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THE STRUCTURE OF SOUTH RENLAND, SCORESBY SUND

WITH SPECIAL REFERENCE TO THE TECTONO-METAMORPHIC EVOLUTION OF A SOUTHERN INTERNAL PART OF THE CALEDONIDES OF EAST GREENLAND

BY

BRIAN CHADWICK

WITH 27 FIGURES AND 1 TABLE IN THE TEXT, AND 2 PLATES

KØBENHAVN
C. A. REITZELS FORLAG
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Abstract

Renland occupies an internal position within the southern extreme of the outcrop of the Caledonian mobile belt of East Greenland exposed between latitudes 70° and 82° N. In south-west Renland migmatised paragneisses derived from sediments comparable to the late Precambrian Lower Eleonore Bay Group form a multilayered sequence with a minimum thickness of 1500 m. The migmatites are interleaved with thick concordant sheets of garnetiferous augen granite, the formation of which may be linked with the low-pressure granulite or transitional amphibolite-granulite facies conditions attained during migmatisation of the paragneisses. These conditions persisted during the folding together of paragneisses and granites into regional structures of nappe dimensions which had a north or north-west direction of transport. Refolding of the nappes under continued high-grade conditions gave rise to structures locally coaxial with nappe axes. Reversals of facing of nappes occur in backfolds. Linear fabrics of sillimanite and biotite and prolate ellipsoidal augen of feldspar are parallel to fold axes and show that constrictional deformation dominated the later stages of the nappe phase and the refolding event. The constriction is attributed to compressing of rocks in south-west Renland between nappes advancing from the south and a rising mass of granite and basement gneisses in the north.

Intrusion of concordant sheets of biotite-rich hypersthene monzonite (mangerite) followed the nappe deformation in south-east Renland. The principal sheet, which is 500 m thick, forms the rim to part of a lopolithic basin. Thinner sheets of monzonite injected into migmatites within the basin have been disrupted by further migmatisation and granitisation. Stable assemblages in pyribolite restite suggest this later event, which was restricted largely to the basin, attained conditions of hornblende-granulite facies. Open warps attributed to monzonite injection and the basin formation are superimposed on nappes west of the principal sheet.

Normal faults with downthrow to east and west relate to the formation of troughs filled with Upper Palaeozoic and Mesozoic sediments in the Scoresby Sund region. The distribution of the faults suggests Renland was a horst area in Upper Palaeozoic times. Tertiary igneous activity in south Renland is represented by rare dykes of olivine dolerite and scattered plugs of pyroxenite which locally contain large blocks of host gneisses.

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INTRODUCTION

Scope of the paper

The Caledonian mobile belt and elements of its foreland are exposed over a length of more than 1200 km along the coast and fjord region of East Greenland north of latitude 70° N. In the south of the belt the inner fjord complex of Scoresby Sund, cut into a 2000 m peneplain on the edge of the inland ice, gives access to a complete section across the intricate structure between the foreland in the west and the more internal parts of the belt in the east. Metamorphic effects increase from west to east and the deeply cut fjord topography makes it possible to trace low-grade sediments into their migmatised equivalents intruded by, or completely transformed to, granites in the interior.

This contribution sets out to describe the tectonic evolution of an internal part of the mobile belt as it appears in south Renland, relating the structures to migmatite and granite development and other regional phenomena significant in orogenic processes. Comparisons are made with structures and events elsewhere in the Caledonides of the North Atlantic realm and in other mobile belts, notably the Western Alps. Descriptions of lithology and petrographic details have been kept to a minimum, although some emphasis is placed on critical aspects of the lithology which are relevant in regional correlations.

Although the principal concern of the paper is with the evolution of structures during a climactic tectonometamorphic episode, some remarks are included on the fractures, many of which relate to the formation of intramontane basins that are filled with late Caledonian 'molasse-type' deposits. South Renland lies 30 km north of the nearest outcrops of Tertiary plateau basalts in Milne Land, but the area contains scattered minor intrusions related to the Tertiary igneous events and brief details of the intrusions will be given at the end of the paper.

Field work

The observations on which this account is based were collected during the course of systematic mapping at a scale of 1:50000 of about 1500 km² (500 square miles) in south Renland (plate 1) during two seasons of field work, each of six weeks duration, in the summers of

1969 and 1970. The field work formed part of a five-year series (1968–1972) of geological expeditions to the Scoresby Sund region under the auspices of the Geological Survey of Greenland and directed by NIELS HENRIKSEN. Preliminary descriptions and maps of the field work done in 1968–1971 have been published by the Survey in a series of reports (HENRIKSEN & HIGGINS, 1969, 1970, 1971 and 1973; COE & CHEENEY, 1972).

Topography

The basis of the topography in the inner fjord complex is a prominent 2000 m peneplain which has been strongly dissected by large glaciers spilling from the inland ice and smaller glaciers with sources in plateau ice-caps isolated from the inland ice by deep valleys and fjords. Central Renland is covered by such plateau ice and the area described in this account lies around its southern flank. The largest glacier draining from the plateau is 40 km long and provides the principal access on foot to the east of the area. In a previous publication (CHADWICK, 1971, Map 1) the glacier was called "Main Valley Glacier", but it has since been named "Edward Bailey Gletscher" in respect of the contributions made by the late Sir EDWARD BAILEY to our understanding of Caledonian geology in particular and mountain belts in general. A southern spur from the glacier ends in an ice-dammed lake, 610 m, at the head of Catalinadal, a long east–west valley which is blocked by lakes and piedmont glaciers in its upper reaches but deglaciated further west where it provides easy access on foot to south-west Renland. Edward Bailey Gletscher ends in the north-east in a large decaying snout heavily pock-marked with transitory lakes and blanketed with loose moraine, its path to the inlet from the fjord complex being blocked by a large glacier, Apusinikajik, in the north. The inlet, known as Skillebugt, marks the boundary with the area to the east that was mapped by J. D. FRIDERICHSEN in 1969.

The most severe topography lies in the area of south-east Renland circumscribed by a thick sheet of hypersthene monzonite (plate 1). The sheet forms the rim to part of a large basin occupied by granites and migmatites which make up a massif deeply dissected by steep valley glaciers. Peaks within the massif reach a summit level of 2000 m and are commonly in the form of pillars and aiguilles surrounded by sheer faces in excess of 1000 m high. Movement on foot within the massif terrain is extremely slow and for this reason the interior was visited only during helicopter reconnaissance.

South-west Renland is covered by a small plateau ice-cap which feeds steep glaciers cutting sharply through the precipitous cliffs of Øfjord to the south and the cliffs of upper Catalinadal to the north. West of the

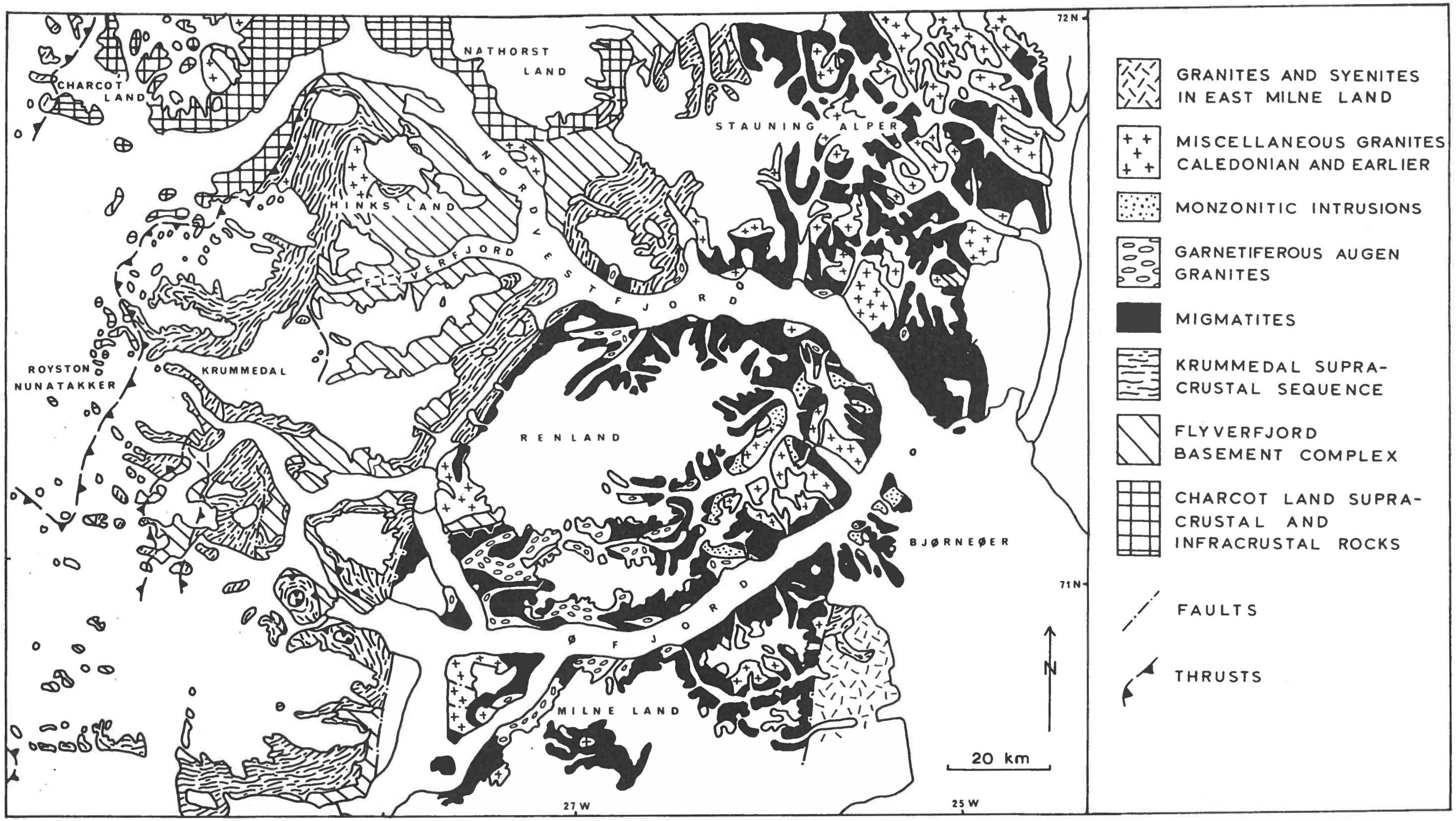

Fig. 1. General geological map of the inner fjord region.

ice-cap the land surface falls to 1500 m and is largely deglaciated making this part of Renland readily accessible on foot, the main routes into the area being Catalinadal and other east–west valleys leading in from Rypefjord. This fjord which links with Øfjord in the south-east marks the boundary of areas to the west mapped by J. D. FRIDERICHSEN, H. RUTISHAUER and K. SØRENSEN in 1970.

Regional setting

The situation of Renland in relation to the geology of the inner fjord complex of Scoresby Sund is shown in fig. 1 which has been compiled from preliminary reports of detailed reconnaissance surveys undertaken during 1968, 1969 and 1970 (HENRIKSEN & HIGGINS, 1969, 1970, 1971). In the extreme west of the inner fjord complex two distinct supracrustal sequences, named informally as the Charcot Land supracrustal sequence and the Krummedal supracrustal sequence by HENRIKSEN & HIGGINS (1969), rest on gneiss complexes which are regarded as basement or infracrustal foundations to the supracrustal sequences. The forementioned authors have given the informal name 'Flyverfjord infracrustal complex' to the basement to the Krummedal sequence. It comprises various granodioritic gneisses, amphibolites and ultrabasic bodies, but it is not represented in south Renland apart perhaps from pyribolitic agmatites in migmatites in the south-eastern massif.

The Krummedal sequence, which is in some respects comparable lithologically with the Lower Eleonore Bay Group, a thick sedimentary sequence of late Precambrian age (see HALLER, 1971), rests with overthrust contact on the Charcot Land sequence, the age of which is uncertain though apparently older than the Krummedal rocks (HENRIKSEN & HIGGINS, 1969). The former division of the Krummedal sequence into two parts (HENRIKSEN & HIGGINS, 1969) is under review, a lower part, about 1000 m thick and distinguished by abundant basic sills intruded into generally homogeneous, grey siliceous gneisses and schists, now being considered as reworked Flyverfjord infracrustal complex (N. HENRIKSEN and A. K. HIGGINS, personal communication, 1972). The upper part, the thickness of which is unknown though in excess of several thousand metres, comprises a monotonous sequence of red-brown pelitic and arenaceous rocks.

As the Krummedal sequence is followed east and south-east from the type locality in the valley of Krummedal (fig. 1) it shows effects of increasing grades of metamorphism until it appears finally to pass into a wide area of migmatites and granites which extends from the Stauning Alper in the north through Renland and into Milne Land in the south where the metamorphites are progressively overlain by Tertiary basalts.

The migmatite and granite terrain in the Stauning Alper is bounded to the east by the faulted margin of the late Palaeozoic-Mesozoic basin of Jameson Land, with Caledonian granites and gneisses of various ages reappearing east of the basin in Liverpool Land. In east Milne Land the migmatite terrain is faulted against non-migmatised, sillimanite- and cordierite-bearing metasediments which are intruded by a suite of granites and syenites.

Preliminary results of a programme of Rb/Sr age determinations by HANSEN & STEIGER (1971) and HANSEN, STEIGER & HENRIKSEN (1972) on minerals from the inner fjord complex show a wide range of ages for rocks previously regarded as products of the Caledonian orogenesis. For example, the migmatite and granite terrain in the Stauning Alper, regarded by HALLER (1958) as late Caledonian, gives ages ranging from 1154 m.y. (biotite) to 474 m.y. (biotite–K-feldspar isochron), and a foliated augen granite from the north coast of central Nordvestfjord, similar to the garnetiferous augen granites in south Renland, has yielded a zircon (U/Pb) age of 950 m.y. (STEIGER & HENRIKSEN, 1972). On the grounds of plots on the 'concordia' curve these authors suggest this age may represent a time of intrusion or last major recrystallisation and, assuming a possible metamorphism 400–500 m.y. ago with episodic loss of Pb or addition of U during Caledonian times, they suggest further that original crystallisation of the zircons may have occurred up to 1200 m.y. ago. In south Renland ages of 435 ± 12 m.y. (K/Ar, biotite) for a migmatised monzonite mass in Skillebugt and 428 ± 10 m.y. (Rb/Sr, biotite) for a grey-pink granite in the south-eastern massif have been obtained by LARSEN (1969) and HANSEN & STEIGER (1971) respectively. Although the ages obtained so far in south Renland are clearly indicative of a Caledonian event, perhaps a late cooling phenomenon, it is conceivable that many of the rocks in the inner fjord complex regarded as products purely of the Caledonian orogeny may have been only partially reworked during the Caledonian deformation and metamorphism, a situation similar to that in the External Massifs and some parts of the Penninic nappe cores in the Western Alps (JÄGER, 1970; HUNZIKER, 1970).

Previous work

Geological observations in the inner fjord complex of Scoresby Sund were first made by E. BAY during an expedition led by C. RYDER of the Royal Danish Navy in 1891–1892. The expedition made exploratory journeys through most of the inner fjord complex and BAY's map together with a brief account was published in the expedition report of activities by RYDER in 1895.

More than forty years passed before further investigations were made in the area of south Renland, this time by members of one of LAUGE KOCH's long series of expeditions to East Greenland over the period 1926–1958. KOCH's expeditions were concerned for the most part with areas north of Scoresby Sund, but among the few visits made by his geologists to the inner fjord complex the motorboat journey made in the summer of 1934 by H. BACKLUND, E. WENK and K. LUPANDER ranks of considerable interest (BACKLUND, in KOCH, 1955). LAUGE KOCH's expeditions were interrupted by the war, but by 1947 geological exploration in East Greenland was gaining momentum again, particularly with the impetus of economic discoveries such as the lead-zinc mineralisation near Mesters Vig. The increasing use of aircraft also led to further activity in the inner fjord complex of Scoresby Sund, notably by WENK and HALLER in 1958. The field work of KOCH's expeditions came to an end in 1958 and full details of the work done by his expeditions in the Scoresby Sund region before and after the war are reviewed in a recent book on the geology of the East Greenland Caledonides by HALLER (1971).

