates of microcline. Biotite forms small flakes strung out in thin sheets undulating around the augen. Individual flakes commonly show disequilibrium textures with exsolved quartz forming vermicular intergrowths or regular micro-slabs parallel to (001) cleavage. This reaction may be indicative of granulite facies conditions with break down of biotite to garnet (mainly almandine) and K-feldspar, with low Mg in biotite inhibiting hypersthene formation.

Table 1. XRF analyses of garnetiferous augen granites, late garnetiferous granite on the Øfjord coast and grey-pink granite from the north-eastern massif.

	103285 Augen sheet	103271 Sillimanite-bearing augen sheet	103230 Augen sheet	103231 Marginal facies to 103230	104202 Garnetiferous granite – Øfjord	103290 Grey-pink granite sheet
SiO_2	77·37	73·63	72·72	79·00	68·57	68·58
TiO_2	0·24	0·40	0·37	0·13	0·73	0·61
Al_2O_3	11·84	13·27	14·00	11·31	15·00	15·72
Fe_2O_3	2·08	2·61	2·73	1·30	4·35	2·43
MnO	0·03	0·03	0·03	0·03	0·06	0·03
CaO	0·83	1·05	1·40	0·68	2·72	2·13
K_2O	4·86	4·43	5·14	5·48	2·99	4·29
MgO	0·27	0·73	0·45	0·12	1·16	0·83
Na_2O	2·29	3·02	2·94	2·30	3·65	3·85
P_2O_5	0·11	0·10	0·15	0·09	0·16	0·27
	99·92	99·27	99·93	100·44	99·39	98·74

Analyst: D. Dallow, Department of Geology, University of Exeter.

Garnet generally forms 2-5% of total minerals; grains are porphyroblastic up to 5 mm – 1 cm in diameter and compressed in the plane of the principal fabric. Inclusions of globular quartz and flaky biotite are common and the garnet has grown around and replaced these minerals during its formation.

Sillimanite occurs relatively rarely but tends to be common in the extreme south-west where it forms a fibrous mineral lineation with biotite. Very rare muscovite forming a complex intergrowth with quartz and plagioclase has been seen in one thin section from a sheet in the centre of the area.

Lithological variations

Local variations in grain size and texture appear as irregular patches with diffuse margins within the sheets and may be up to 50 m in size, for example in the northern valley walls in the west of the main glacier. Similar irregular patches or blotches were seen in the pink granitic massif at the head of the same glacier and in the sheets in Catalinadal. The patches were not examined in detail but they may represent areas lacking the regular planar fabric.

Other variations include a marginal facies of a sheet in the head of the main valley glacier and a flaser texture seen in coast outcrops of Øfjord. The marginal facies is about 10 m thick; it has a sharp contact with the brown gneisses but is gradational over a few cm into the main augen granite. The mineralogy, exemplified by sample 103231, is similar to the granite but the texture is coarse-grained, sugary and equigranular, and there are small differences in chemistry, notably SiO_2, Al_2O_3, and CaO, Table 1. The flaser structure seen in Øfjord is parallel to the normal planar fabric and may be attributed to more intense shearing or flow on this fabric plane during crystallisation.

Parts of the augen granites, for example in the west of the main valley glacier and in the south-west of Catalinadal, contain large isolated blocks or enclaves of brown gneisses; these outcrops were seen only from a distance of 1-2 km but they appear to be areas where the grey augen granite overwhelmed rusty-brown paragneisses during injection.

Heterogeneous features also include a 30-50 m thick, dark grey-black biotitic layer with quartz-feldspar lenticles seen within 100 m of the top of sheets in the area of Catalinadal. This layer is slightly discordant and may be followed for 2-3 km. The significance of the layer is not clear; it seems unlikely that it is an isolated injected layer and is probably best regarded as a mafic concentrate from the granite itself.

Lamprophyres

Medium-grained, dark green-black lamprophyric dykes occur in shoreline outcrops of an augen sheet about 5 km south-west of Grundtvigskirken in Øfjord. The dykes are about 1 m thick, slightly discordant to the granite fabric and show incipient boudinage. One appears to be tightly folded, but this appearance may be due to shear movements on planes parallel to the sheet fabric. A planar fabric formed by lenticular aggregates of pyroxene and feldspar is visible in one of the lamprophyres, but thin section shows no regular planar arrangement of constituent minerals. The planar fabric is roughly parallel to the fabric in the granite. The lamprophyre texture is mainly equigranular, 2-8 mm, of fresh subhedral grains.

Principal minerals include brown kaersutite with pleochroic scheme α pale brown, $\beta = \gamma$ dark brown; extinction angles are small and simple twinning is uncommon. Orthopyroxene is pleochroic pale red to pale green and is intergrown with kaersutite. Biotite occurs in accessory proportions, but is very obvious from its marked pleochroism from very pale brown to red-brown; this is indicative of relatively high Ti content which concurs with the Ti-amphibole. Biotite is intergrown with pyroxene and kaersutite and appears to have replaced them. Plagioclase forms fresh anhedral grains commonly with lamellar twinning, and quartz, apatite and opaque minerals occur in accessory proportions. Although there are no traces of olivine, the composition indicates a camptonitic lamprophyre. Injection of the dykes as part of the augen granite sheet seems to be the obvious origin. Definite lamprophyric fractions were not seen elsewhere.

Origin of the augen sheets

The sheer volume of the augen granites indicates an injection origin, probably of a granite melt derived from local crustal melting. Although sheet boundaries are locally discordant to foliation in the paragneisses, their broad concordance suggests injection into more or less horizontal metasediments undergoing migmatisation deep in the orogenic structure. The schistose, augen fabric may be attributed to protoclasis with contemporaneous crystallisation and deformation taking place under a predominantly vertical compressive stress. Deformation of the fabric in hinges of large-scale isoclines and tight folds indicates injection and protoclasis prior to, or partly synchronous with, the folding. Maintenance of high temperatures kept sheets and gneisses at low viscosities and development of the large-scale folds probably occurred during or soon after the sheet emplacement.

PINK GRANITIC ROCKS

This group is restricted to a poorly-exposed, ice-covered massif at the head of the main valley glacier. The group was seen only on helicopter reconnaissance. It is a porphyritic to augen granite, commonly garnetiferous and with a crude schistose fabric suggesting partial cataclasis of mineral constituents, especially the larger feldspars. Binocular views and helicopter flypast suggest large-scale mixing of pink and grey varieties of the granite.

Thin sections have not been studied in detail, but there is an abundance of microcline perthite showing subsolidus reaction with myrmekitic plagioclase. Quartz and biotite are also common.

Boundaries with adjacent augen sheets appear to be sharp although there is a zone of mixed pink and grey granitic rocks about 1000 m wide at the margin of the pink granite. The pink granitic rocks may be genetically associated with the augen granites.