The current series of expeditions (1968–1972) mounted by the Geological Survey of Greenland in the Scoresby Sund region has aimed at completing the investigations in the tract of East Greenland between latitudes 70° and 72° N that were left unfinished by KOCH's teams. Preliminary accounts describing areas within the inner fjord complex in more detail have been prepared by KALSBEEK (1969) for the Bjørneøer, a group of small islands off south-east Renland, and by CHADWICK (1971) for south-east Renland itself. STECK (1971) has provided a detailed account of metamorphism in the Charcot Land supracrustal sequence in the north-west. COLLINSON (1971, 1972) has described the Røde Ø conglomerate in the inner fjord complex and related Permian sediments east of Stauning Alper.

LITHOLOGY IN SOUTH RENLAND

Various paragneisses showing different degrees of migmatisation are hosts to hypersthene-bearing monzonites (mangerites) and a wide variety of granites emplaced at different times in the structural evolution.

Rusty brown garnetiferous gneisses and quartzites

Rusty brown garnetiferous gneisses and quartzites, recorded together as migmatised paragneisses (plate 1), and garnetiferous augen granite are the principal elements of lithology west of the extensive monzonite sheet in south-east Renland. The rusty brown metasediments are interleaved with grey augen granites to form a regionally simple layer-cake structure which has been complicated by large-scale polyphase deformations. Generally, there is a distinct colour contrast between the two groups which aids mapping, although superficial pale brown staining on the granites can sometimes lead to misidentification.

The metasedimentary rocks show a diversity of composition ranging from pure psammites through impure psammites and semi-pelites to heavily migmatised pelitic gneisses that merge into granites. Seen as a whole the metasediments weather rusty brown or red, but to different degrees depending on garnet and biotite content. Locally extreme red colours in pelitic schists appear to be due to disseminated hematite. Quartzitic gneisses are paler pink or grey. Garnetiferous, quartzo-feldspathic pelitic gneisses with biotite and sillimanite predominate over quartzites and meta-arkoses. The usual occurrence of the more psammitic varieties is as thin layers, rarely more than 1 metre thick, within the pelitic gneisses. The term pelitic gneiss is used in a general sense to encompass an extreme range of composition and appearance of the rusty brown garnetiferous rocks. One extreme is represented by brick-red micaceous schists with abundant prolate ellipsoidal nodules of fibrous sillimanite: the other is a heavily migmatised gneiss which in hand sample seen in isolation from the outcrop is essentially granite; it is only the presence of swarms of lenticular biotite-rich schlieren and the relation of the migmatite to paragneisses in adjacent outcrops that serve to distinguish the original sedimentary affinity. Between these extremes there are various quartz-rich schists, garnetiferous schists and flecky gneisses, and quartzo-feldspathic psammitic gneisses. Most of the range of pelitic gneisses carry proportions of garnet, sillimanite, potash feldspar and rarer cordierite.

The whole sequence of metasediments is built up of irregular alternations of thin layers of psammitic and pelitic gneisses (fig. 2). Within this monotonous pile there are local sequences of thicker quartzites and meta-arkoses up to 300 m thick. Very rare, discontinous layers and schollen of marble occur in south-west Renland, but there is little other variation apart from some rare hypersthene-bearing pyribolites and amphibolites. The total thickness of the metasedimentary sequence west of the extensive monzonite sheet is difficult to estimate because of the effects of migmatisation, granite intrusions and large-scale folding, but minimum thicknesses in south-west Renland are probably in the order of 1500 m. No base to the sequence was recognised.

The different degrees of migmatisation are a function of original sedimentary lithology, the quartzites and meta-arkoses showing fewer effects while the more pelitic gneisses in adjacent outcrops may be almost

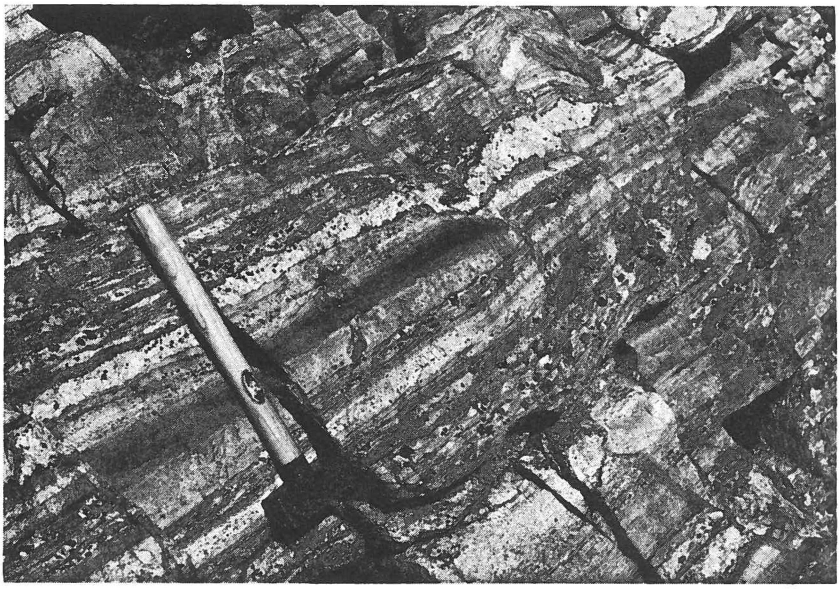

Fig. 2. Typical outcrop of rusty brown migmatised paragneisses showing psammitic and pelitic restite and garnetiferous alaskitic mobilisate. Dark spots in the gneisses are garnets. North-east of synform in south-west Renland.

entirely transformed to garnetiferous alaskitic granite. The migmatite mobilisate, which forms discontinuous lenticular sheets parallel to bedding foliation, is normally less than 5 cm thick and consists of saccharoidal quartz and feldspar with garnet and local graphite, the composition being that of garnet alaskite (JOHANNSEN, 1932). Small lenticular aggregates of garnet alaskite commonly occur within the restite, and incipient neosome formation is commonly represented by flecky aggregates of garnet and feldspar which locally reach an extreme where garnets up to 5 cm in diameter are surrounded by haloes of coarse-grained microcline perthite elongated parallel to the regional mineral lineation (fig. 3). The seams of garnet alaskite concordant with bedding provide an additional element in the paragneiss foliation to which the term *migmatite foliation* may be applied. Mineral fabrics formed by biotites, especially in pelitic schists, form local schistosities that are also parallel to bedding foliation. With increase in the proportion of mobilisate the seams become discordant and adjacent seams join across the bedding foliation to form an anastomosing series of veins in diffuse contact with the restite. A small increase in the proportion of mobilisate leads to an almost complete transformation to homogeneous granite. Such granite, which is commonly garnetiferous alaskite, does not form areas large enough to be mapped separately except on the north-east of Rypefjord (described later under

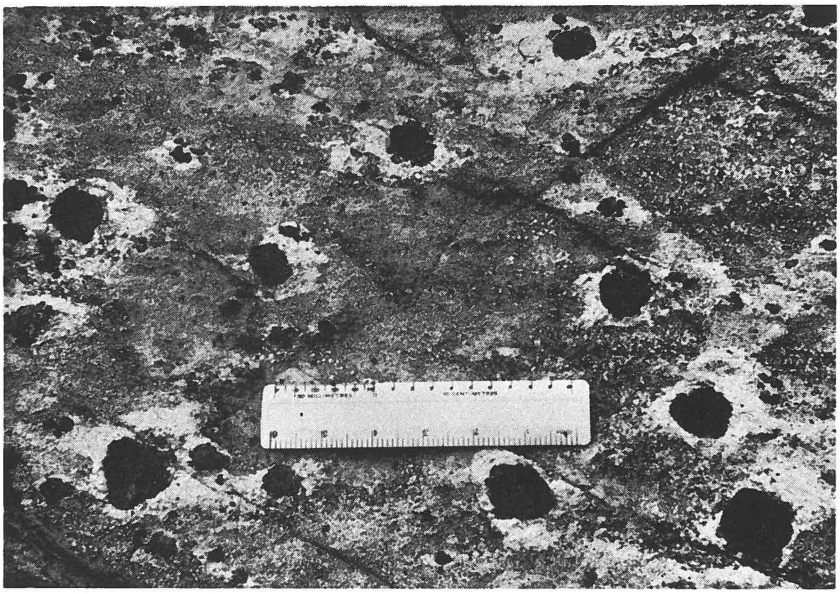

Fig. 3. Large garnets surrounded by feldspathic haloes in pelitic gneiss. Note elongation of haloes parallel to *X* finite strain extension on foliation surface. North of synform in south-west Renland.

the heading of Miscellaneous Granites). Quartzitic layers in outcrops of partly transformed pelites tend to be thoroughly disrupted and broken into lenticular forms.

Boundaries between quartzites and intervening pelites are relatively sharp although some may be gradational or interrupted by mobilisate. In spite of the intensity of migmatisation and potential transposition on foliation surfaces during deformation, there is evidence of cross-bedding within the paragneisses in the extreme south-west of Renland. Such structures, though seen rarely on account of the scale of the mapping, have been invaluable in determining the facing direction of tectonic structures. Other possible sedimentary phenomena include small concentrations of apatite and opaque grains.

The remaining elements of lithology in the metasediments include marbles and dark basic gneisses. These were seen only rarely and their role as sedimentary phenomena is less significant than the value of their mineralogy in determining metamorphic facies. The marbles occur either as discontinuous layers 10 cm thick or as balls up to 1 m in diameter within neosome mobilisate. The marble is siliceous and contains coarse-grained poikiloblasts of plagioclase sieved with calcite and quartz; other minerals include scapolite, diopside, forsterite(?), sphene, garnet and colourless mica. Basic gneisses locally invaded by neosome form layers 1–2 m thick concordant with bedding and migmatite foliation. Two varieties were distinguished: one is a plagioclase-rich, diopside-hornblende-garnet-quartz gneiss and the other is a hypersthene-bearing pyribolite. These gneisses may be metavolcanic.

The migmatised paragneisses forming the metasedimentary sequences in south Renland are closely comparable with the regionally metamorphosed, but non-migmatised, sequence of supracrustal rocks named informally by HENRIKSEN & HIGGINS (1969) as the Krummedal supracrustal sequence, the closest comparison being with the upper part of this sequence. Reference to summary tables of the rocks in the so-called 'Caledonian geosynclinal pile' (HALLER, 1970, Table II; 1971, Table 3) suggests that the rocks of the upper part of the Krummedal sequence and the migmatised paragneisses in south Renland are lithologically similar to the Arenaceous-Argillaceous Series (Alpefjord Formation of KATZ, 1961) of the Lower Eleonore Bay Group. These comparisons are based on original sedimentary lithology and it must be emphasised that at this stage in the programme of radiometric age investigations in the inner fjord complex precise stratigraphic correlations are uncertain.

Garnetiferous augen granite

Like the rusty brown paragneisses, the garnetiferous augen granites are prominent west of the extensive monzonite sheet but they are not seen within the area of Renland east of the sheet. The granites are interleaved with the paragneisses as sheets commonly between 50–500 m thick and locally in excess of 1000 m. The sheets are concordant with foliation in the paragneisses on a regional scale but some contacts show local discordances of up to 15°. Garnetiferous alaskitic apophyses emanating from some sheets may also cut at low angles across gneiss foliation.

The grey colour of the sheets provides a strong contrast with the rusty brown of the paragneisses, and the layer-cake arrangement of the granites and gneisses, though complicated by folding, bears resemblance to a bedded sequence when viewed on the scale of a 2000 m fjord wall. Apart from local aplite dykes, pegmatites, camptonitic lamprophyres and irregular marginal bodies of ganetiferous alaskite, the sheets are remarkably homogeneous in terms of composition and internal fabrics. The principal mineral constituents are microcline perthite forming large megacrysts or augen aggregates, plagioclase, quartz, biotite, globular red-brown garnet up to 1 cm in diameter and rarer sillimanite.

The principal fabric found in all outcrops of the granite sheets is a schistosity defined by parallel films of biotite, stringlets and small lenticular concentrates of quartz and feldspar and abundant augen aggregates of microcline. Garnets are locally oblate within the plane of the fabric. On a regional scale the schistosity is parallel to sheet boundaries and foliation and biotite fabric in the paragneisses, but its precise relation to the locally discordant sheet contacts was not seen. Lamprophyre dykes (CHADWICK, 1971) possess a similar mineral fabric, though formed by lenticular aggregates of pyroxene and feldspar, which is parallel to schistosity in the host granite. The schistosity is parallel to axial surfaces of folded garnetiferous aplites and lamprophyres within the granite, but it has not been possible to relate it to any folds of regional extent: in most folds, especially the regional structures, the schistose fabric of the granite is deformed. Such a relation indicates development of the fabric early in the structural history of the region, either during or soon after the augen granite emplacement. Detailed discussion of the mechanics of origin will be deferred to later pages. An additional fabric element common in the augen granites of west Renland comprises a preferred dimensional orientation of long axes of prolate ellipsoidal augen of microcline. Though common in blocks of augen granite in moraines, the linear fabric was not seen *in situ* in the area of Edward Bailey Gletscher, possibly because of the scale of the mapping in this part. Biotite and fibrous sillimanite may also be parallel to the augen elongation. The lineation lies within the plane of the granite schistosity and is parallel to regional fold axes.

The petrography of the granites in south-west Renland does not differ from that in the east (CHADWICK, 1971), but two points may be emphasised here, both of them significant in the history of the augen granites. In most thin sections from outcrops of augen granite over the whole area biotite shows disequilibrium textures with exsolution of quartz either in micro-slabs parallel to (001) or as vermicular intergrowths. The exsolution occurs commonly in biotite in the neighbourhood of garnet, the textural relation indicating that garnet itself formed at the expense of biotite. On these grounds it seems likely that dehydration reactions have taken place with biotite reacting to form garnet and potash feldspar. Some considerable part of this reaction took place after injection of the sheets, but the abundance of garnet in mobilisate of the migmatised paragneisses suggests the reaction may also have taken place during anatectic melting along the lines of 'water deficient' reactions of the type suggested by FYFE (1970). Additional evidence for such reactions producing 'dry melts' comes from the fact that aplitic apophyses within and radiating from the augen granite sheets contain biotite only rarely, garnet, microcline and, in some instances, sillimanite being the principal constituents.

Feldspar exsolution phenomena such as myrmekite and marginal albitic rims to potash feldspars are also common in the Renland augen granites. Other textures associated with the feldspars include sillimanite precipitated at feldspar–feldspar grain boundaries; sillimanite does not appear to be associated with the breakdown of biotite. In a recent study of feldspar exsolution, STURT (1970) relates sillimanite nucleation and growth to an excess of Al_2O_3 in plagioclase which has been exsolved during age-hardening processes. Such processes were certainly prominent later in the history of the augen granites during and after their involvement in the polyphase deformations.

Streaky augen granite

Flaser fabrics parallel to the schistosity are visible locally in the augen granites in Øfjord, but the largest development of an extreme streaky aspect occurs in augen granites close to certain contacts with paragneisses in south-west Renland. The widest area occurs on the north of the large synform in the extreme south-west (plate 1), and thinner zones lie around the southern boundary of the synform in paragneisses further north. Contacts with the normal granite are gradational over a few metres but boundaries with paragneisses are sharp; thin sheets of garnet alaskite intervene locally between the gneisses and streaky granite.

The streaky rock is pink and the garnets are darker red-brown than those in the normal augen granites, the darker colour being an effect of finely disseminated iron oxides along micro-fractures in the garnets. The streaky aspect is derived from the degeneration of the usual feldspar augen to smeared lenses of coarse- to medium-grained feldspar and quartz with small garnets. Films of biotite complete the schistose fabric.

The schistosity in these streaky rocks is folded with the usual schistosity in the augen granites and the foliation in the paragneisses. It appears to be cogenetic with the granite fabric and may be attributed to more intense deformation or protoclasis during the evolution of the schistosity in the neighbouring granites.

Hypersthene monzonite

The most dramatic occurrence of hypersthene monzonite is in the form of an extensive sheet up to 500 m thick which circumscribes the large area of severe topography cut into granites and migmatites in south-east Renland. Dykes and isolated bodies of hypersthene monzonite which may be the remains of other thick sheets, occur within this area. Such rocks are not found to the west of, i.e. structurally below, the extensive sheet apart from two thin sheets exposed high on the coast of Øfjord. Some details of the petrography and chemistry of the monzonite have been published already (CHADWICK, 1971).

The extensive sheet, which may be traced continuously for at least 25 km north-east from the Øfjord coast, is broadly concordant with foliation in the adjacent gneisses, but local discordances occur for example on the coast of Øfjord west of peak 1882. Furthermore, the gently dipping paragneisses and augen granites on both sides of the southern spur of Edward Bailey Gletscher are cut by high-angle dykes that are regarded as apophyses of the overlying sheet. The dykes are not deformed and indicate intrusion of monzonite after the regional nappe development in the gneisses and augen granites. A dark margin to the sheet high on inaccessible cliffs further north suggests chilling against the paragneisses. Such evidence for an intrusive origin after the principal deformation shows that the monzonites outcropping on the coast of Øfjord can no longer be regarded as ophiolites associated with the Lower Eleonore Bay Group as suggested by HALLER (1971, fig. 32). Additional marginal phenomena in the upper part of the sheet exposed on the north of Edward Bailey Gletscher include agmatisation of the monzonite by pink granite that is the equivalent of neosome in the migmatites within the area surrounded by the sheet. Veins of this granite also penetrate the isolated bodies of monzonite in the inlet in the extreme north-east. Injection of the hypersthene monzonite therefore took place after the principal regional migmatisation and deformation in the west of Renland, but was followed by further migmatisation and granite development that was restricted in the main to the area east of the extensive sheet.

The sheet may be traced north-east of Edward Bailey Gletscher through a group of largely inaccessible outcrops isolated by steep glaciers and thence across the large glacier Apusinikajik to the area mapped by J. D. FRIDERICHSEN in 1969 where it becomes more acid. The general disposition of the sheet is shown on a preliminary compilation by HENRIKSEN & HIGGINS (1970, Map 1). Hypersthene-bearing dioritic rocks similar to those of the sheet are also present on the north-west of the Bjørneøer (KALSBEEK, 1969) and it is conceivable that there is a connection through Øfjord between the Renland sheet and parts of the Bjørneøer diorites. Even in the absence of such a link, the shape of the extensive sheet in Renland suggests it forms part of a lopolith centred on Skillebugt. Gneisses within the basin accommodated higher-level intrusions cogenetic with the sheet which were migmatised and disrupted during the generation of later granites, the grey-pink granites described below.

The monzonites are dark green, coarse-grained equigranular rocks, but with local megacrysts of K-feldspar. Shadow-zoned plagioclase, locally antiperthitic, occurs in approximately equal proportions with microperthitic microcline and orthoclase, the feldspar altogether making up 55–60 % of the mode. Textures show that K-feldspar formed late in

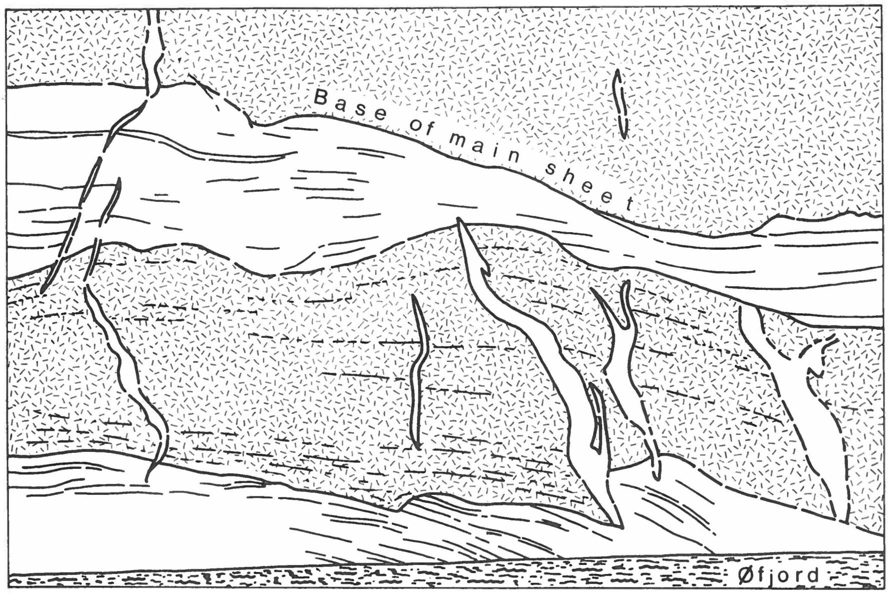

Fig. 4. Quartz–K-feldspar–muscovite–biotite pegmatites 15 m thick cutting apophysis of main monzonite sheet on coast below peak 1882. Note local discordances between monzonite (ornament) and foliation in paragneisses. Sketch from photograph.

the crystallisation history. Quartz may form up to 12 % of the mode in veined monzonite. Hypersthene and diopsidic augite together make up 10–20 % of the mode, but locally may exceed 40 %. Hypersthene is slightly less abundant than the clinopyroxene. Both may be overgrown by biotite or replaced by hornblende or cummingtonite in the vicinity of later granite veins. Biotite, whose modal proportion does not exceed 18 % except in the vicinity of granite veins, is a relatively late mineral but it also shows disequilibrium textures of vermicular and micro-slab quartz exsolved parallel to (001) cleavage like that noted in the augen granites. Such breakdown suggests the biotite may be contributing to the formation of late K-feldspar.

Internal features of the sheet include local megascopic layering and some regional variations in composition (CHADWICK, 1971), but systematic collections for the study of internal variations were not possible. The main sheet is cut transversely by planar, undeformed pegmatites up to 15 m thick, comprising quartz, microcline, muscovite and biotite, (fig. 4). The pegmatites are relatively common but rarely penetrate beyond the sheet margin, although some examples of projection beyond the contact of a monzonite body were seen below the summit of peak 1882: in this case the rectilinear pegmatites in the monzonite changed abruptly to aplite which penetrates as irregular veins for about 1 m into the surrounding migmatites. These relations suggest the pegmatites are related either to regional migmatisation or were precipitated from hydrous solutions concentrated in hydraulic fractures that were generated by high pore pressures during crystallisation of the monzonite sheet.

Bodies of monzonite in the terrain east of the sheet take the form of disrupted sheets, dykes or isolated masses which are veined by pink or grey granite. Their composition is similar to that of the sheet monzonite except in the vicinity of the granite veins where the pyroxene and biotite show varying degrees of alteration to hornblende or cummingtonite. An agmatised body veined by grey granite neosome from surrounding migmatites on the coast east of peak 1882 shows a pronounced lack of feldspar in the dark components, otherwise the composition is similar to the other monzonites (CHADWICK, 1971).

In a preliminary description of the monzonites (CHADWICK, 1971), it was suggested that they might have an affinity with the charnockite suite on the basis of their regional associations with rocks of the granulite facies, the abundance of hypersthene in a stable condition and the presence of pyribolite xenoliths with stable mineral assemblages of hornblende-granulite facies. In a review of the classification of the charnockite-anorthosite suite, DE WAARD (1968) recommends the use of the term mangerite (after KOLDERUP, 1904) for hypersthene-bearing, magmatic or metamorphic plutonic rocks with monzonitic composition. However, biotite occurs commonly in excess of 8 $^0/_0$ indicating more water than is normally found in rocks such as the mangerite-jotunite suite, the intermediate igneous representatives of the charnockite suite. Such a condition suggests the hypersthene monzonites in Renland may relate more closely to a biotite diorite series of igneous rocks regarded by BARTH (1966, p. 222) as the anatectic products of metasediments during 'synorogenic plutonism.' BARTH views the parental magma of the series as a water-rich diorite which yields copious precipitates of biotite, locking up potassium with a consequent lack of potash feldspar. However, this mineral is common in the Renland monzonites, crystallising last in the sequence of principal minerals, and its presence may be attributable to breakdown of biotite, which commonly shows disequilibrium textures, during the period of migmatisation and granitisation that affected east Renland after the injection of monzonite.

Alternatively, the abundance of biotite and potash feldspar, both late-stage minerals in the monzonites, might be attributed to regional potash metasomatism associated with the prolific development of granites and migmatites in the massif of south-east Renland. XRF-analyses (CHADWICK, 1971, table 3) show potassium (K_2O) content in the order of 4.5 $^0/_0$ with MgO about 5.5 $^0/_0$, the latter approaching the values for 'basic' igneous rocks. Such a profound introduction of potash could mean a more basic original composition for the monzonites and in such a case these rocks should be regarded as mangeritic-noritic members of the charnockite-anorthosite suite (DE WAARD, 1968). A detailed chemical analysis of such a metasomatic transformation is beyond the scope of this paper, but such a possibility must be borne in mind in consideration of the origin of the monzonite intrusions.

In either event the monzonites in south-east Renland could be regarded as the products of deep-seated, differential anatexis that were injected as magmatic rocks after the early migmatisation and augen granite formation in the west. The monzonites may represent the more basic, more dense accumulations from ultrametamorphosed sediments and basement rocks whose less dense, more acid differentiates are represented by the augen granites in the west which were injected earlier because of their higher density contrast with the surrounding host rocks and therefore rose more rapidly than the monzonites. Subsequent rise of monzonitic magma (or its more basic parent) and intrusion at higher levels may have been achieved as a result of changes in regional stress conditions. The position of monzonite injection in the sequence of regional metamorphism and granitisation suggests the original magma crystallised under granulite facies conditions, in which case a charnockitic affinity is indicated.

Migmatites in east Renland

The severe topography of the massif east of the sheet of the hypersthene monzonite in south-east Renland is cut into a complex of migmatites and granites that differ significantly from the migmatised paragneisses and augen granites west of the sheet, the difference lying in the effects of a migmatisation/granitisation event which occurred after the monzonite intrusion. Access to the interior of the massif is difficult and the only details of the geology of the interior have been obtained during helicopter fly-past, a few landings on the coasts of Øfjord and Skillebugt and inspection of oblique aerial photographs.

In the field the migmatites were subdivided into a 'coastal migmatite complex' and a group of 'grey-brown granitised gneisses', but for the purposes of this account they have been grouped together (plate 1). The coastal migmatites contain a high proportion of granitic mobilisate with the restite occurring in most instances as discontinuous layers, schollen or agmatites. There are all gradations between layered to raft migmatites thoroughly shot through with pink-grey or grey granite *sensu lato.* Strings of enclaves indicate pre-existing lithological layering which comprises both original bedding and concordant mobilisate generated prior to the disruption. This foliation may be folded or otherwise dis-

Fig. 5. Gneissic schollen in grey-pink granitic mobilisate in migmatites on Øfjord coast 4 km south-west of Skillebugt. Note folds and earlier mobilisate in blocks on left.

rupted by boudinage, the deformation having taken place before the migmatisation event represented now by the abundant mobilisate surrounding the gneiss rafts (fig. 5). The newer mobilisate itself may be foliated or isotropic in terms of fabric, and where the original gneisses were pelitic the inclusions are reduced to schlieren or biotitic wisps which swim in a sea of granitic neosome (fig. 6). Areas of such appearance may be very large and grade into the sheets of grey-pink granites described below.

In addition to pelitic and psammitic migmatites, inclusions of pyribolite are common in the coast outcrops of the migmatite complex. The inclusions may be widely scattered in large volumes of newer granite mobilisate, but in some instances agmatised pyribolite forms layers up to 5 m thick which may be followed continuously for 200–300 m. The pyribolite enclaves, which possess a pre-agmatisation schistosity, are formed largely of plagioclase, bronzitic hypersthene, diopsidic augite and greenish brown hornblende, all showing stable intergrowth and common Y-junctions. Reactions with the surrounding neosome appear in the form of pale green margins 2 cm wide with feldspar-rich haloes of similar width in the neosome. Similar inclusions with biotite taking the place of hornblende also occur in the migmatised bodies of monzonite in Skillebugt and on the north of the snout of Edward Bailey Gletscher. The mineral assemblage in the pyribolites, which is that of the granulite

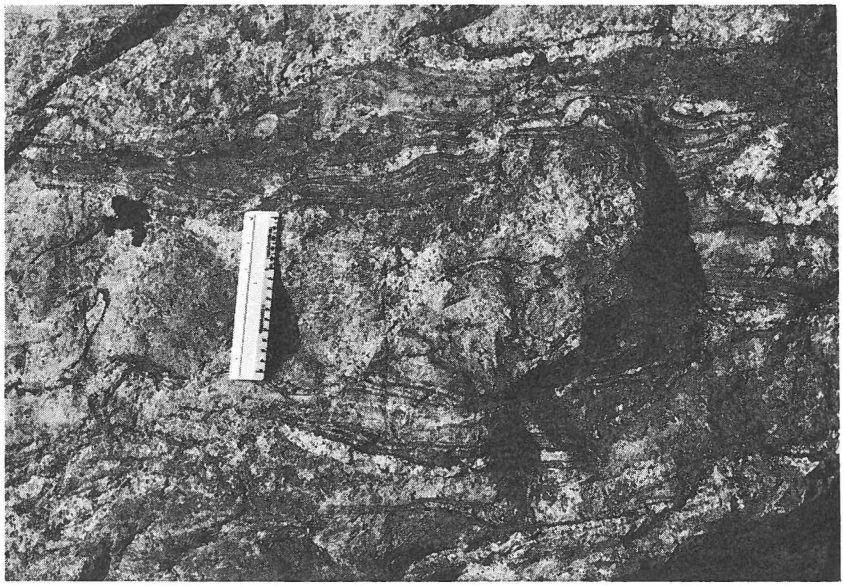

Fig. 6. Pelitic gneiss degenerating to schlieren in east Renland migmatite complex. This example from outcrops high above the coast 5 km north-east of peak 1882 is typical of the effect of the migmatisation in the massif region.

facies, may have been downgraded slightly by later granitisation to give the reaction rims. The pyribolite inclusions suggest that the original rocks of the migmatite complex in the massif region may have had affinities with either ophiolite-bearing rocks in the Lower Eleonore Bay Group (*sensu* HALLER) or the basement complex represented further north-west by the Flyverfjord complex.

The migmatite complex exposed along the Øfjord and Skillebugt coasts compares closely with rocks mapped on the Bjørneøer by KALSBEEK (1969) as 'Variable migmatites, generally with remnants of metasedimentary rocks'. A further point of agreement with KALSBEEK lies in his observation that the bulk of the neosome may be allochthonous; the volume of neosome in south-east Renland commonly exceeds that of restite remnants and also suggests introduction of granitic material from outside the area.

The other group of gneisses included in the massif migmatite complex bears a closer resemblance to the paragneisses west of the monzonite sheet than the migmatites exposed along the Øfjord coast. They are best seen immediately above the monzonite sheet in the north-west of the massif; as they are followed to the east they become increasingly overwhelmed by grey-pink granite described below. Concordant sheets of this granite within the gneisses vary from 2–200 m in thickness (fig. 7) and

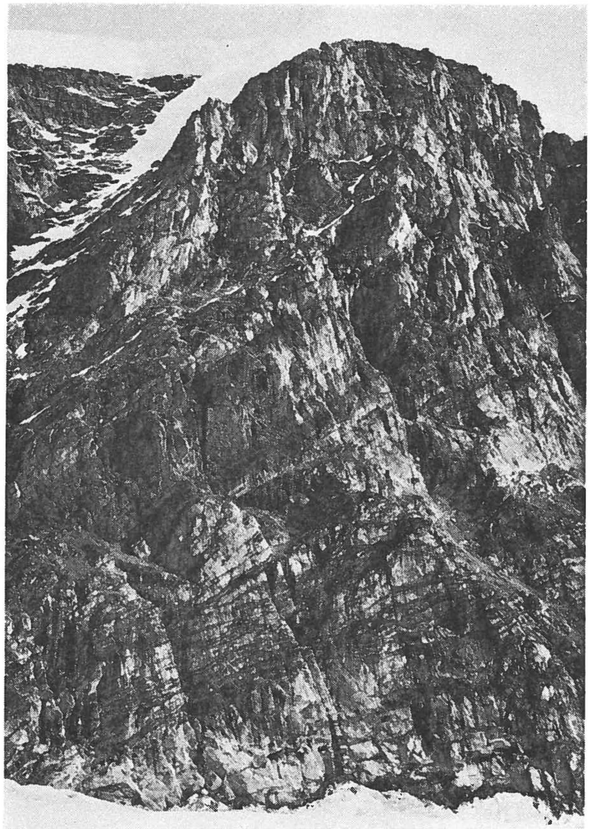

Fig. 7. Grey-brown, migmatised paragneisses and concordant sheets of grey-pink granite in the central part of the massif in south-east Renland. Granite dominates the upper part of the cliff face which is about 600 m high. About 5 km north of peak 1882.

the different proportions of granite to gneiss commonly made the allocation of a lithological boundary very difficult. Because there are all gradations between migmatised gneisses, gneisses with concordant granite sheets and nearly homogeneous granite, it was decided in the field to map the gneisses on the basis of an arbitrary subdivision of $< 60\,\%$ granite on the scale of a cliff face.