INTERMEDIATE IGNEOUS ROCKS

Occurrence and variations

Intermediate intrusive rocks were mapped in the field as diorites but modal and chemical analyses (Tables 2 & 3) show that most are monzonites. This term is used in a purely descriptive, compositional sense because the intrusions have a charnockitic affinity which will be described below. Where the composition is still uncertain these rocks will be referred to as intermediate or dioritic.

The intermediate igneous rocks have two principal modes of occurrence: first, as an extensive sheet up to 500 m thick with subsidiary apophyses, and second as isolated sheets and irregular masses lying structurally above the main sheet and restricted to the north-eastern massif. Dioritic rocks also occur in an agmatitic complex on the coast of Øfjord and in thin dykes chilled against granitic neosome of the coastal migmatite complex of this fjord.

The extensive sheet

The extensive sheet may be traced continuously for about 25 km from the coast of Øfjord whence it swings in an arc through to the valley of the main glacier. The sheet reappears north of this glacier and passes north-east in a set of irregular outcrops that were seen only from helicopter flypast. The sheet has an average thickness of 500 m and is broadly concordant with foliation in the surrounding gneisses. The sheet dips about 30° to the east and forms a quadrant of a broad saucer shape. The north-east quadrant appears north-east of the map-area, where incidentally the composition becomes more acid (J. D. Friderichsen, pers. comm., 1970). Migmatites and concordant granites lie within the saucer.

Small dyke-like bodies regarded as apophyses of the main sheet occur in the highest reaches of Catalinadal and semi-concordant masses occur near the coast of Øfjord. The apophyses in Catalinadal cut sharply across rusty-brown gneisess and augen granite and indicate intrusion after the folding in the western half of the area.

This post-tectonic relation is also indicated by the general absence of tectonic fabrics in the sheet itself. A dark border in the monzonite adjacent to brown gneisses high in the cliffs on the north of the main valley glacier appears to be a chilled margin, otherwise the sheet contacts are veined by granite and chilling seems to be uncommon. Megascopic layering a few cm thick was seen locally and variations in composition are evident within the sheet as a whole (Tables 2 & 3), but variations have not been studied systematically because of the scale of the mapping.

Veins and irregular masses of grey-pink granite are relatively common in top and bottom margins of the sheet especially in the north-east. Parts of this granite may be synmagmatic with the monzonite but much of it may be post-magmatic and injected from migmatites in the north-eastern massif. The significance of this granite is important in the metamorphic chronology which is outlined in a later section.

Pink and white pegmatites of quartz, microcline and biotite are common as thick dykes up to 15 m wide cutting transversely across the sheet and in many instances they appear to be confined to the sheet and do not extend into adjacent gneisses.

Petrography of the sheet (monzonite)

Principal minerals in the sheet rocks are plagioclase, alkali feldspar, biotite and pyroxene with generally accessory proportions of quartz. Modal analyses of five samples are given in Table 2. Sections were stained with Na-cobaltinitrite to facilitate the recognition of alkali feldspar. Proportions of plagioclase to total feldspar average about 55% and dark minerals average about 30% of the total; quartz forms

Table 2. Modal analyses of some intermediate intrusive rocks from the main sheet and migmatised bodies.

	103201	103206	103213	103243	103299	103256	103259
	main sheet					migmatised bodies	
Plagioclase	35·8	30·5	33·2	34·6	25·3	28·3	32·1
K-feldspar	27·4	27·8	26·1	28·4	21·2	25·1	0·1
Quartz	6·0	8·7	6·9	6·4	0·1	11·1	12·3
Biotite	13·5	17·5	12·6	8·6	5·4	21·6	36·6
Hornblende/ cummingtonite	–	–	–	–	–	–	10·3
Pyroxene (orth+clin)	15·9	10·9	20·1	19·8	46·1	12·1	tr
Apatite/zircon	0·4	0·3	0·2	0·3	0·1	0·7	0·3
Sericite/chlorite	–	–	–	–	–	–	6·6
Opaque	0·9	0·8	0·8	1·9	1·8	1·1	1·0
Plag:total feldspar(%)	56·6	52·3	56·0	55·0	54·4	53·0	99·7
Counts	4000	2499	3000	3000	3000	3000	4000

less than 10%. On this basis the sheet rocks should be called monzonites.

Plagioclase is generally fresh, subhedral and mildly zoned with Ca-rich interiors grading into Ca-poor exteriors. Grains are twinned on Albite and combined Carlsbad-Albite laws; pericline twins are less common. Extinction angles of Carlsbad-Albite twins indicate a composition of An_{40} for intermediate zones. Plagioclase may be replaced by alkali feldspar and myrmekitic reactions are common at some grain boundaries.

Alkali feldspar is mainly orthoclase although microperthitic microcline may also be present and gradations with orthoclase showing partial triclinic inversion occur. Simple Carlsbad twins are common. The alkali feldspar has commonly grown along boundaries between other pre-existing minerals and its reaction and replacement of plagioclase and biotite indicate late formation of the alkali feldspar either synmagmatically or as a metasomatic phenomenon associated with late migmatisation. The latter origin would indicate a more basic composition for the intrusion and would account for the dominance of pyroxene and absence of hornblende as a mafic constituent. On the other hand if the intrusion was originally monzonitic then the absence of hornblende could be accounted for by low magmatic P_{H_2O}.

Pleochroic pink to pale green orthopyroxene is generally slightly less abundant than non-pleochroic pale green or colourless clinopyroxene. Total pyroxene is about 15% of total mode and 50-60% of total mafics. Some orthopyroxene grains are overgrown by clinopyroxene and the former may show exsolution lamellae of pyroxene. Some pyroxenes may also be overgrown or replaced by biotite. Fresh samples do not contain amphibole unless they are in close proximity to invading granite or pegmatite; this observation has been made on only eight thin sections from the whole sheet, but it may have considerable petrogenetic significance which will be outlined in a later section.

Biotite is typically of normal appearance with brown pleochroism, and its relatively late growth is indicated by inclusions of pyroxene, overgrowths and interstitial occurrence. Some samples (103206, Table 2) show biotite that is unstable with exsolution of quartz along (001) planes and partial replacement by orthoclase, features similar to some seen in the augen granites. Biotite may also show kink bands deforming (001) cleavage; the kinks radiate from angularities on plagioclase or quartz grains and suggest synmagmatic deformation.

Amphibole has been noted only once in sections of the main sheet and in this case the sample, 103204, was collected in the proximity of a pegmatite vein. The hornblende occurs as uralitic rims to the pyroxene.

The sheet composition and its place in the metamorphic evolution of the Renland massif indicate a charnockitic affinity (Howie, 1964; Singh, 1966), to the extent that the sheet and other intermediate rocks of the north-east may represent the products of crystallisation of injected magma with intermediate composition under granulite facies conditions. The petrography of biotite and potash feldspar is indicative of late growth, perhaps under lower facies conditions with higher P_{H_2O}

associated with the period of injection of overlying grey-pink granites in the north-eastern massif.

Irregular masses

The irregular masses and sheets of intermediate rocks in the eastern half of the area, i.e. above the main sheet, form bodies within and invaded by granite of the coastal migmatite complex. The masses vary greatly in size from a metre to hundreds of metres, and the sheets may be up to 200 m thick. The chemistry and modes of two samples of granitised masses are given in Tables 2 and 3.

The mineralogy of the granitised rocks is broadly similar to that of the main sheet apart from the common occurrence of amphiboles replacing pyroxene. This replacement does not occur in every sample of granitised diorite and some samples are identical to the sheet monzonite. However, most of the granitised samples examined show a predominance of amphibole over pyroxene. There are two amphiboles. One is very slightly pleochroic pale green to colourless; it has oblique extinction of about 10°, $2V\gamma$ 88°–74° (+ve), and common lamellar twinning with very narrow lamellae. These properties suggest the mineral is cummingtonite with 45% Mg: ($Mg+Fe^{2}+Fe^{3}+Mn$), after Deer, Howie and Zussman (1967, fig. 57, p. 161). The second amphibole is pleochroic, pale brownish-green to darker green hornblende. It appears to have formed slightly later than cummingtonite. Reaction and replacement of biotite by hornblende may also occur.

Significance of amphibole

The dominant occurrence of amphibole, in particular cummingtonite, in the granitised masses leads to the assumption that alteration of pyroxene took place in association with granitisation and is not a magmatic phenomenon. It also suggests that the intermediate intrusions altogether were originally relatively dry melts and later granites were wetter with higher P_{H_2O}. Formation of cummingtonite from orthopyroxene suggests granulite facies conditions may not have been attained completely throughout later granitisation.

Marginal areas of the main sheet in the north-east are invaded by granites believed to be associated with the migmatisation in the north-eastern massif, and amphibole replaces pyroxene in monzonite close to the invading granite. However, the bulk of the pyroxene remained stable throughout the granitisation and the sheet appears to have remained impervious to introduction of water apart from areas near pegmatites and granite veins. In view of the pre-amphibolisation similarity between the sheet and granitised bodies, it may be inferred that they had a common origin and the isolated masses of dioritic rocks in the north-eastern massif could be regarded as parts of original sill-like intrusions disrupted by later granitisation.

Inclusions

Various inclusions of biotitic schlieren and dark basic xenoliths are relatively common in the sheet monzonite north of the main valley glacier. The inclusions are 10-100 cm in size and rounded. Similar inclusions of dark basic material were seen in the large apophysis of the main sheet on the coast of Øfjord and rare pieces of grey gneiss were found in morainic blocks of sheet monzonite 700 m above the coast 10 km south-west of Grundtvigskirken.

Gneissic and basic inclusions, 10-15 cm in size, also occur in migmatised dioritic bodies in Skillebugt. Similar basic inclusions occur in the surrounding granite neosome of the coastal migmatites and an agmatitic pyribolite from the migmatites will be described later. Basic inclusions in the diorite have a schistose fabric formed by elongation and thin layering, ~ 3 mm, of constituent minerals. Thin section of a basic inclusion from Skillebugt shows plagioclase and pyroxene as principal minerals with accessory biotite, hornblende and opaque. The texture is intergranular, medium- to fine-grained with plagioclase commonly having Y-junctions between adjacent grains. Extinction angles of Albite twin lamellae suggest An_{40} composition. Ortho- and clino-pyroxene are present and may be partly replaced by green-brown hornblende and biotite. Estimated modal proportions are: plagioclase 40%, pyroxene 35%, hornblende 10%, biotite 10%, opaque 5%. On the basis of its composition and texture the rock may be described as a hornblende-pyriclasite, after Berthelsen (1960, fig. 2).

The basic inclusions may have an infracrustal origin and their stable assemblages of granulite facies minerals and textures seems a further indication of the charnockitic affinity of the intermediate intrusions.

Agmatite complex

A large mass of veined basic rocks outcrops within the coastal migmatite complex of Øfjord about 3 km east of Grundtvigskirken. The outcrop was mapped as a net-veined diorite, the term net-veining being used in a descriptive sense only to describe the intense veining of the green basic rocks by grey granodiorite *s.l.* However, subsequent examination suggests the term agmatite is more appropriate. The basic blocks are angular, from a few cm to 5 m long, and vary in grain size from block to block as if brittle or semi-brittle disruption of an original mafic body took place with subsequent movement within the granodioritic matrix bringing blocks of different grain size adjacent to one another. The outcrop of the agmatite complex is about 100 m by 1000 m and has been faulted.

Thin sections of the mafic blocks (103263, 103266) show the following features. Among the most striking is the general absence of feldspar, only rare plagioclase being seen as an interstitial growth or as inclusions in amphibole (103266). The dominant minerals are biotite, ortho- and clino-pyroxene with apatite and opaque minerals as accessories. Orthopyroxene is colourless and probably Mg-rich; it tends to occur in granular aggregates or isolated grains that are partly replaced by clinoamphibole or biotite. The amphibole has features similar to those seen in migmatised diorite and is probably cummingtonite. Biotite is a relatively late product because it surrounds pyroxene and amphibolised pyroxene. On the other hand some of the biotite itself seems to have been replaced by amphibole. The biotite is pale brown and may be Mg-rich.

It is not known how uniform this composition is through the mass as a whole because of the very local sampling: additional material collected in 1970 is awaiting examination. However, the absence of feldspar is unusual for the intermediate rocks as a whole. The veined complex cannot be considered as part of the pyribolites found in the coastal migmatites because the composition and textures are very different. For the present it is best regarded as a basic or ultramafic variety of the intermediate intrusions.

The matrix surrounding the angular blocks is pale grey, medium-grained to pegmatitic sometimes with books of biotite crystals 2 cm in diameter. The composition is granodioritic with microcline perthite, plagioclase, quartz and biotite as principal minerals and zircon and apatite common accessories; zircon is particularly common. Texture of the quartz is notable for the strongly sutured sub-grain boundaries indicating crystallisation under flow or tectonic stress. Plagioclase grains tend to be altered at the margins. Microcline formed late and includes small granules of plagioclase and zircon.

The complex was revisited in good weather in 1970 and the contact with the surrounding migmatites was examined in detail. The homogeneous, non-garnetiferous grey granite (grain size 3-5 mm) forming the neosome of the coast migmatites passes without a marked interface, apart from a yellowish colour change, into the agmatite matrix which is slightly coarser (grain size about 10 mm) and richer in biotite. The granodiorite matrix may have been injected from the surrounding migmatite complex, but in view of the fact that the dark minerals of the blocks seen so far are identical to those in the monzonitic bodies it is conceivable that the matrix was derived in situ by diffusion from an original intermediate mass by rheomorphic activation during the granitisation of the surrounding migmatites.