The gneisses are grey-brown, typically foliated, pelitic to psammitic and with variable proportions of concordant granitic neosome. Because of their inaccessibility they were not seen in any detail, but their structural position and resemblance to the paragneisses further west permits a tentative correlation with metasediments of the Krummedal sequence. Their relation to the migmatites with abundant pyribolite inclusions on the coast is far from clear.

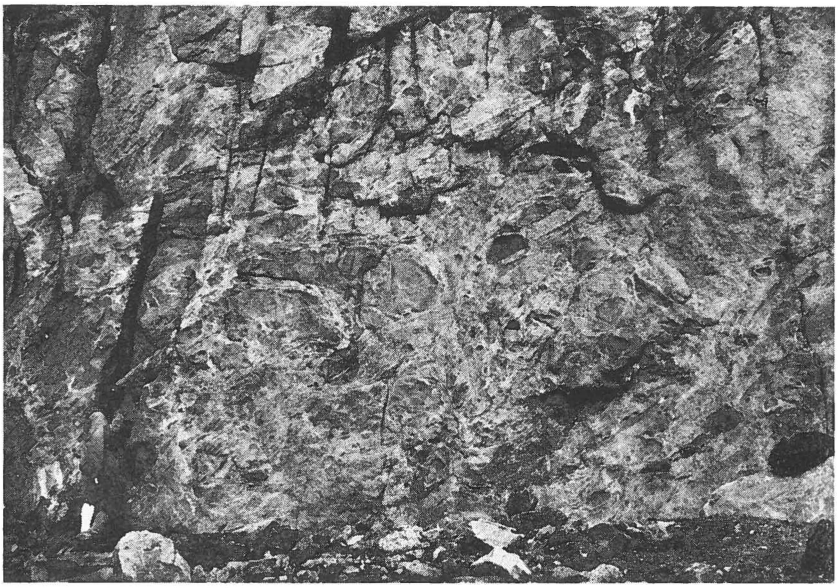

Fig. 8. Grey-pink granite in south-east Renland containing abundant gneissic schollen and schlieren. 4 km west of head of Skillebugt.

Grey-pink granites

This particular variety of granite is confined to the massif in south-east Renland. It is interleaved with grey-brown migmatites and becomes a dominant rock type to the east. Shoreline outcrops in Skillebugt show the granite connecting with the neosome in the migmatites of the Øfjord coast, and in the other direction towards the snout area of Edward Bailey Gletscher the granite may be traced into areas where it veins the hypersthene monzonite. On the north of the glacier where outliers of the monzonite sheet are exposed there are clear views of the granite veining the upper part of the sheet continuation. The granite also veins large, isolated bodies of monzonite in the interior of the massif.

The grey-pink granite commonly adopts a sheet form concordant with foliation in the surrounding gneisses. The sheets may be up to 500 m thick, and in the west may be as thin as 2 m where they are interleaved with grey-brown gneisses. The granite sheets may be homogeneous, but more commonly they contain abundant schlieren or quartz-rich enclaves from psammitic restite; evidence of *in situ* transformation of the gneisses into granite is conspicuous in the few outcrops examined in the interior of the massif (figs 8 & 9), but because of the abundance of granite particularly in the east, it seems likely that some of it is allochthonous. Comparison of figures 5, 6, and 8 show the close relation between the

Fig. 9. Detail of biotitic restite forming a schliere in grey-pink granite (lower right fig. 8).

migmatites and grey-pink granites and illustrate the blurring of boundaries between the different units within the south-eastern massif.

Microcline is dominant over plagioclase; quartz is abundant and biotite is the mafic component; garnet occurs as an accessory in some outcrops, but apatite and zircon appear to be universal. A large sample from the granite illustrated in fig. 8 which occurs high to the west of Skillebugt was collected in 1970 for radiometric age determination on the zircons. HANSEN & STEIGER (1971) have already published a Rb/Sr age of 428 ± 10 m.y. for biotite from the same outcrop.

Miscellaneous granites

Other rocks of broadly granitic composition, texture and mode of occurrence outcrop in addition to the garnetiferous augen granites and grey-pink granites in south Renland. Two larger areas are shown on the north-east of Rypefjord and in the highest reaches of Edward Bailey Gletscher (plate 1), and a smaller area, covered to a large extent by plateau ice, caps the paragneisses in the cliffs of central Øfjord. Other areas of miscellaneous granite too small to be shown on plate 1 occur in the massif of south-east Renland. Although they are all granitic in the widest sense there are marked differences between the granites of the different areas which include not only certain features of composition but also their age and *mise-en-place.*

The area of granitic rocks at the head of Edward Bailey Gletscher was seen only on helicopter reconnaissance and many aspects, including the contact relations with the nearby augen granites and paragneisses, are far from clear. The granite has been described briefly by CHADWICK (1971) under the heading of 'Pink granitic rocks' and there is little to add here apart from emphasising that the contacts with adjacent augen granite sheets on both sides of the glacier appear to be sharp and trend north-east with moderate dips to the north-west. This orientation is relevant in consideration of the possible structural correlation with the miscellaneous granites of north-east Rypefjord described below.

Traverses by boat along the coast of Rypefjord and on foot across the highlands inland (in the area of 1460 m, plate 1) lead through outcrops of paragneisses that become increasingly granitic towards the north-west. In many instances where the transformation to garnetiferous granite is complete the only remains of paragneiss are wispy schlieren of biotite and quartzitic schollen. Other outcrops within the large areas of paragneiss in south Renland show similar transformations, but it is only in north-east Rypefjord and the area further north-west mapped by J. D. FRIDERICHSEN in 1970 that granite is of sufficient extent to be shown as a separate map formation. In outcrop the granite is creamy yellow to pink, contains variable proportions of small red garnets and has saccharoidal texture. A thin section confirms the xenomorphic-granular texture and shows quartz in excess of microcline and plagioclase. Both feldspars are partly altered to sericite and an unidentified brown dust. Garnet is the only coloured mineral and forms small irregular grains which are altered in part to iron oxides along fractures. The composition and mode of occurrence suggest the rock be described as garnet alaskite (JOHANNSEN, 1932).

Inspection of the geological map (plate 1) shows that extrapolation north-east of the gradational boundary between paragneisses and the garnet alaskite on the north-east of Rypefjord leads to a probable link with the pink granitic rocks at the head of Edward Bailey Gletscher. Although biotite is more common in these rocks, there is a broad compositional similarity between the two masses which, taken in conjunction with the trend of their boundaries, suggests they form parts of a large mass of granite-alaskite concealed beneath the plateau ice. The connection in three dimensions is illustrated in plate 2 (blocks A, B, C) which also show how the dip of the boundary changes from north-west to south-east between the head of Edward Bailey Gletscher and Rypefjord. The change in dip took place during the latter stages of the structural evolution when the synformal basins were forming in south-west Renland as a result of the rising body of granite-alaskite forming a barrier to the further northward progress of the regional nappes.

J. D. FRIDERICHSEN (personal communication, 1971) has mapped a narrow zone of rocks with basement affinity between the alaskite-bearing paragneisses in north-west Rypefjord and granite (alaskite) rocks further north-west. He suggests the paragneisses were initially brought into thrust contact with the basement rocks and the thrust was subsequently obliterated to some degree by the generation of alaskitic material in the paragneisses. The position of the thrust is marked in fig. 1.

High on the cliffs of central Øfjord a sheet of garnetiferous grey granite with a minimum thickness of about 250 m forms a capping to the rusty brown paragneisses (fig. 18; plate 1). The granite appears to be homogeneous, non-porphyritic with approximately equal proportions of microperthite and plagioclase and abundant quartz. Garnet is common in hand sample and has grown at the expense of biotite which is also common and is the only mafic constituent. Prismatic zircon is a prominent accessory. The garnetiferous grey granite capping the paragneisses on the cliff tops of central Øfjord bears considerable resemblance to many of the grey granites in the massif of south-east Renland which were described as 'Younger granites' (CHADWICK, 1971) because of their discordant relation to migmatites on the coast of Øfjord. Although the discordant younger granites are among the final manifestations of plutonic activity in south Renland, they comprise different suites each with a slightly different age of injection, making precise correlation with the capping in central Øfjord difficult. Within the massif area, the principal younger granites are grey, commonly feldsparphyric, garnetiferous and isotropic in terms of fabric, so that on the grounds of composition and textures there is a broad correlation between these granites and the central Øfjord capping. It is also likely that both areas of granite correlate with the so-called post-kinematic granites which form thick sheets capping the mountains of northern Milne Land (HENRIKSEN & HIGGINS, 1971, p. 13).

Microgranites, aplites and pegmatites

Microgranites, aplites and pegmatites were developed through the whole of the plutonic history of the area beginning with the augen granites and ending with the younger granites of south-east Renland and Milne Land. This section refers only to the undeformed late-stage dykes which cut with marked discordance through the various migmatites and granites of south Renland, reference having been made already to dyke rocks and other smaller masses generated during earlier plutonic activity.

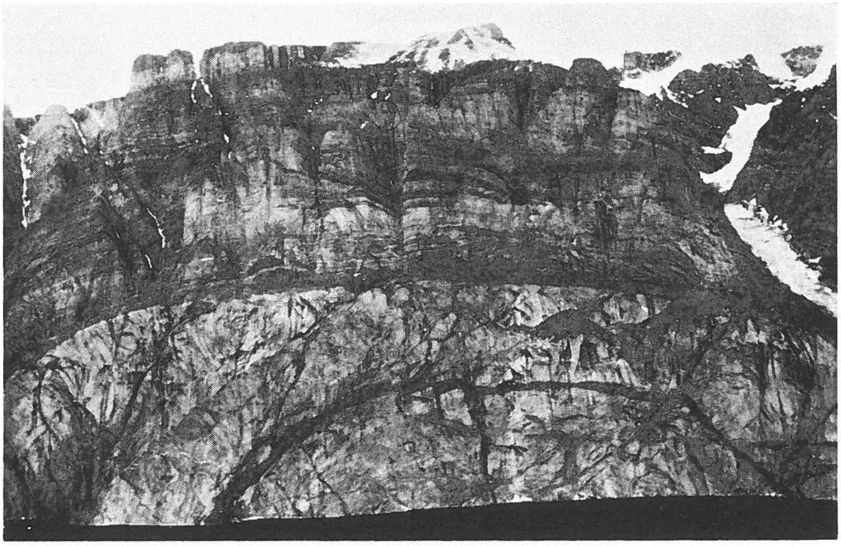

Fig. 10. Arch of garnetiferous augen granite below migmatised paragneisses, central Øfjord. Cliff face is about 1600 m high. Isoclinal folds in the paragneisses are warped over the arch which is one of the late north-north-west structures that appear in the coast profile. Microgranite dykes occur in granite in arch centre.

Of the late-stage phenomena, pegmatites have the widest distribution, being found in outcrops across the whole area as steeply dipping rectiplanar dykes between 1–5 m thick. The principal constituents are quartz, feldspar, biotite and muscovite with local tourmaline.

Grey microgranite dykes, which are commonly graphite-bearing like the mobilisate in some of the adjacent migmatites, appear to be restricted to the massif of south-east Renland and its surroundings. Among the more significant outcrops are those in the great arch of augen granite in central Øfjord (fig. 10). The dykes are situated in the crest and flanks of the arch, but do not appear to extend above the augen granite into the overlying paragneisses. The dykes are vertical and appear to follow planes where offsets have taken place in the thin layer of gneisses in the central part of the augen granite. Their orientation suggests they may be associated either with the development of the arch (syntectonic) or they may be following fractures developed during the arch formation (post-tectonic). Some show a schistose fabric parallel to the dyke walls, and an additional element of the mineralogy includes the presence of local muscovite.

METAMORPHIC GEOLOGY

Metasedimentary rocks over the entire area of south Renland show varying degrees of migmatisation, the incidence of mobilisate development depending on original sedimentary composition. Metamorphic mineral assemblages within the restite of migmatised metasediments and other rocks west of the extensive monzonite sheet are represented by the following samples:

1. Pelitic and semi-pelitic gneisses

   134603 Quartz–microcline–plagioclase–garnet–sillimanite
   134628 Quartz–microperthite–plagioclase–garnet–biotite
   134634 Quartz–microperthite–plagioclase–garnet–biotite–graphite
   134653 Quartz–microperthite–plagioclase (antiperthite)–garnet–biotite–sillimanite–cordierite
   134680 Quartz–microperthite–plagioclase–garnet–biotite–sillimanite–graphite

2. Psammitic rocks

   134637 Quartz–plagioclase–clinopyroxene–carbonate
   134642 Quartz–plagioclase–garnet–biotite
   134685 Quartz–microcline–plagioclase–biotite

3. Marble

   134686 Carbonate–plagioclase–quartz–garnet–diopside–? forsterite
   134700 Diopside–scapolite–calcite

4. Basic or dark gneisses

   134607 Diopside–pale green amphibole–garnet–plagioclase–quartz
   134679 Hypersthene–diopside–green-brown hornblende–plagioclase–quartz

The mineral assemblages are generally in a stable condition, although effects of retrogression in the form of amphibolisation or chloritisation of biotite and pyroxene may be found locally. Their association with mobilisate generated by *in situ* anatexis of metasedimentary supracrustal rocks and the presence of minerals such as hypersthene, sillimanite and cordierite indicate that the principal episode of metamorphism in Renland west of the monzonite sheet reached granulite or transitional amphibolite-granulite facies conditions (TURNER, 1968) of an intermediate or low-pressure facies series (MIYASHIRO, 1961). Sillimanite and garnet are found everywhere in the gneisses but cordierite and hypersthene have a more limited distribution, their formation being controlled more closely by original rock composition. Because of the uniform distribution of the stable mineral assemblages, it has not been possible to distinguish any isograds within this large area. Metamorphic grade changes west of the faulted Upper Palaeozoic sediments west of Rypefjord where Krummedal metasediments contain kyanite and show only incipient or negligible migmatisation.

The mobilisate in the migmatised paragneisses, particularly the more pelitic rocks, is closely similar to the composition of the garnetiferous augen granites, especially when the alaskitic mobilisate is intimately mixed with wispy biotitic restite. The extreme migmatitic transformation is closely similar in appearance to that of the augen granites which suggests the latter have not travelled far on the scale of the plutonic events in Renland and Milne Land and were produced as accumulations of mobilisate proportions from metasediments similar to the migmatised pelitic gneisses in south Renland. It is even conceivable that the augen granites were formed *in situ* by complete anatectic transformation of thick homogeneous sequences of pelitic rocks within the sequence in Renland. The field relations and composition of the granites leave little doubt that they were cogenetic with the principal episode of high-grade metamorphism west of the monzonite sheet.