"Younger diorites"

The so-called younger diorites occur in dykes outcropping in the coastal migmatite complex of Øfjord. They are described as younger because their contacts with adjacent migmatites are sharp and in some instances chilled, and invasion by granite neosome like that seen in the migmatised diorites is lacking. The largest dyke is well exposed on the coast about 7 km north-east of Grundtvigskirken. At the shoreline it is 60-100 m thick, strikes 113° and dips 40°SW. About 500 m above the shore it fingers up into granitic neosome of the migmatite complex and the total outcrop shown on the map suggests either a swing to a northerly strike and steeper dip or a series of dykes with varying dip.

The dyke is homogeneous, medium-grained even to the sharp contacts, but within marginal zones 10-15 m wide on each side of the dyke there is a prominent planar fabric parallel to the contacts. The interior of the dyke does not show this fabric. A few thin, brownish quartz-feldspar veins, some irregular and others with a more regular alignment, occur within the planar fabric which could be interpreted either as an igneous flow feature or as a tectono-metamorphic phenomenon formed during migmatisation with recrystallisation of original igneous minerals in granulite facies conditions as suggested by Kalsbeek (1969, p. 32) for some foliated diorites on the Bjørneøer. The fabric is not found in adjacent granite neosome where it might be expected if it were a tectono-metamorphic feature, and the lack of granite veins in the diorite suggests post-migmatitic intrusion. However, in view of the charnockitic affinity of the intermediate intrusions, it is conceivable that the fabric is a convergent igneous/metamorphic phenomenon formed by crystallisation under granulite facies conditions.

Composition of sample 103267 collected 10-15 m from the south-west contact is monzonitic comprising orthoclase, mildly-zoned plagioclase, quartz, biotite, bronzitic orthopyroxene and diopsidic augite. The rock is completely fresh and no amphibole replacement has taken place such as one sees in the migmatised diorites. Subhedral plagioclase and biotite are elongated parallel to the planar fabric described above. The chemistry of 103267 is in most respects identical to monzonite samples from the main sheet (Table 3).

Table 3. XRF analyses of some intermediate igneous rocks.

	103206	103213	103243	103224 apophysis of main sheet	103256 migmatised body	103267 "younger diorite"
	main sheet					
SiO_2	60·04	59·86	59·38	59·00	58·45	58·45
TiO_2	1·15	1·03	1·13	1·09	1·17	1·00
Al_2O_3	12·49	12·64	13·24	12·90	12·24	12·56
Fe_2O_3	6·56	6·13	6·77	6·64	6·88	6·52
MnO	0·10	0·09	0·10	0·10	0·11	0·11
CaO	4·20	3·92	4·88	4·35	4·45	4·25
K_2O	4·70	4·46	4·55	4·17	4·62	4·09
MgO	5·75	5·60	5·00	6·65	6·00	7·60
Na_2O	2·99	3·12	3·53	2·90	3·08	2·96
P_2O_5	0·49	0·48	0·49	0·54	0·50	0·49
	98·47	97·33	98·97	98·34	97·50	98·03

Analyst: D. Dallow, Department of Geology, University of Exeter.

Another dyke occurs about 4 km north-east along the coast. This dyke is about 30 m thick, strikes 138° and dips 85°NE. It has a thin chilled margin against granite of the migmatite complex, but is veined by rectilinear pink pegmatites that extend from the migmatite for about 4 m into the dyke. Composition of the dyke is similar to the above but alkali feldspar is lacking and some amphibole replaces pyroxene, a feature that could be attributed to pegmatite injection. Other dyke-like bodies occur further along the coast to the north-east but they were not examined.

The position of the so-called younger diorites with apparent chilled contacts and igneous/metamorphic fabrics in the metamorphic history is enigmatic, but assuming the invading pegmatites are associated with migmatisation of the coast complex, then in the wide sense the "younger diorites" could be regarded as synmigmatitic; however, some appear to be definitely younger than the granitic neosome of the coastal complex.

COASTAL MIGMATITE COMPLEX

Occurrence and petrography

The shoreline outcrops of Øfjord and Skillebugt are dominated by a granitic migmatite complex in which basic agmatitic rocks are relatively common. Pink-grey granitic neosome is abundant and there are all gradations from layered to raft migmatites, the latter being predominant. Strings of enclaves indicate pre-existing lithological layering in many instances. The neosome may be foliated or non-foliated and where migmatisation has been particularly intense the enclaves are schlieren-like and commonly reduced to biotitic wisps within a normal igneous-looking granite. Areas of such appearance may be very large and appear to grade up into the overlying sheets of grey-pink granite described in the following section. Such gradations make the placing of a firm boundary very difficult and the only certain boundary, indicated by a solid line on the map, is on the south-west of Skillebugt where the bottom of a grey-pink granite sheet is clearly defined.

Helicopter flypast suggests that the coastal migmatite granite neosome becomes predominant over inclusions towards the interior of Skillebugt and this granite may be followed into the valley of the main glacier. The granite on the north of the decaying glacier snout is identical to this migmatite granite and it veins the monzonite. In addition, large masses of the monzonite 'float' within this granite. On this basis it is argued that the coastal migmatites, the overlying grey-pink granites and grey-brown granitised gneisses were developed during an important late phase of granitisation and migmatisation after the emplacement of the main monzonite sheet.

Further evidence supporting this view is provided by migmatised monzonitic/dioritic masses within the coastal migmatite complex itself, for example in Skillebugt.

The neosome is essentially granitic, generally with an equigranular coarse-grained fabric. In some instances the neosome has a parallel alignment of mineral grains forming a schistose fabric and micaceous mineral lineation. This fabric is parallel to overall layering in the migmatite complex. Alkali feldspar as microcline or orthoclase occurs in excess of plagioclase, the latter showing varying degrees of alteration while alkali feldspar is fresh. Quartz is common. Biotite is the only mafic mineral and commonly shows alteration to chlorite. Garnet has a patchy development forming 10% of the rock in some places and being widely scattered or absent in others. Accessories include zircon, apatite, chlorite and opaque minerals; muscovite associated with biotite has been seen very rarely.

Enclaves in the granite neosome are predominantly quartzitic and biotitic gneisses and pyribolite. The fragments are generally aligned indicating previous lithological layering. Furthermore, they also show quartzo-feldspathic segregations parallel to layering within the fragments indicating a phase of migmatisation prior to the development of the surrounding granite neosome. This earlier phase could be correlated with the earlier migmatisation seen west of the monzonite sheet. Hypersthene has been recorded in similar, migmatised metasedimentary rocks on the Bjørneøer (Kalsbeek, 1969, p. 9), but so far it has not been seen in the Renland inclusions.

Pyribolite

Pyribolite inclusions are common in the coastal migmatites in Skillebugt and the north-east of Øfjord. In many instances the inclusions are scattered in the granite neosome, but locally agmatitic layers up to 5 m thick may be traced continuously for 200-300 m.

Pyribolite (103260) is homogeneous, medium-grained and has a schistose fabric formed by thin layers and elongation of constituent minerals. These comprise plagioclase (possibly An_{80}) with common Y-junctions, pleochroic orthopyroxene and pale green clinopyroxene, and greenish-brown hornblende; an opaque mineral is a common accessory. Estimated modal proportions are: plagioclase 40%, pyroxene 30%, hornblende 25%, others 5%. Fragments with almost identical composition and fabric, apart from biotite in place of hornblende, occur in the granitised diorite masses in Skillebugt.

Although pyroxene and hornblende are intergrown in the agmatitic pyribolites, the amphibole is not a replacement phenomenon like that in the granitised monzonites within the migmatite complex. The pyribolite fragments show reaction with the surrounding granite neosome but this is limited to a marginal zone about 2 cm wide with concentration of feldspar in a zone of similar width in the granite matrix adjacent to the fragments. These basic fragments in the migmatite and in the monzonites could be regarded as hornblende granulite facies rocks with an infracrustal affinity disrupted during the generation of the migmatites and intermediate igneous melts.

Origins and correlations

The migmatite and granite complex on the Bjørneøer has been described recently by Kalsbeek (1969) following his mapping there in 1968. Personal visits to Bjørneøer I and XI in 1969 and discussion with R. H. Steiger and F. Oberlie who mapped in great detail a small area on Bjørneøer I in 1969 confirmed that the coastal migmatites of east Renland are identical to the Bjørneøer migmatites (Variable migmatites, generally with remnants of metasedimentary rock of Kalsbeek, 1969, map 1). Parts of other granitic and migmatitic divisions listed by Kalsbeek are also comparable to the coastal migmatites.

The presence of basic rocks and quartzitic gneisses within the coastal migmatites invites comparison with both the Krummedal sequence of supracrustal rocks and the Flyverfjord infracrustal complex described by Henriksen and Higgins (1969, pp. 10-12). According to their descriptions enclaves compare closely with the Krummedal sequence, but the presence of pyribolites could be evidence of reworked basement analogous to the Flyverfjord complex. However, the tectonic picture of Renland indicates that such lithological comparisons, especially with regard to basement rocks, are tenuous and firmer correlations should be made on the basis of radiometric age determinations on the paleosome of the coastal migmatites, in particular the pyribolites.

The large volume of granite neosome and the presence of quartzitic and basic fragments suggests that although local in situ anatexis may have taken place, the bulk of the neosome may be allochthonous. Such a conclusion has also been reached by Kalsbeek (1969, p. 13) for the origin of the Bjørneøer migmatites.

Younger granites

The coastal migmatites are locally intruded by a grey granite in the form of thin, irregular sheets slightly discordant to migmatite layering: more discordant, dyke-like bodies 1-10 m thick also occur, in particular just south of the entrance to Skillebugt. An example of the granite from shoreline outcrops on the promontory in the snout area of the first glacier south-west of Skillebugt contains blocks of coastal migmatite neosome and paleosome and is in turn cut by pink pegmatites. The granite is clearly younger than the grey-pink neosome of the coast migmatites and it may be related to the younger granites of the Bjørneøer (Kalsbeek, 1969, p. 19).

A distinctive, garnetiferous, porphyritic grey granite forming intrusive masses within the migmatite complex occurs in the coastal platform beneath Grundtvigskirken. The area of the largest outcrop is about 500 m by 1000 m. The granite is coarse-grained with abundant garnet and anhedral megacrysts of microcline up to 2 cm long. Biotite is common and associated with rare muscovite. The mineralogical and chemical composition (Table 1) show some similarities with the augen granite sheets and on this basis the porphyritic granite could be regarded as a fraction of the augen sheet dipping beneath the coastal migmatites in this area that was remobilised and injected late in the migmatisation of the coast complex.

GREY-PINK GRANITE

This variety of granite is confined to the north-eastern massif and lies above the coastal migmatite complex and the main monzonite sheet. It forms sheets of varying thickness within granitised brown gneisses and is dominant towards the east. There are all gradations between migmatised gneisses, gneisses with concordant granite sheets and nearly homogeneous granite. Such gradations make the allocation of boundaries very difficult and an arbitrary field division of > 60% granite component on the scale of a cliff face has been used to delimit the grey-pink granite division.

The sheet form of the granite concordant with foliation in the gneisses is visible in most outcrops. Generally, the sheets are at least 50 m thick and some may be at least 500 m thick. Lithological layering in the form of variations in mica or feldspar content is common, and strings of gneiss rafts contribute to the foliation. The strings of inclusions are characteristic of the granite sheets and in many instances they are reduced to biotitic schlieren. Irregular bodies and sheets of dioritic rocks also occur with the granites.

The composition is typically granitic with alkali feldspar as microcline, and less commonly orthoclase, dominant over plagioclase. Biotite is the mafic constituent and so far no hornblende has been seen. Garnet occurs in accessory proportions in some outcrops, and accessories in thin sections include apatite, zircon, chlorite, muscovite and opaques. An XRF analysis of the granite (103290) is shown in Table 1.

Digestion of gneisses within the granite sheets suggests in situ anatexis but the volume of grey-pink granite, particularly in the brown gneisses, is indicative of injection of allochthonous material like the neosome of the coastal complex. The granite sheets bear many resemblances to the coastal migmatite complex and both are regarded as broadly consanguineous although there have been anatectic admixtures of locally digested gneisses. The grey-pink granite could be correlated with the grey granite of Bjørneøer described by Kalsbeek (1969, p. 16-17, 31).

GREY-BROWN GRANITISED GNEISSES

This group of gneisses occurs above the extensive sheet of monzonite and is best seen in the west of the north-eastern massif. As the gneisses are followed into the east of the massif they become increasingly overwhelmed by grey-pink granite described above. Within the gneisses the concordant sheets of this granite vary from 2-200 m thick and the arbitrary selection of a boundary between gneisses and granite has been outlined above.

The gneisses are typically foliated, biotitic or quartzitic. and with variable amounts of concordant granitic neosome. Later discordant veins of aplite or microgranite occur in some parts. Compositionally the gneisses resemble the rusty-brown gneisses further west apart from lower proportions of garnet. Few samples of the gneisses were obtained because they were seen only on helicopter reconnaissance, and although some material remains to be sliced the sections seen so far have not revealed cordierite or hypersthene. The granitised gneisses lie structurally above the rusty-brown gneisses to the west and may represent a higher stratigraphic level in the Krummedal sequence.

PEGMATITES AND APLITES

Concordant and discordant, pegmatitic and aplitic fractions were developed during most stages of the regional migmatisations and have compositions broadly similar to related neosome described in previous sections. Discordant pink pegmatites of quartz, microcline, biotite and muscovite, and aplitic dykes and veins are especially common in the north-eastern massif and seem to be the final manifestations of granitisation in this region. Investigations of compositions and trends is incomplete at the time of writing.