The migmatite foliation in the paragneisses, which comprises restite and concordant mobilisate, and the sheets of augen granite are folded by regional nappe structures and later folds. Such evidence indicates an early development of the high-grade metamorphism. The high-grade conditions appear to have persisted during the folding events because local mobilisate occurs parallel to fold axial surfaces and a prominent sillimanite-biotite-garnet lineation is coaxial with nappe and later fold axes.

Apophyses of monzonite cross-cutting augen granites and paragneisses in the area of the southern spur of Edward Bailey Gletscher show that the principal episode of monzonite injection took place after the regional nappe folding. Monzonite masses in south-east Renland are invaded by grey-pink granites that appear to be related to mobilisate in migmatites on the coast of Skillebugt and Øfjord. These relations suggest that the gneisses in the south-east underwent further migmatisation and granitisation after injection of the monzonite. The persistence of stable hypersthene in the monzonite, locally altered to hornblende and cummingtonite adjacent to granite veins, and the occurrence of cordierite on the Bjørneøer (KALSBEEK, 1969) and agmatitic pyribolites with stable granulite facies assemblages in some of the coast migmatites along Øfjord, suggests that the later migmatisation event in south-east Renland also attained granulite facies conditions.

STRUCTURAL GEOLOGY

South Renland divides naturally on the basis of lithology and structure into a western part, which comprises about two–thirds of the total and is occupied by migmatised paragneisses and augen granites, and an eastern part which is circumscribed by the extensive monzonite sheet and contains various migmatites and granites. The structure will be described under two principal headings corresponding to the areal divisions. More general aspects, including the origin of certain fabrics and other finite strain phenomena, will be discussed after the regional descriptions, and an assessment of the structure in relation to metamorphism and plutonism will be dealt with in a later chapter.

Structure in south-west Renland

Deglaciated tract east of Rypefjord.

Reference to the geological map (plate 1) and block diagram (plate 2) shows how the structure in the extreme west is dominated by two synforms separated by a central tract of garnetiferous augen granite.

The synform in the north is cast in migmatised paragneisses surrounded by augen granite; a thin sheet of augen granite also occurs within the core of the fold. The tip of the fold in the north-east is concealed beneath the margin of the plateau ice, but in spite of this it is clear that the form of the structure is a closed basin more open in style in the south-west but tighter towards the north-east. The elements of the structure are summarised in stereogram form in fig. 11 (sub-area 3). The fold axial surface has a constant, moderate dip to the south-east (fig. 11(3)) but the fold hinge is curved, having a shallow north-east plunge in the south-west and a plunge parallel to the dip of the axial surface in the north-east. Such parallelism makes the north-east of the structure a neutral fold that closes north-east. The term *neutral fold* was devised by Bailey & McCallien (1937) to describe structures in the Dalradian rocks of Scotland where the plunge of the fold axis is parallel to the dip of the fold axial surface: because of this relation the folds must of necessity close sideways.

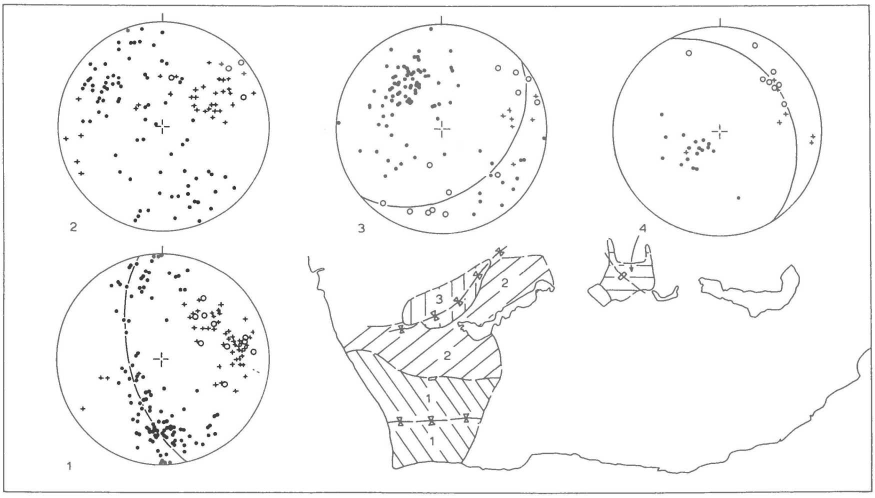

Fig. 11. Equal-area, lower hemisphere stereographic projections of structural data in south-west Renland. Sub-areas based on structural domain. Solid dots = poles to lithological layering (bedding and migmatite foliation) in paragneisses and schistosity in augen granites; circles = small-scale fold axes; crosses = sillimanite, biotite, feldspar augen lineations. Great circles – see text.

Small-scale folds are common in the outcrop of the core area of the synform, particularly in the north-east. The style of the folds varies from tight to open depending on lithology, but in most examples the arrangement of dip isogons is indicative of Class 1C geometry (RAMSAY, 1967). A partial growth of micas and quartz has given rise to an indistinct planar fabric largely parallel to axial surfaces, but in most examples pre-existing mica fabrics are deformed round the folds. Such a relation is seen locally in the thin sheet of augen granite in the fold core where the schistose fabric is strongly crenulated. A few examples of folds deforming a sillimanite lineation were found, and one example of a small-scale interference pattern of open folds superimposed on isoclinal folds was seen in a pyribolite in the paragneisses within the basin. Small-scale intrafolial folds are common in the paragneisses and are typical of those found in the whole of south Renland. They illustrate the complex relation between processes of deformation and migmatisation from the fact that in the same outcrop they may fold mobilisate and also have similar mobilisate developed along transposition surfaces parallel to axial surfaces of the folds which in turn are parallel to overall migmatite foliation. The intrafolial folds are regarded as products of early deformations related to the evolution of regional nappe structures described below.

North of the synform the augen granite forms a thin strip between paragneisses in the synform itself and other paragneisses further north in the area mapped by J. D. FRIDERICHSEN in 1970. The gneisses in the north are heavily migmatised, large areas being replaced by garnetiferous alaskite. In outcrops along the coast of Rypefjord the alaskite has a crude schistosity which is broadly parallel to foliation in the gneisses. Locally, this schistosity and the enclosed gneissic schollen appear to be folded suggesting relatively early generation of the alaskite mobilisate, although reports by HENRIKSEN & HIGGINS (1971), based on mapping by J. D. FRIDERICHSEN, that the granite north-east of Rypefjord contains an enclave of augen granite suggest the alaskitic rocks formed after the principal migmatisation and augen granite development in south Renland.

A central tract of garnetiferous augen granite which emerges from the plateau ice north and south of the 920 m lake in Catalinadal and reaches a width of 6 km before tapering west to the coast of Rypefjord lies between the synformal basin and another large synform further south. The granite possesses its normal schistose aspect over most of the tract but becomes more streaky, suggesting more intense compression, over a width of 2 km north of the brown paragneisses which mark the boundary of the synform in the south. A thin skin of the streaky variety is also found around parts of the exterior of the northern synform. The boundary between the normal and streaky varieties is gradational over 50–100 m.

The basic structure within the tract is a fan of the schistosity which shows a regional change in dip from south to north (fig. 11, sub-area 2). Compositional inhomogeneities with ductility contrasts sufficient to give rise to megascopic folds within the granite tract are limited to scattered aplites and lamprophyres. Dykes of aplite, 0.40 m thick, in the centre of the tract are tightly folded with axial surfaces parallel to the granite schistosity and axes parallel to an augen elongation direction described below. The lamprophyres carry the schistose fabric but no folded examples were seen. In addition to the folded aplites, a crenulation of the granite schistosity occurs locally in the central part of the tract: the crenulation planes are broadly parallel to the regional trend of the granite schistosity itself and the axes plunge gently east.

Feldspar augen within the garnetiferous granite generally take the form of prolate ellipsoids which locally reach extreme cigar or rod shapes; the dimensions of some measured shapes are recorded in fig. 25. The long axes of the ellipsoids have a preferred parallel orientation and form a linear fabric that lies within the granite schistosity, but some outcrops along the coast of Rypefjord where the augen take an extreme cigar shape the linear fabric is developed to the exclusion of the schistosity. The augen lineation generally plunges at gentle or moderate angles to the east (fig. 11(2)). An additional linear element occurs in some aplites in the lower reaches of Catalinadal as prolate ellipsoidal aggregates of sillimanite and quartz (figs 12 & 13), and elsewhere within the augen

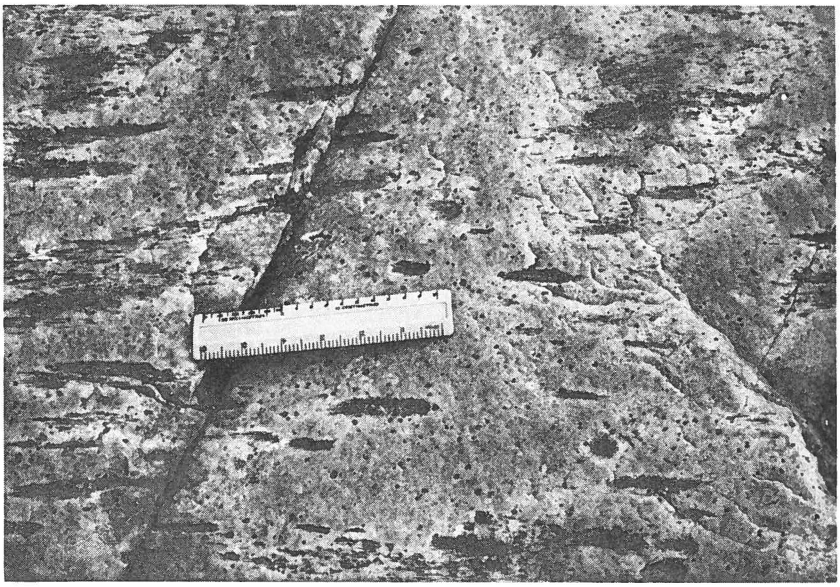

Fig. 12. Ellipsoidal aggregates of sillimanite and quartz in garnetiferous aplite in augen granite in lower reaches of Catalinadal. Sections lie approximately in XY finite strain plane.

granite the augen lineation is enhanced by elongate flakes of biotite and fibres of sillimanite.

Outcrops along the coast of Rypefjord provide a departure from the relatively simple structure described so far. Midway along the east coast and south of the tapered central tract of granite, large outcrops of brown paragneisses and grey augen granites occur in two large antiformal closures separated by a tight synform in intervening paragneisses. The axial traces of the antiforms converge as they are followed along strike inland (plate 1) and the axial surface dip changes progressively from steep to the south, through vertical to steep to the north. The closures peter out eventually into a thin strip of paragneisses that are in contact with streaky augen granite to the north. Plate 1 shows augen granites south of this strip passing beneath the major synformal closure and, although partly concealed by the waters of Rypefjord, the paragneisses south of the antiform in the augen granite must also continue beneath the basin to link with the strip of paragneisses emerging on the southern limb. Such continuity implies that the augen granite in the antiform on the coast also extends south beneath the large synform.

The simple interpretation of this central section of the Rypefjord coast is that of two isoclinal closures, the limbs of which pass south beneath the large synform (block A, plate 2). In so far as the limb lengths exceed 5 km, the structures may be regarded as nappes, but the extent

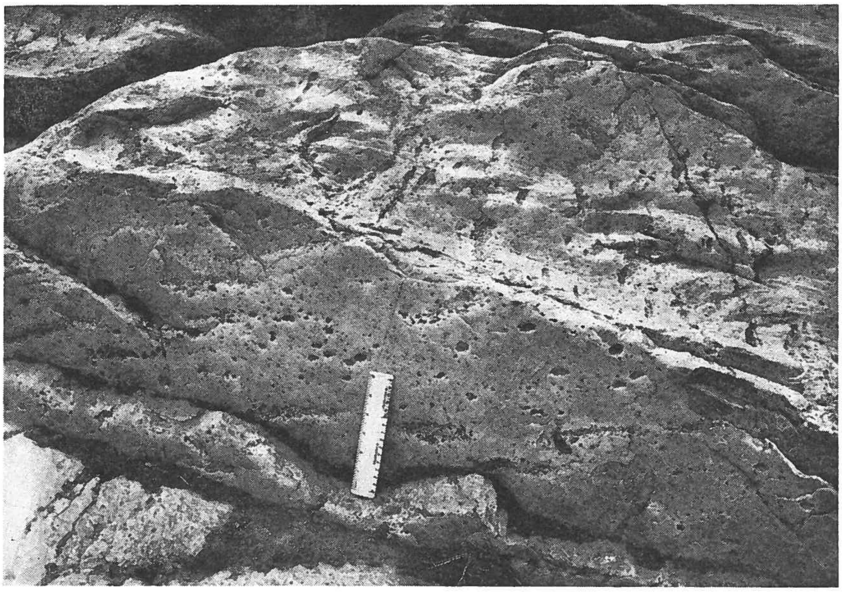

Fig. 13. *YZ* profiles of sillimanite–quartz aggregates in fig. 12.

to which they are complete fold or thrust nappes is not clear. Cross-bedding in coast outcrops of the southern limb of the northern antiform closure in the paragneisses suggests the nappes faced north and had a north-west transport direction before being warped by the later synform. Such a facing is reversed where the nappe axial surfaces change their dip from south to north and converge in the narrow strip of paragneisses on the north of the synform, the reversal being confirmed by inverted cross-bedding in gneisses in the main body of the synform south of this strip. Reversal of facing by superimposed deformations is common in orogenic belts and comparisons of this example in Renland with the type 'back-folding' or 'pli en retour' described by ARGAND (1911) in the Western Alps will be made later in the discussion.

The attitude of foliation in the paragneisses in the core of the antiform to the north, the closure of the lower nappe, indicates a gentle to moderate axial plunge to the east, and biotite lineations which appear to be parallel to the nappe axes, also plunge gently east in the gneisses and granites within the closures.

The structure in the south of the deglaciated terrain east of Rypefjord comprises a regional synform containing a large central mass of rusty brown paragneisses outlined to north and south by thick sheets of augen granite and other brown gneisses. Views of the structure profile from Rypefjord show a relatively simple form (plate 2, block A), but there is no obvious connection across the fjord with gneisses and granites

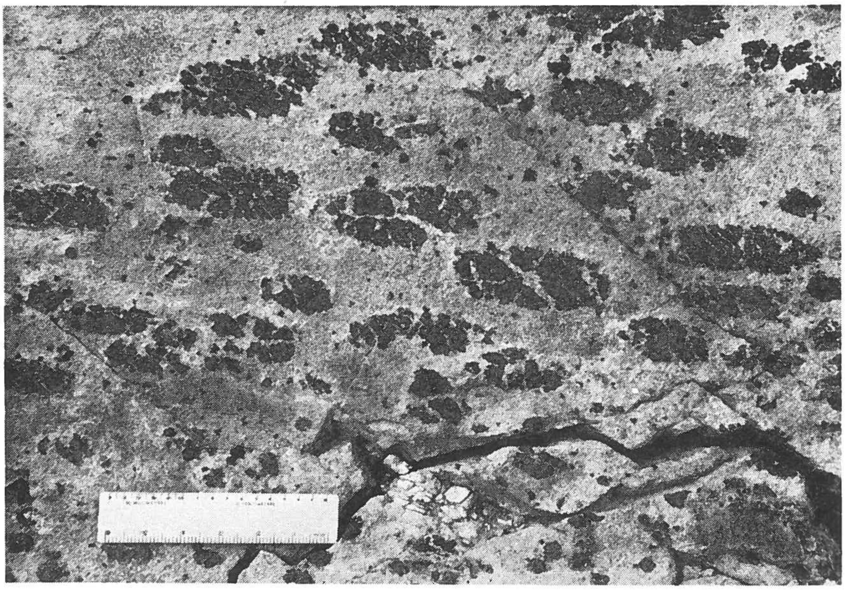

Fig. 14. Elliptical aggregates of garnet with radial structure on bedding surface in quartzites on northern limb of synform in south-west Renland. Ellipses are elongated parallel to regional mineral lineation.

mapped by K. SØRENSEN on C. Hofmann Halvø in 1970 although distant views suggest a broad synformal outline there.

Structural data measured within the synform area (fig. 11, sub-area 1) include a prominent mineral lineation that is found on most foliation surfaces in the paragneisses. The lineation is normally of flaky biotite or fibrous sillimanite, but variations include the parallel preferred orientation of long axes of aggregates of garnet and quartz, prolate ellipsoidal aggregates of prismatic sillimanite locally up to 5 cm long, and elliptical aggregates of garnet with a radial structure; the latter which occur in quartzites on the north of the synform, are illustrated in fig. 14. The mineral lineation found within the paragneisses in the synform is clearly the same as that formed by the prolate augen of feldspar in the augen granites to the north and their significance will be discussed later.

A summary of structural data from the synform presented in fig. 11 (sub-area 1) shows that the regional fold axis derived geometrically as the pole to the great circle distribution of poles to foliation plunges about 25° to the north-east of east parallel to a marked concentration of mineral lineations. Axes of small-scale folds within the paragneisses are also parallel to the lineation; no definite examples of folded lineations were seen. However, axial surface fabrics are rarely developed in the small-scale folds apart from some crystallisation of biotite and minor development of quartz-feldspar neosome.

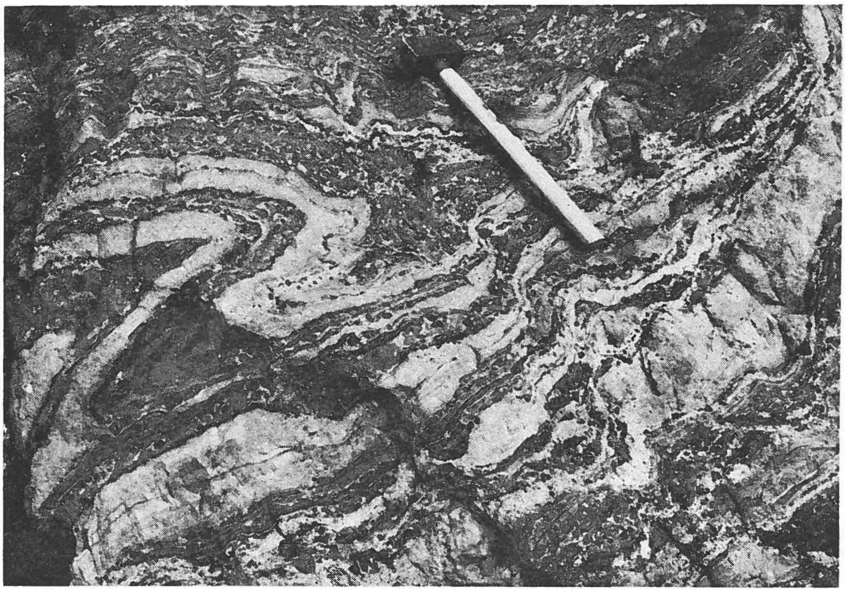

Fig. 15. Folds in garnetiferous pelites and psammitic layers on northern limb of synform in south-west Renland. Note feldspathic haloes round garnets and folded lenticles of garnet-feldspar mobilisate in area of fold interference left of hammer.

The style of small-scale folds is variable from open to tight or isoclinal. In all the examples seen the neosome parallel to bedding foliation is folded (fig. 15). Many of the small-scale folds in the central area of paragneisses may be regarded as parasitic folds generated with the synform, and their frequency of occurrence compared with an absence of folds in the sheets of augen granite that outline the synform illustrates the behaviour of the layered inhomogeneity of the paragneisses as a multilayer complex during the genesis of the synform, with the paragneiss – augen granite interface acting as a décollement.

There is, however, a regional distribution of folds with wavelengths of 2–3 km in the central area of paragneisses which suggests they are refolded by the synform. The distribution, which is outlined on the map (plate 1), may connect with the sheet of augen granite that tapers out to the west high in the sequence on the southern limb of the synform. The tapering is attributed to the position of the granite within the core of a fold-nappe, the hinge region of which has been refolded by the synform and now forms the central zone of folded paragneisses. Such a nappe structure is directly comparable to the underlying isoclines illustrated in block A of plate 2. Cross-bedding in quartzitic migmatites on the north of the central paragneisses which now faces south suggests back-folding by the synform similar to that described for the underlying structures.

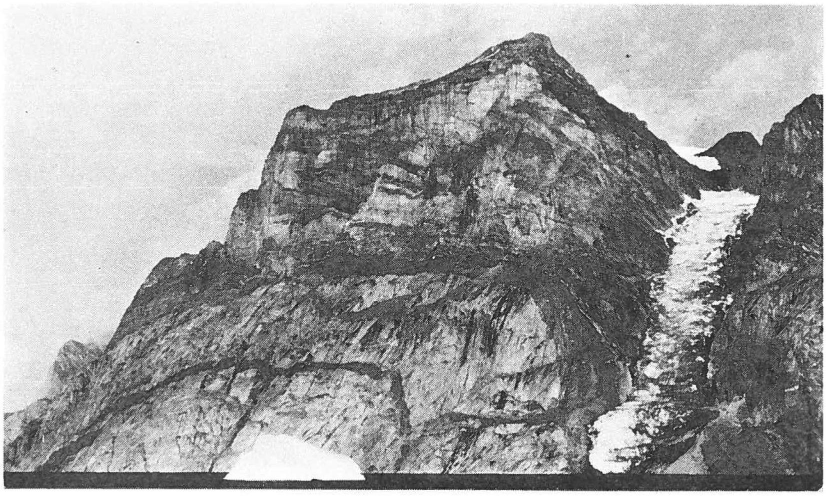

Fig. 16. Isoclinal folds in migmatised paragneisses dipping off late-stage warp outlined by underlying augen granite, cf. fig. 10. Coast of central Øfjord; summit stands 1600 m above sea level.

The orientation of axes of the folds attributed to nappe generation appears to be coaxial, or nearly so, with the mineral lineation and regional synform axis. The relation of the mineral lineation to the central refolding of the nappe structures will be discussed later.

The coast of Øfjord west of peak 1882.

The steep walls of Øfjord, commonly 2000 m high, and cut through by narrow, but vigorous, valley glaciers discharging from the plateau ice, provide a magnificent display of the regional folds. West of peak 1882 and the monzonite sheet an embayment in the coast, which is backed by talus-covered slopes of augen granite (plate 1), lies within a domed area of granite that is flanked to the west by a thick pile of brown paragneisses. Visible within this pile are numerous recumbent isoclines which together with the foliation in the gneisses dip west off the dome into a synform trending north to north-west (plate 1) that is followed in turn by another dome or arch of augen granite to the south-west (figs 10, 16). The paragneisses descend to the coast once more beyond this arch but then their outcrop climbs again above augen granites and brown gneisses that form the core of a tight antiformal closure extending about 10 km further west. The brown gneisses in the cliffs above this closure may be followed west across a number of north-east trending faults into a large closure surrounded by augen granites. The closure is inaccessible but the orientation of regional foliation shows that its axis plunges gently north-east down the dip of the fold axial surface making the structure a neutral fold

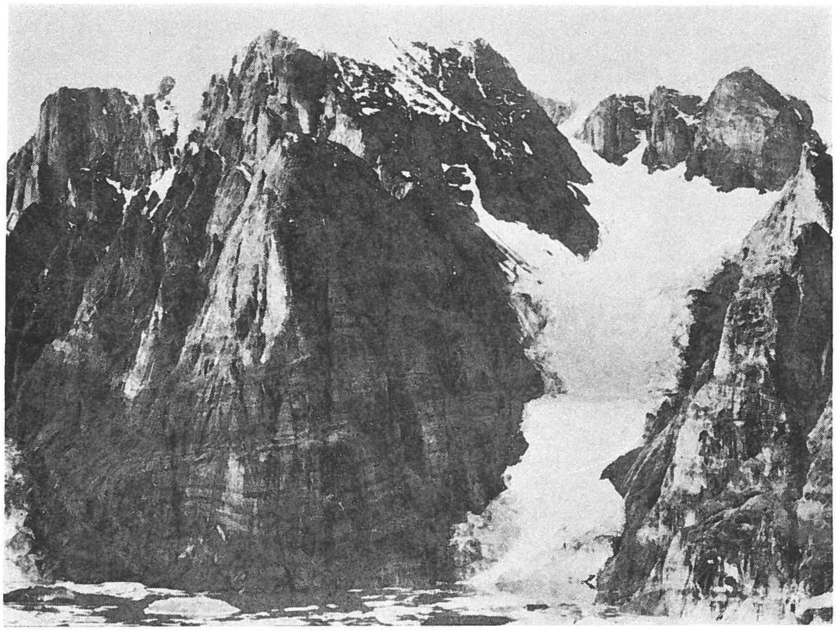

Fig. 17. Isoclinal folds in rusty brown paragneisses on south side of 610 m lake in upper Catalinadal. Summits stand 1200 m above lake level.

closing north-west in this part of the coast. Attitudes of thin sheets of brown paragneisses within the augen granite to the west allow the fold axial trace to be followed as far as a prominent north-east fault (plate 1). Outcrops on the coastal cliffs beyond this fault are associated with the southern limb of the large synform in south-west Renland.

Foliation surfaces in gneisses along the whole coast almost invariably carry a prominent biotite-sillimanite lineation like that in the rocks of the deglaciated terrain of south-west Renland. Like the mineral lineation in this area, the linear fabric along the Øfjord cliffs is commonly parallel to the axes of folds of all scales. From this general relation it may be inferred that the mineral lineation is also coaxial with the axis of the inaccessible neutral fold closure.

The augen granite overlying the paragneisses in the hinge of the neutral fold is hidden by the plateau ice beyond spot height 1990 m and it reappears in nunataks about 5 km to the north. On the basis of this evidence it is possible to draw a smooth line linking the lower boundary of the augen granite in the Øfjord cliffs with the sheet of granite dipping gently north-west in the area of the 610 m lake in upper Catalinadal. The form of the paragneisses extending from Øfjord across the plateau ice into upper Catalinadal and the southern spur of Edward Bailey Gletscher may then be regarded as the interior of a large nappe closing

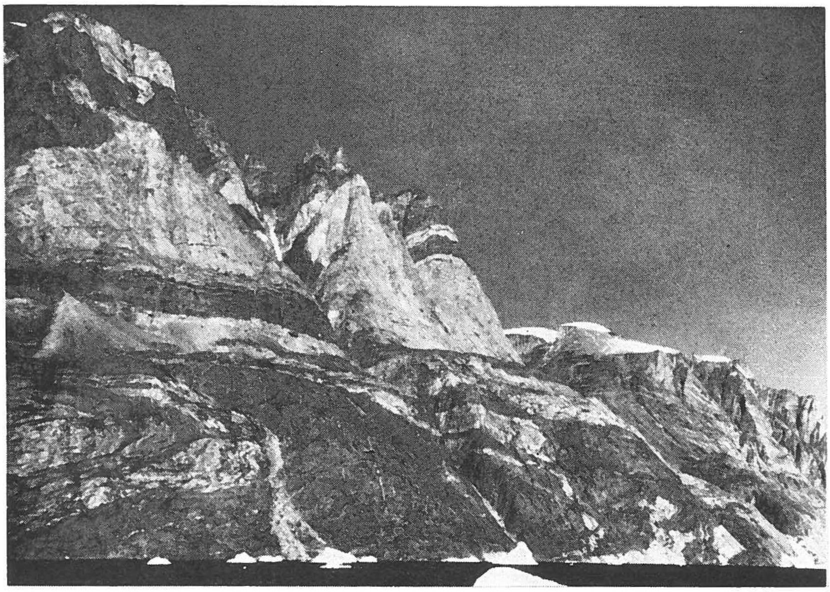

Fig. 18. Large-scale closure in augen granites (pale) and rusty brown paragneisses (dark) in central Øfjord. Summits stand 1500 m above sea level. Capping to distant cliffs is of grey, garnetiferous granite believed to relate to younger granites of east Renland and Milne Land.

to the north-west, a view that is supported strongly by the abundance of large isoclines in the paragneisses both in the cliffs of Øfjord (fig. 16) and in the cliffs south of the 610 m lake (fig. 17). The shallow plunge of the isocline in the latter illustration is also parallel to the inferred plunge of the neutral fold closure and orientation of mineral lineations on the Øfjord coast. Therefore, on the basis of the foregoing, the whole of this area of paragneisses and the envelope of augen granite to the north-west is represented as a fold-nappe in plate 2 (blocks C & D); the limit of the structure to the north is uncertain.

In visual terms the most impressive unit of the structure along the Øfjord coast must be the large antiform closing to the south-east with augen granites in the upper limb giving rise to the spectacular walls midway along the western part of the coast (fig. 18). The hinge, exposed continuously over 10 km, exhibits an 'eye' structure in an erosional embayment in the west. The fold axial surface strikes 50–60° and dips about 30° NW, and the axis plunges 10° NE. Folds of all magnitudes are developed within paragneisses and interlayered augen granites in the hinge area; large parasitic folds are also visible in paragneisses high above the great cliffs of augen granite in the upper limb.

Small-scale folds in the hinge region plunge gently north-east parallel to the prominent mineral lineation. There is an incipient crystallisation

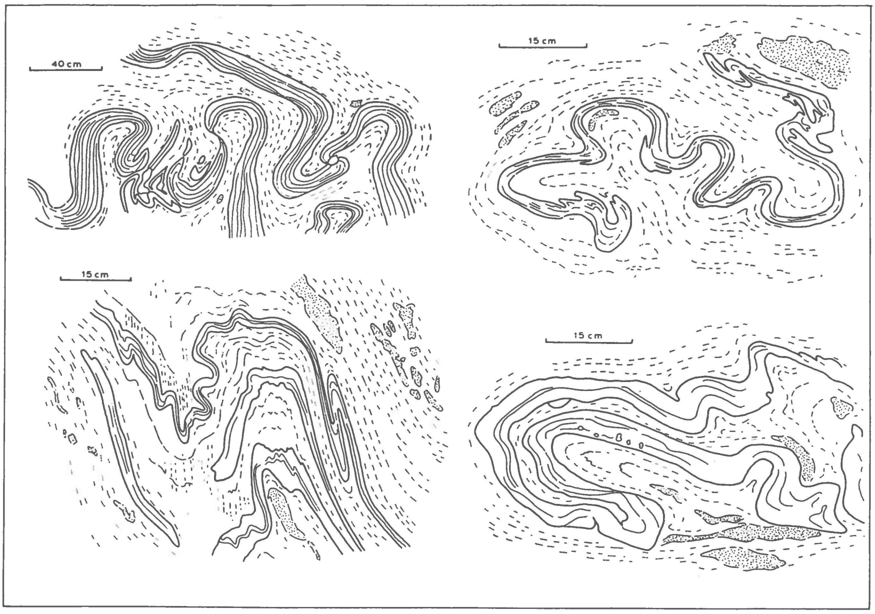

Fig. 19. Examples of small-scale folds in quartzitic layers in paragneisses in western part of Øfjord coast. Sketches from photographs.

of biotite and local leucosome aggregates parallel to axial surfaces but in general the gneiss foliation, migmatite fabrics and granite schistosity are folded. Further west, below the neutral fold closure, the isolated sheets of brown paragneisses in augen granite change their attitude on reaching the water-line and may be involved within a continuation of the antiform. Small-scale folds developed in one of the sheets are illustrated in fig. 19. The folds are generated in quartzitic layers, representing original psammitic beds, contained in heavily migmatised biotitic gneisses. Fold axes are coaxial with a prominent sillimanite-biotite lineation. The fold geometry is indicative of a complex history that involved a succession of discrete phases of folding or a continuous sequence of rotational strains that formed during a 'synchronous refolding' event of the type described by WYNNE-EDWARDS (1963).