STRUCTURAL GEOLOGY

Folding west of the monzonite sheet

Deep valleys with near vertical walls and the distinct lithological contrast between grey augen sheets and rusty-brown paragneisses make the folds in the west of the area show up very clearly. On the other hand the lack of contrasts in the granites and gneisses east of the monzonite sheet makes the recognition of folds very difficult and no certain large-scale structures have in fact been determined.

The principal folds in the west are large-scale isoclinal structures with axial surfaces having a sub-horizontal dip in the east and becoming steeper towards the west until near the head of the main valley glacier the axial surfaces dip 60°W (fig. 3). Limb lengths of the folds may be up to 5 km or more and in a purely descriptive sense the structures could be called fold nappes. Orientation of hinge lines and fold axes is uncertain in many instances because the cores of many structures are exposed on inaccessible cliffs. However, the large-scale fold geometry and measured small-scale structures indicate plunges of fold hinges to the west or north-west. Such down-dip plunges make the structures neutral folds. Facing directions are unknown because stratigraphic relations within the paragneisses are also unknown. Furthermore, the movement direction (Bewegung) of the folds is also uncertain, although it may be towards the west or north-west on the basis of the inferred westward displacement on Hinks Land or a related overthrust described by Henriksen and Higgins (1969, p. 9) about 60 km north-west of the present area.

Although the contrasting rusty-brown and grey gneisses show up the folds in valley walls, it is very difficult to correlate structures across valleys and ice-covered highlands on account of the lithological similarities within both groups of rocks. Changes in thickness of grey granite sheets and apparent overwhelming of the

Fig. 3. Hinge area of steepened isoclinal fold north-west of the main valley glacier. Dark grey layers are rusty-brown paragneisses and pale grey is garnetiferous augen granite. Peak stands 300 m above glacier surface.

brown gneisses by the grey granites, especially towards the head of the main valley glacier, add to the difficulties of correlation. Fold axial traces and tentative correlations are shown on the map.

Geometry of the folding on a large scale is also shown on the map. This geometry and the presence of intrafolial folds in some of the paragneisses suggest flow of material parallel to fold limbs and axial surfaces. However, disharmonic fold relations and a décollement between paragneisses and augen sheet in the hinge of a large structure on the north of Catalinadal are functions of inhomogeneity and competence difference. These relations suggest that shear or flow parallel to axial surfaces was not the only mechanism of fold formation. Buckling by flexural flow within the layers, especially in the paragneisses with more variable ductility contrasts, may also have been significant in the evolution of the fold structures.

Deformation of the augen granite fabric in the hinges of large- and small-scale folds shows that the structures formed after the mise-en-place and development of the planar fabric of the augen sheets. Some neosome formed parallel to axial surfaces and suggests temperatures were still high during fold formation. The augen fabric indicates crystallisation of injected granite under stress and in view of the ductility shown by the fold structures, a further indication of maintained high temperature during deformation, it may be inferred that injection of granite sheets, formation of the augen fabric and migmatisation of the paragneisses together with subsequent fold formation all occurred during one broad episode (time) of the tectono-metamorphic evolution of east Renland. At present, the field evidence suggests that a second migmatisation occurred after the emplacement of the main monzonite sheet and for convenience the broad episode outlined above may be referred to as "Early Phase". This phase may correlate with early events in the "Old"-Caledonian folding and migmatisation described by Haller (1961) which he assumed to be of Silurian age.

Superimposed folding

A number of areas west of the monzonite sheet contain evidence to suggest superimposed folding. The most obvious is the steepening toward the west and northwest of isoclinal fold axial surfaces. This might be associated with the late-stage gentle warping on approximately north-south axes found on a large scale in the Stauning Alper (Henriksen & Higgins, 1970). A definite axis of warping with a northnorth-east trend is located through the east of the 610 m lake in Catalinadal and thence into the southerly spur of the main valley glacier and on into the north of the area. However, it is not clear whether this axis relates directly to the late-stage warping in the Stauning Alper because it may be associated with the development of the basin structure of the granite-migmatite complex in the north-east and so be earlier than late-stage warps further north.

On the other hand the steepening of axial surfaces in the west may have taken place during the development of the folds themselves. Overriding of nappes giving rise to involutions during the mobile phase of fold formation may have led to synchronous refolding of the type suggested by Wynne-Edwards (1963).

Two other parts of the area contain problematical fold geometries that may have formed as a result of such refolding. The first occurs in the head of the main valley glacier. It comprises an open mushroom type of structure of brown gneisses and augen granites (fig. 4). The mushroom is associated with an isoclinal or nappe fold closure (fig. 3) of normal aspect in the area where steepened axial surfaces dip about 60°NW. At first sight the structure appears to be due to superimposition on the isocline of a tight fold with axial surface striking north and dipping sub-vertically. However, there is no fabric in the gneisses with this orientation and the only fabric one sees is that related to the large-scale isoclines. The measured data (fig. 5a) and the absence of structures or fabrics related to a phase of superimposed folding tend to support the view that the mushroom structure may be a product of synchronous refolding.

The second problematical area is in the west of Catalinadal where rusty-brown gneisses interlayered with augen granites make a sharp change in strike from north-

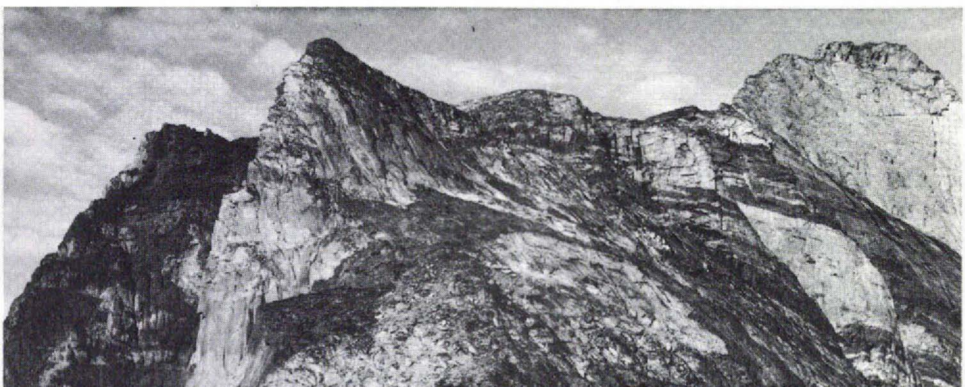

Fig. 4. Mushroom structure in folded rusty-brown paragneisses (dark grey) and garnetiferous augen granite (pale grey) north-west of the main valley glacier. Peak left of centre is same as that in figure 3 and stands 300 m above glacier surface.

west to north. Measurements of various structures in this part are summarised in fig. 5b. Both small-scale structures and stereogram analysis indicate a large fold with axial surface strike 155° and dip 20°-30°NE. The fold axis plunges 20°-30°NE down dip and so the structure is neutral, closing south-east. A mineral lineation mainly of sillimanite fibres lies nearly parallel to fold axes. The fold is tight with interlimb angle about 35°. Small-scale folds fall within the hinge zone of the large-scale structure and resemble those seen in the nappe structures in the region of the main valley glacier.