The augen granite in the east of the antiform hinge dips east with the fold axial surface beneath a synformal warp marked by rusty brown paragneisses. Augen granite re-emerges east of the synform in an arch, the outcrop of which extends over 3 km along the coast and is more than 500 m high on the cliff (fig. 10). Recumbent isoclines in paragneisses above the granite are warped across the top of the arch (fig. 16). The granite in the arch forms a continuation of that in the antiform, and its presence may be accounted for by the generation of interference patterns

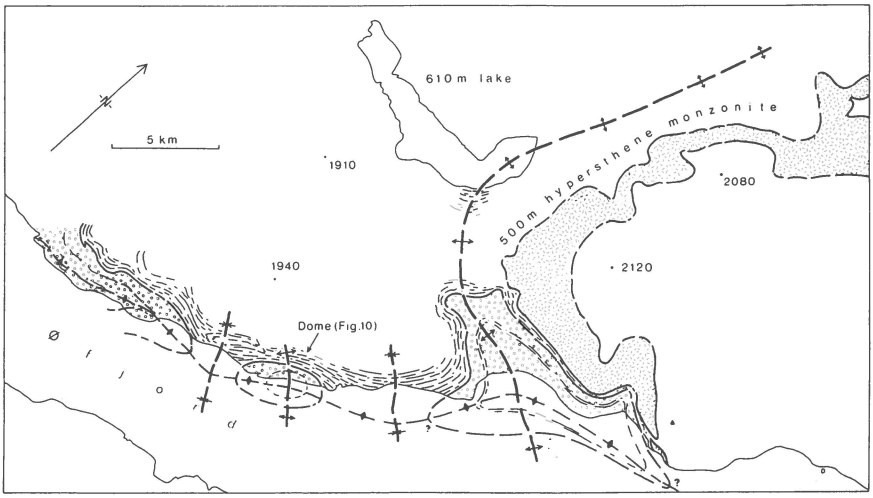

Fig. 20. Scheme of interference between early folds and superimposed warps giving trough and arch profiles along central Øfjord coast.

as a result of the superimposition of late-stage regional warps on the antiformal closure. The presence of the large area of augen granite in the embayment west of peak 1882 may be attributed to the same phenomenon, and the scheme is illustrated in fig. 20. This figure shows the antiformal warp west of peak 1882 which may be traced round the west of the boundary of the extensive monzonite sheet into the valley of the southern spur of Edward Bailey Gletscher. Such a parallelism with the edge of the sheet suggests a genetic connection of the warps with the formation of the basin structure of south-east Renland.

The higher reaches of Catalinadal.

This area includes the many large nunataks or isolated masses of outcrop separated by steep valley glaciers on the flanks of Catalinadal east of the 920 m lake. The central tract of augen granites in the deglaciated terrain of south-west Renland may be traced east through two ice-bound outcrops into a large area south of spot height 1740 m (plate 1). The granite schistosity swings from its north-east strike in the east of the central tract through east and thence to a south-east trend; the dip also changes from steep south-east, through vertical, to moderate north-east. Most detail of the structure was collected from the large area south of spot height 1740 m which is the site of a large neutral fold closing south-east. The axial surface strikes south-east and dips about 30° north-east parallel to the plunge of the fold axis (fig. 11, sub-area 4); see also CHADWICK (1971). The fold is outlined by changes in the trend of schi-

Fig. 21. Small-scale folds in migmatised paragneisses in hinge of large-scale recumbent structure closing south high on large nunatak north of 610 m lake, Catalinadal. Note folded mobilisate (white).

stosity and thin sheets of brown gneisses in the augen granites; it is enveloped by thicker paragneisses with limited outcrop in the south and east. Within the immediate hinge zone the schistosity of the augen granite is crenulated, and, although local divergences were noted, the axes are coaxial with a sillimanite-biotite lineation. Axial surface fabrics are not well developed.

Though interrupted by steep valley glaciers, profiles of a large recumbent fold closing south are visible close by the margin of plateau ice high on outcrops east of the neutral fold. The core of the fold is occupied by augen granite and the southern envelope of paragneisses is thrown into a series of parasitic small-scale folds with wavelengths of 1–2 m (fig. 21). The folds plunge gently west. Axial surface fabrics are not prominent. The fold structurally overlies the large neutral fold closure to the west and their geometrical relation suggests the large recumbent structure may be part of a back-folded early nappe (plate 2, block D).

Further east along Catalinadal the structure becomes more simple as the units of paragneiss and granite take on constant gentle dips to the west. Tight folds with axial surfaces parallel to the foliation are visible locally. Outcrops south of the neutral fold (plate 2, block C) contain folds trending east–west. Schistosity in the augen granites is crenulated in the fold hinges, but there is some crystallisation of biotite to form an axial surface fabric.

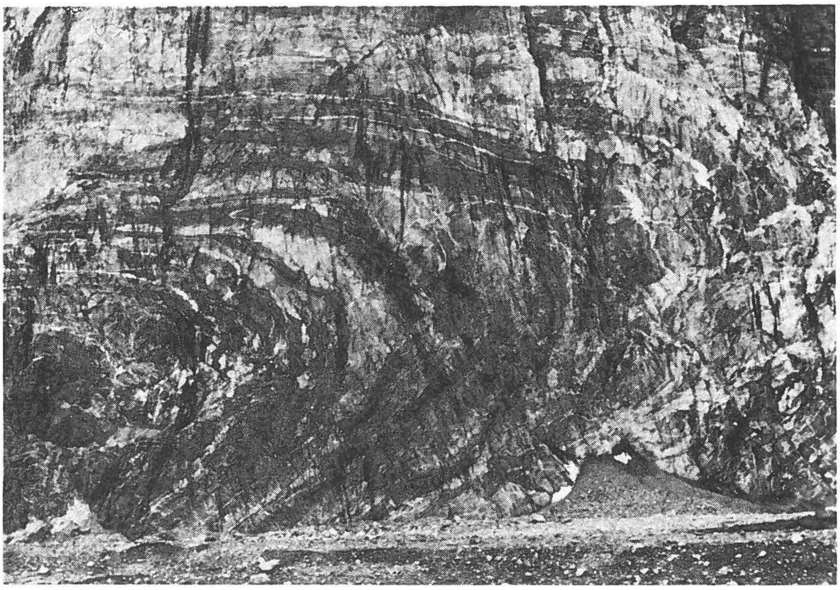

Fig. 22. Recumbent fold in west cliff of southern spur of Edward Bailey Gletscher. Note deformation of mobilisate and local rupture of paragneisses in areas of thickened aplitic mobilisate in fold hinge. Earlier phase of folding is suggested by possible closure upper right of photograph. Height of outcrop is approximately 150 m.

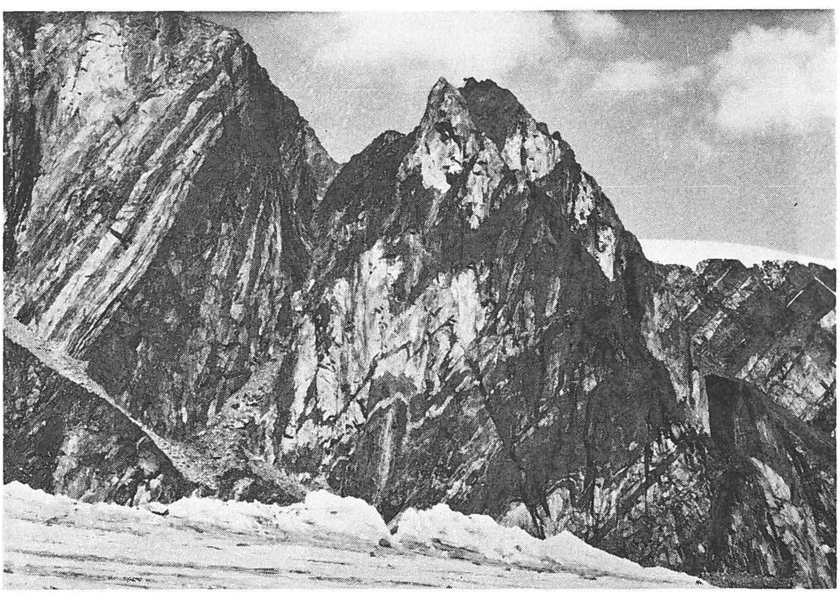

Fig. 23. Folds in rusty brown paragneisses and grey augen granites on north side of the upper part of Edward Bailey Gletscher. Peak stands 300 m above glacier surface.

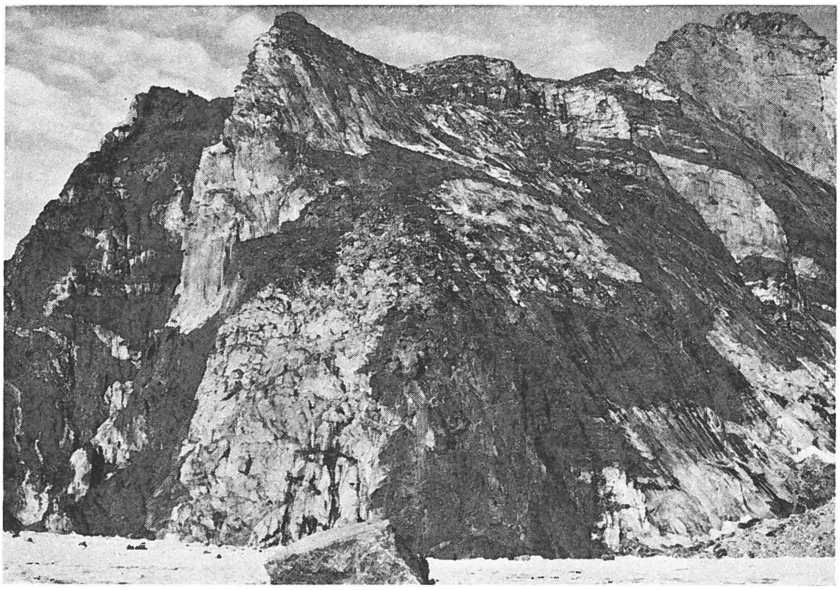

Fig. 24. Mushroom structure in rusty brown gneisses (dark) and augen granites (pale) on east of outcrop shown in fig. 23. Peak standing 300 m above glacier is same as that in fig. 23.

The higher reaches of Edward Bailey Gletscher.

This sub-area includes the outcrops on both sides of the glacier extending 20 km west of the southern spur. The outcrops display sections showing a gradual steepening to the west and north-west of the sheets of augen granites and paragneisses. Recumbent folds in the cliffs of the southern spur (fig. 22) deform the gneiss foliation, and similar but inaccessible folds are visible high on the cliffs north of the glacier.

As the structures are followed west up the glacier the dips increase until they reach values of about 60° close to the boundary with a large mass of granite exposed in the head of the glacier. The folds illustrated in fig. 23 are part of the steepened structure. A large mushroom structure (fig. 24) may be interpreted as an interference pattern that may have been generated either as part of the steepening or as a later phenomenon associated with regional warping like that exhibited in the arch and trough structures of Øfjord.

The massif in south-east Renland

The structure of the massif is a simple basin as indicated by the systematic changes in dip of the peripheral monzonite sheet and overlying migmatites in the west and sheets of grey-pink granite interlayered with migmatites in the snout area of Edward Bailey Gletscher and along the coast of Skillebugt. The extensive monzonite sheet in Renland, its more acid equivalents mapped by J. D. FRIDERICHSEN in east Renland (HENRIKSEN & HIGGINS, 1970, Map 1) and the dioritic rocks on the Bjørneøer (KALSBEEK, 1969) could together be regarded as parts of a continuous sheet with a lopolithic form centred in the area of Skillebugt.

Locally steep dips occur along the coast of Øfjord and there is tentative evidence of discordant boundaries between migmatites on the coast and some of the overlying sub-horizontal sheets of grey-pink granite. Within the interior of the massif large-scale recumbent isoclines occur in the migmatites but their relation to granitisation and events outside the massif area is not clear.

The structure of the massif is far from clear but it seems likely that the basin structure was superimposed on migmatites deformed in a manner similar to the paragneisses in south-west Renland. Development of the basin probably occurred in association with the intrusion of monzonite and generation of the grey-pink granites.

Small-scale shear belts

Small-scale shear belts spaced at irregular intervals of more than 2 m are common in the augen granites and paragneisses in south-west Renland. Similar phenomena, but less well defined, were seen in augen granites in south-east Renland. The shear belts have a general south-east trend, steep or vertical dip and dextral sense of displacement. The schistose fabric in the surrounding rocks, particularly obvious in the augen granites, may be traced directly into the shears, curving progressively until in the centre of the shear zone it becomes parallel to the walls. Deformation has been extremely intense within the shears as shown by the common development of lineated ultramylonites, quartz and microcline being especially deformed, though some microcline and garnet survive as porphyroclasts that have been reduced only slightly in size from that of grains in the surrounding undeformed rock. The lineation is formed by smears of biotite and sillimanite. Sillimanite is particularly common in thin sections of mylonites from some shear zones and its fresh appearance suggests it grew during the shearing movements. Other minerals in the zones are also fresh and there is generally little evidence for introduction of large quantities of fluids (cf. BEACH & FYFE, 1972).

The shear belts are similar to those from the Helvetic and Pennine Alps and the Lewisian complex of the Outer Hebrides that have been analysed by RAMSAY & GRAHAM (1970). The most significant points of their analysis lie in the demonstration of the facts that new schistosity is generated by heterogeneous simple shear within the shear belts and is parallel to the XY finite strain plane, where $X > Y > Z$ are the directions of the finite principal strain axes. Unlike most of their examples, the rocks surrounding the shears in Renland possess a pre-existing fabric anisotropy in the form of a marked schistosity, especially in the augen granites. This schistosity may be followed into the shears where it is enhanced by re-working which locally gave rise to mylonites. RAMSAY & GRAHAM restricted their analyses to shear belts in rocks such as granites and metagabbros where the wall rocks are not deformed and possess isotropic fabrics, the reasons for the restriction being that the shear belt structures could be interpreted unambiguously as the product of progressive simple shear and there is a minimal influence of pre-existing strains in the wall-rock fabrics. However, the geometrical similarity between the attitudes of schistosity in the Renland shears and the new schistosity in the shears described by RAMSAY & GRAHAM makes it likely that the schistosity within the Renland shears is also parallel to the XY finite strain plane for the shear belt deformation. Many of the Renland examples contain a fibrous mineral lineation on the schistosity surfaces within the shears, a feature not recorded in the examples described by RAMSAY & GRAHAM. The lineation is formed largely of biotite smears, locally with quartz and sillimanite. This lineation is not the same as the regional lineation parallel to fold axes, but was generated solely by movements within the shear belts. In view of its position on the schistosity, the XY finite strain plane, the lineation may be regarded as the X finite strain direction.

Most of the shears measured in south-west Renland have steep dips, with a moderate plunge for the mineral lineation in an example where it has been possible to estimate a total displacement of approximately 50 cm. There are few exceptions to the general south-east trend and moderate dip so that, on the assumption of a maximum displacement of 50 cm on each shear, the total combined movement on the shears in south-west Renland could amount to at least 500 m oblique downthrow to the east.

The position in time of the shear belts in the structural evolution of Renland is problematical, though on the basis of trend and their effect on the pre-existing schistosity they appear to post-date the synforms in south-west Renland. RAMSAY & GRAHAM have emphasised one of the most striking features of shear belts, namely, the concentration of displacements and high strains within narrow zones surrounded by undeformed rock. They suggest the initially deforming material within the zone became 'strain softened' which gave rise to local reduction of yield strength possibly as a result of the introduction of mobile constituents during the deformation, evidence for the latter being found in the form of chemical modifications within some of the examples they analysed.

The mineral textures of the mylonites in the Renland shears show no evidence of profound chemical modification and the presence of stable sillimanite and garnet suggests an absence of fluids, but moderate temperatures and confining pressures. Some shears contain aplites and pegmatites which appear to have been injected subsequent to the shear formation, but these form the only evidence of hydrothermal activity in the shear zones.

Schistosity in the augen granites

Apart from the shape of feldspar augen within the schistose fabric of the augen granites, there is no other evidence such as deformed objects of known original shape to indicate unequivocally that the schistosity is parallel to a finite strain plane, XY, where $X > Y > Z$ are the principal finite strain axes. On the other hand, folded aplites and lamprophyres have fold axial surfaces co-planar with the schistosity and this relation provides a more definite indication that the schistosity is parallel to the XY plane, such a relation having been firmly established in areas of slaty cleavage and schistosity tectonics elsewhere (CLOOS, 1947; RAMSAY, 1967; RAMSAY & GRAHAM, 1970, p. 808).