Immediately north-east a major, tight fold axis and associated small-scale folds plunge 20°-30°W. This abrupt difference in attitude from the north-easterly plunge of fold axes described above may be attributed to later folding superimposed on nappe structures. However, the fabrics in the later folds are again identical to small-scale folds in the regional isoclines, a feature comparable to that in the mushroom structure 10 km due north. The similarity in fabrics suggests similar physical conditions during both deformations and leads again to the possibility of synchronous refolding.

Such refolding involutions in the regional isoclines could be attributed to piling up of nappes against a more resistant mass or to overriding of higher nappes dragging against lower structures. The fact that the strongest steepening of axial surfaces, the mushroom structure and the example from Catalinadal lie on an approximately

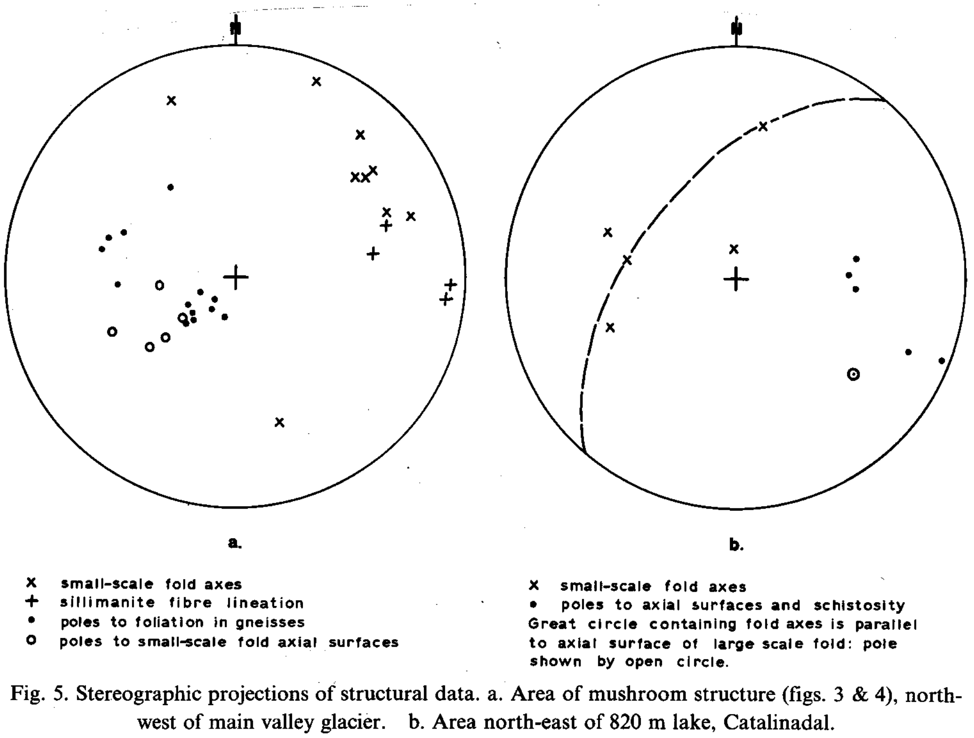

Fig. 5. Stereographic projections of structural data. a. Area of mushroom structure (figs. 3 & 4), north-west of main valley glacier. b. Area north-east of 820 m lake, Catalinadal.

north-south line through the west of the area suggests a common origin. If synchronous refolding took place by compression against a resistant mass, then the mass itself may be represented in part by the massif of pink granitic rocks in the extreme north-west of the area.

Folding in the north-eastern massif

Definite folding on a large scale within this massif has not been recognised although numerous examples of intrafolial folds are visible in the migmatised grey-brown gneisses. The massif area is generally one of gentle dips with sheets of granite and gneisses having sub-horizontal attitudes or dips up to 30°-40°. There are some parts however with steep dips of 65°-75°. During helicopter flypast in the interior of the massif a possible closure of a large-scale recumbent structure was seen. This closure may be a relic of folding like the regional isoclines in the west that was overwhelmed during granitisation of the massif region.

Steep dips are also seen in parts of the migmatite complex along the coast of Øfjord and there is tentative evidence of unconformable relations between steep migmatitic foliation in parts of the complex and the overlying sub-horizontal sheets of grey-pink granite. However, systematic variations in orientation of the foliation were not recognised because of the scale of the mapping, and the structure of the massif region is far from clear.

Fractures

Like the folds, the fractures show up best in the west of the area because of contrasts between rusty-brown and grey gneisses. Apart from ubiquitous joints the dominant fractures are normal faults trending approximately north to north-north-west with steep dips and downthrow to the east. Downthrow on individual faults varies from a few metres to 200 m. The total cumulative throw to the east on the faults exposed along the upper reaches of the main valley glacier is about 1000-1500 m. Outcrop patterns suggest that faults with similar trend occupy some of the glaciated tributary valleys running north and south into the main valley glacier and Catalinadal. Topographic lineaments with north-south trend occur in the north-eastern massif region but amounts of movement, if any, are not clear and it appears that the normal faults may be restricted more to the west of the area.

Although the normal faults are not exactly parallel to the faults trending north to north-north-east along the boundary of the eastern Stauning Alper, they are probably related to the tensional block faulting that gave rise to the graben structure of Jameson Land.

Other fractures with north-west trend occur in the north-eastern massif region.

Movement on the fractures appears to have been slight although many contain pink crush zones filled with mylonitised quartz and feldspar. The zones are nearly vertical and about 1 m wide. Feldspars in adjacent gneisses tend to be stained red in zones about 1 m wide on each side of the fractures. Skillebugt and valleys in the massif region generally trend north-west parallel to this set of fractures.

The relation of the north-west fractures to the normal faults is not clear. Haller (1961) has described various tensional block faults of late Caledonian age and trending approximately north-west in the fjord region of East Greenland between 72° and 76°N, and the Renland crush zones might be linked with these faults on the basis of trend.

METAMORPHIC GEOLOGY

Regional metamorphic conditions over the entire area were sufficient to give rise to pervasive migmatisation. Migmatisation is currently believed to have taken place in two distinct phases of one broad episode of metamorphism. These phases were separated by intrusion of intermediate rocks with charnockitic affinity. Effects of the first or early phase are seen principally in the west. The second phase is dominant in the east (above the extensive monzonite sheet) where it has tended to overwhelm effects of the early phase.

Early phase

The widespread occurrence of thin concordant neosome, the presence of such indicators as cordierite and sillimanite and the absence of kyanite and hypersthene in the rusty-brown paragneisses of the Krummedal sequence suggest that early phase migmatisation, represented west of the monzonite sheet, took place under low pressure, upper amphibolite facies conditions. Concordant neosome was probably produced by in situ anatexis of the gneisses with injection of the sheets of augen granite taking place during the migmatisation. Structural evidence suggests that subsequent regional isoclinal folds or nappes developed under maintained high temperatures associated with this early phase. Petrographic relations between metamorphic minerals in the paragneisses have not been fully established and although sillimanite is an early phase mineral, being mostly parallel to fold axes, the relation of cordierite to the early phase is not yet clear.

Intermediate igneous intrusions

The principal monzonite sheet was injected after the early migmatisation as shown by apophyses of non-migmatised monzonite cutting augen granite and migmatised paragneisses in the valley of the southern spur of the main glacier. Cross-cutting relations are also shown by the monzonite on the coast south of Grundtvigskirken. Other discontinuous dioritic sheets and irregular masses in the migmatite complex of the north-eastern massif are at present considered to be consanguineous and injected at the same time into migmatised Krummedal paragneisses which have since been overwhelmed by the later migmatisation and are now represented by grey-brown granitised gneisses above the main monzonite sheet.

The charnockitic affinity of the intrusions suggests attainment of granulite facies conditions in the surrounding gneisses at the time of intrusion. The western limit of the facies is not yet clear.

Late phase

The principal granitisation of the north-eastern massif belongs to this phase and apart from rare pegmatite dykes effects of this phase are not seen in the west. Although injection of granite, now in the form of augen sheets, took place during the early phase, the migmatites in the west may be considered as largely autochthonous whereas apart from local in situ anatexis in the second phase much of the granite neosome is probably allochthonous, though it may not have travelled far on the broad scale of the orogeny. Metamorphic grade is not yet completely clear though it was at least in upper amphibolite facies. Kalsbeek (1969) reports that migmatisation of similar age on the Bjørneøer took place under low pressure granulite and amphibolite facies conditions, but, apart from the charnockitic affinity of the intermediate intrusions, no evidence has been found so far in the *gneisses* of the Renland massif to be certain of granulite conditions being maintained throughout the later phase. Reaction rims round some pyribolite inclusions in the coast migmatites and alternation of pyroxene to cummingtonite in the migmatised diorite masses in Skillebugt and Øfjord suggest upper amphibolite conditions.

Retrogressive metamorphism

Effects of retrogressive metamorphism are uncommon and are restricted to local development of chlorite replacing some mafic minerals in neosome and paleosome.

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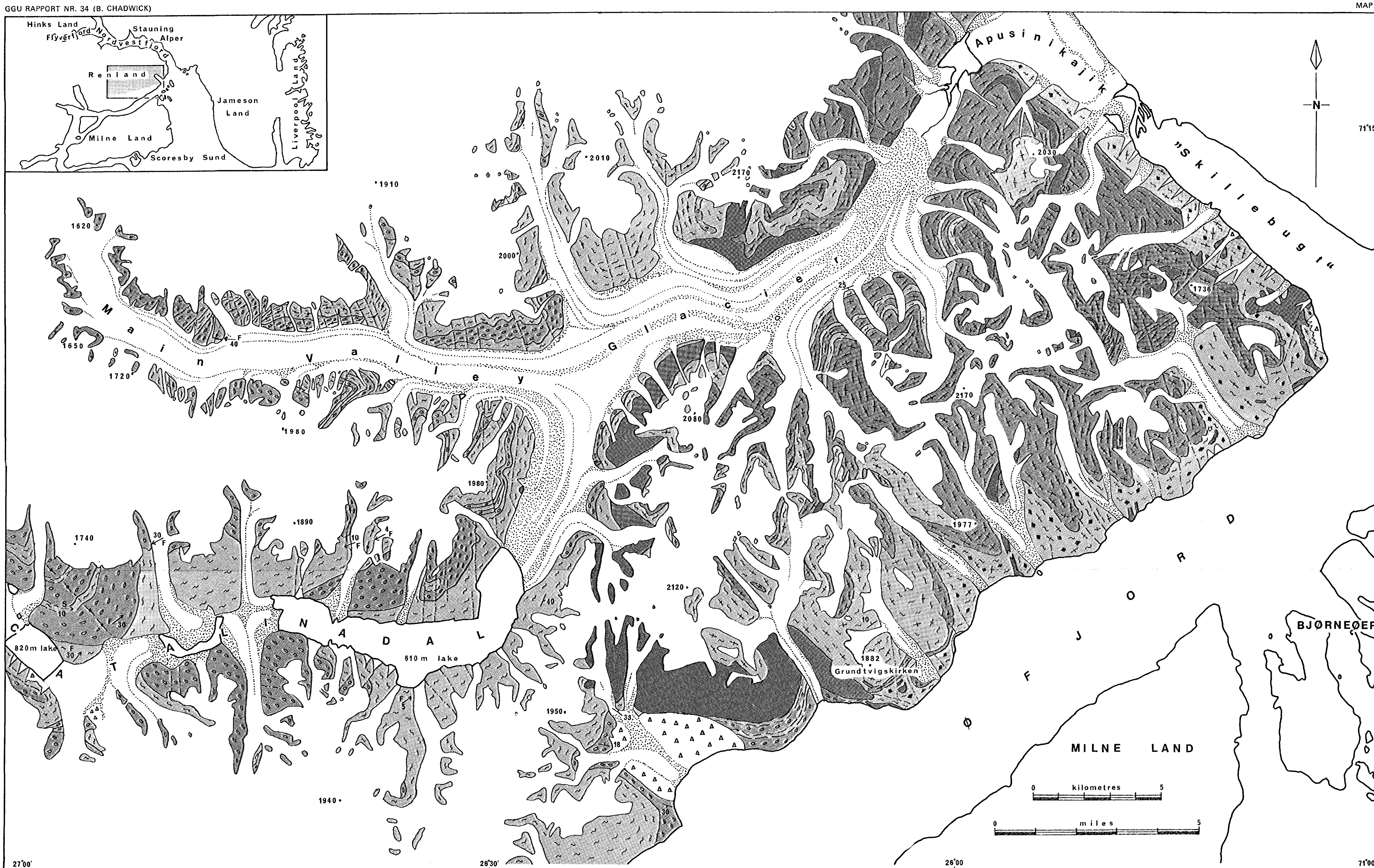

LEGEND

- Grey-brown granitised gneisses
- Grey-pink granite; commonly foliated and with gneissic inclusions
- Coastal migmatite complex
- Intermediate intrusive rocks
- Pink granitic rocks in the northwest
- Grey, garnetiferous augen granite
- Rusty-brown garnetiferous gneisses and quartzites
- Foliation (lithological layering)
- F Fold axis
- S Sillimanite fibre lineation
- Fold axial surface trace
- Lithological boundary - known, inferred
- Fault or topographic lineament
- Moraine
- Talus
- 2130 Summit or spot height in metres

Note: Distortions in topography occur in the northeast where outcrop boundaries have been sketched from aerial photographs. Slight irregularities in enlargement of 1:50,000 field maps have produced additional small distortions.

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