Of significance in the problem of the origin of the schistosity are the similarities between the Renland nappe fabrics and those in the pre-Mesozoic 'granite-gneiss' forming the core of the Lower Pennine Antigorio nappe in the central Alps (MILNES, 1965). MILNES suggests that the schistose fabric, which he describes as a foliation, was formed during rotational deformation associated with the emplacement of the Antigorio nappe early in the tectonic history of the Penninic realm. In a later paper, MILNES (1968) demonstrates that this early Alpine fabric is parallel to the XY finite strain plane. In some parts of the nappe cores micaceous xenoliths and a mineral lineation of feldspar augen, regarded as deformed phenocrysts of the pre-Mesozoic granite, lie parallel to X, the principal finite extension direction. The schistose fabric is locally associated with 'vague fluidal folds without axial planar structure' (MILNES, 1968, p. 71), but the axial surfaces are parallel to the schistosity. MILNES regards the fabric as the result of ductile flow at the time of nappe translation.

The geometrical similarity to the Alpine fabrics suggests that the augen granite fabrics in Renland had a similar origin, forming as a result of ductile flow during the nappe emplacement. The fabric certainly formed early in the evolution of the nappe phase because it is folded, together with foliation in the paragneisses, by the nappes in Renland. On these grounds the evolution of the nappes must be regarded as a continuous process with formation of the augen granite schistosity taking place, perhaps by a protoclastic process, at an early stage. It was then deformed

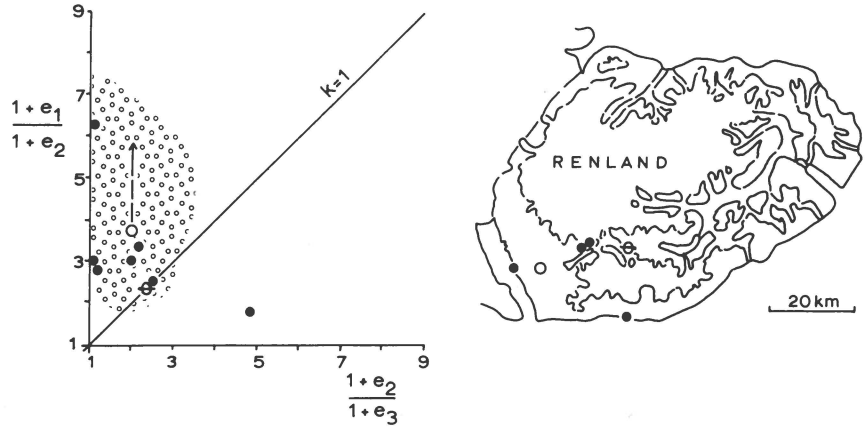

Fig. 25. Deformation plots of feldspar augen (black dots), sillimanite-quartz aggregates (circle) and garnet-feldspar aggregates (ellipse + bar). Small circle ornament covers general field occupied by deformed augen. $k = 1$ is the plane strain path ($e_2 = 0$) which for equivolume deformation divides the diagram into two parts: $k > 1$, constrictional deformation, and $k < 1$, flattening deformation. Sketch map shows outcrops where measurements were taken.

in nappe fold hinges later as the folds developed. During these later stages the schistosity may have been enhanced by ductile flow in the nappe limbs under the influence of vertical loading concomitant with shear (viscous deformation) within the nappe pile. Locally more intense deformation at this stage gave rise to the flaser and streaky varieties of the augen granite.

Lineation

The shapes of measured ellipsoidal aggregates, including feldspar augen, sillimanite-quartz and garnet-feldspar nodules, are presented as ratios of the principal axes, $X > Y > Z$, in fig. 25. This type of graphical representation, which was developed by Flinn (1958, 1962) after a method first suggested by Zingg (1935) for pebble shapes, allows any triaxial shape, be it finite strain ellipsoid or particle shape, to be represented by a point. The origin of the graph (1,1) is a sphere. During progressive deformation the sequence of shapes of the strain ellipsoid built up by the addition of incremental strains may be represented by a series of points, each one described as a *deformation plot* (Flinn, 1962), and the line joining successive deformation plots was described by Flinn as the *deformation path.* The final point on such a path is the finite strain ellipsoid. Modifications and elaborations of such representation are described by Ramsay (1967).

Because little is known about the history of aggregate growth, it must be emphasised that the plots of ellipsoid shapes from south-west Renland do not necessarily represent rock finite strain ellipsoids; they represent only the aggregate finite strain shapes. However, for two reasons they may be considered to be not far from the bulk or rock strain ellipsoids. First, the augen formed early in association with migmatisation and folding, and second the ductility contrasts between augen aggregates and their host were probably very small, especially in the augen granites. With this in mind, two significant conclusions may be drawn from the augen shapes. First, in spite of the absence of detail concerning their formation all the augen shapes, with one exception, fall in the field of constrictional deformation, $k > 1$ (fig. 25). For equivolume deformation the line $k = 1$ divides the graph into two equal parts, $k > 1$ where the deformation is constriction-type and $k < 1$ where deformation is of flattening-type. Where $k = 1$ for equivolume deformation the principal intermediate strain, $1 + e_2 = 1$. Further details of the significance of k are described by FLINN (1962) and RAMSAY (1967). Irrespective therefore of previous deformations such as a flattening event for the schistosity formation and the loci of deformation paths, the augen underwent strong elongation parallel to X, $(1 + e_1)$, and shortening parallel to Y, $(1 + e_2)$, and Z, $(1 + e_3)$. Secondly, their shape, together with the fact that there is negligible fluctuation, gives an indication of the orientation of the principal finite bulk strains, i.e. $1 + e_1 > 1 + e_2 > 1 + e_3$. $1 + e_1$ is parallel to certain nappe and later fold axes, but because the values of Y and Z are close together, i.e. the ellipsoid YZ sections are nearly circular, it is difficult in many outcrops to distinguish the $1 + e_2$ and $1 + e_3$ directions specifically. However, in some $1 + e_2$ lies within the plane of the schistosity with $1 + e_3$ perpendicular. In the absence of aggregate shapes elsewhere in south-west Renland, the linear fabric of biotite and sillimanite provides the orientation of $1 + e_1$, the direction of maximum finite elongation for the constrictional deformation.

The constrictional deformation

The prolate ellipsoidal augen, sillimanite-quartz aggregates and mineral lineations show that the bulk finite elongation direction is parallel to the axes of nappes and commonly coaxial with structures that refold the nappes, especially in parts of south-west Renland (fig. 11). This geometrical relation suggests that the constrictional deformation developed late in the evolution of the nappes and extended into the period of subsequent refolding. This type of deformation which is also found elsewhere in the Caledonides, for example the Dalradian quartzites of Scotland (RAST, 1963) and the Bygdin conglomerates of Norway (HOSSACK, 1968), and in other mobile belts, for example the Mozambique Belt in Rhodesia (JOHNSON, 1968), leads generally to the preferential development of linear fabrics and an absence of planar fabrics. Slaty cleavages, and schistosity equivalents at higher grades of metamorphism, co-planar with fold axial surfaces are developed preferentially in flattening deformations, $k < 1$, and so the general absence of fabrics co-planar with the synform axial surfaces in south-west Renland may be understood in terms of the constrictional deformation that appears to have dominated this particular folding episode.

The constrictional elongation direction, X, is horizontal or gently plunging, though locally it may be steep as in the eastern end of the synform in the extreme south-west. The general orientation suggests that overall relief of constrictional stresses took place by horizontal extensions. The orientation of the lineation swings, in broad terms, from east to north-east (fig. 11), and its regional disposition suggests compression of the lineated rocks between two masses, one in south or south-east and the other north or north-west. Such masses may be identified readily from a study of the regional geology (fig. 1). That to the south may be accounted for by the piling up of nappes advancing north from the interior of the mobile belt in Milne Land. The mass to the north forming an obstruction to the nappe advance is represented by the broad domal complex of miscellaneous granitic rocks, marginal parts outcropping as garnet alaskite north-east of Rypefjord and pink granitic rocks at the head of Edward Bailey Gletscher. Larger areas of similar granitic rocks have been mapped further north-west by J. D. Friderichsen. In addition to the granites, which may have risen under buoyancy forces, an area of gneisses comparable with the Flyverfjord infracrustal or basement complex occurs further north-west (fig. 1) and uplift of this tract in association with the granite emplacement may also be envisaged as part of the obstructive mass. The situation is outlined in a generalised cross-section across the region (fig. 26) which has been compiled from preliminary accounts of field work by Henriksen & Higgins (1969, 1970, 1971).

The deformation plots (fig. 25) suggest considerable sub-horizontal extensions took place during the structural evolution of south Renland. The distribution of such extensions north of Renland is unknown, but the effect and variations in the extension direction may be relatively local depending on particular elevations of masses such as the granite-basement complex north of Rypefjord to impede nappe transport. In the latter case the extensions could be accommodated by local variations in strain patterns, but sub-horizontal extensions along the whole length of the mobile belt lead to considerable problems of strain accommodation. Such problems which probably depend on factors including patterns of strain, volume change, deformation paths and strain rates remain for future investigation.

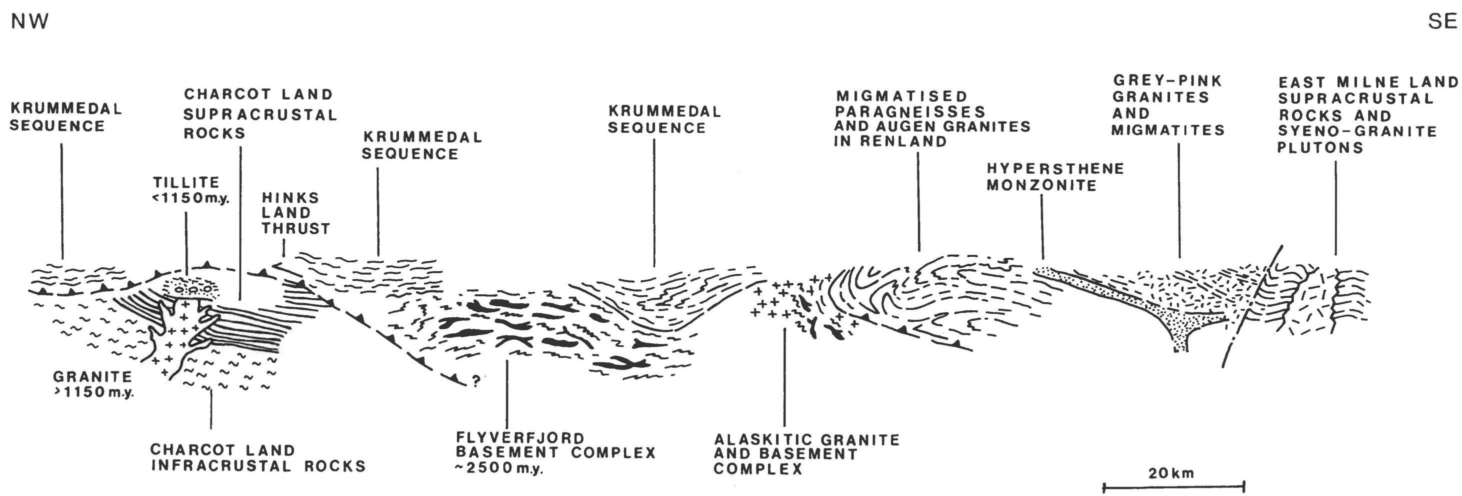

Fig. 26. Generalised cross-section across the inner fjord complex to illustrate the constriction of nappes in Renland between rocks in Milne Land to the south and rising mass of granites and basement gneisses to the north-west.

Back-folding

Cross-bedding in paragneisses shows that nappes in south-west Renland faced north and had a northward direction of transport prior to their deformation around the synforms east of Rypefjord. Among the effects of this superimposed deformation are local reversals of facing of nappe closures (plate 2, blocks A, B). Similar reversals may be deduced from the geometry of the large neutral fold in Catalinadal and changes in attitudes of fabrics in the augen granite as they are traced from the west into the area of Catalinadal (plate 2, blocks C, D). The attitudes of large-scale isoclinal folds in the upper reaches of Edward Bailey Gletscher which are illustrated in the same plate may also be attributed to similar effects of the superimposed deformation. The reversals produced by this deformation, one of mainly constriction-type, thus form a significant element of the regional geometry which may be linked directly with the constraint imposed on the rocks sandwiched between nappes advancing from the south and the rising mass of granites and mobilised basement to the north.

Reversals of facing directions of early structures in mobile belts are relatively well-known, although little has been published on the mechanics of deformation, the associated strains or conditions of metamorphism. The classic area of back-folding (Rückfaltung) is that of the Mischabel in the Pennine nappe complex of the Western Alps described by Argand in 1911 as 'l'énorme pli en retour.' The Mischabel structure is a south-facing arch of Mesozoic cover rocks on the upper limb of the Grand St. Bernard nappe which overlaps on the front of the higher level Monte Rosa nappe. The arch is about 10 km wide and is broadly comparable in scale with the folds in Renland illustrated in block C, plate 2. Although Argand (1911) described the broad outlines of the structure, which have stood unmodified for sixty years, little is known of the geometrical detail or states of strain.

Argand's view of the evolution of the Mischabel back-fold involved several sequences of independent nappe movements, each a part of the northward advance of the Pennine nappe complex. Bailey (1935) in his collection of essays on Alpine tectonics suggested a modification in the series of nappe movements to give rise to disharmonic folding in the Mesozoic cover rocks of the Grand St. Bernard nappe. However the proximity of autochthonous basement rocks elevated as parts of the Aar and Gotthard massifs to the north suggests a more compelling reason for the back-folding which bears a close resemblance to the scheme envisaged for the evolution of the back-folding in Renland. It seems likely that the reversal of facing in the Mischabel area is a result of the constriction of this part of the Grand St. Bernard nappe between higher-level Pennine and Austroalpine nappes advancing from the south and rising autochthonous or para-autochthonous massifs of basement which formed an obstruction to this advance. Although this is a simplified view which together with states of strain and conditions of metamorphism requires further investigation, it finds support in other areas of the Western Alps, for example on the south of the Gotthard Massif where reversals of the normal northward facing direction of Alpine structures are known in the area of the Scopi syncline (CHADWICK, 1968) and elsewhere. Such reversals here may be linked directly with the elevation of wedge structures in the massif and the consequent obstruction of further northward advance of Pennine nappes from the south.

Because of their importance in the literature the Alpine back-folds have been reviewed here at greater length than similar reversals in other orogenic belts, for example, the reversals in facing of early recumbent folds in the Dalradian rocks in the Caledonides of Scotland (BAILEY, 1960). In his essay on the Pennine Alps in 1935, BAILEY emphasised that back-folding is a 'natural mountain phenomenon' to be expected when the one-way transport of structures, part of the orogenic polarity, is interrupted for one reason or another. The Alpine examples considered with the examples in Renland suggest there may be some general pattern of events common to Phanerozoic and late Precambrian belts at least. This pattern very broadly involves interruption of nappe or recumbent fold advance by rising masses of basement similar to the rising domes in experimental studies by RAMBERG (1967). The extent to which the pattern is generally applicable in terms of metamorphic conditions, its timing and the states of strain require further investigation.

Patterns of fracture and their regional significance

Topographic lineaments which are the expression of faults or other fractures along which there has been little or no displacement are shown in fig. 27. The two principal trends, north-east and north-west, are reflected strongly in the topography but a less common set with north–south trend has had a less profound effect. Normal faults, locally with antithetic components, are particularly obvious in the layer-cake arrangement of the brown paragneisses and grey augen granites in the upper part of Edward Bailey Gletscher. They trend north-north-east, dip steeply east and have a total cumulative downthrow to the east of about 1000–1500 m. The layer-cake structure in the west of Øfjord provides a similar situation for normal faults which in contrast to those in the area of Edward Bailey Gletscher dip steeply west and have a cumulative downthrow to the west of about 700 m. In central Øfjord two faults with

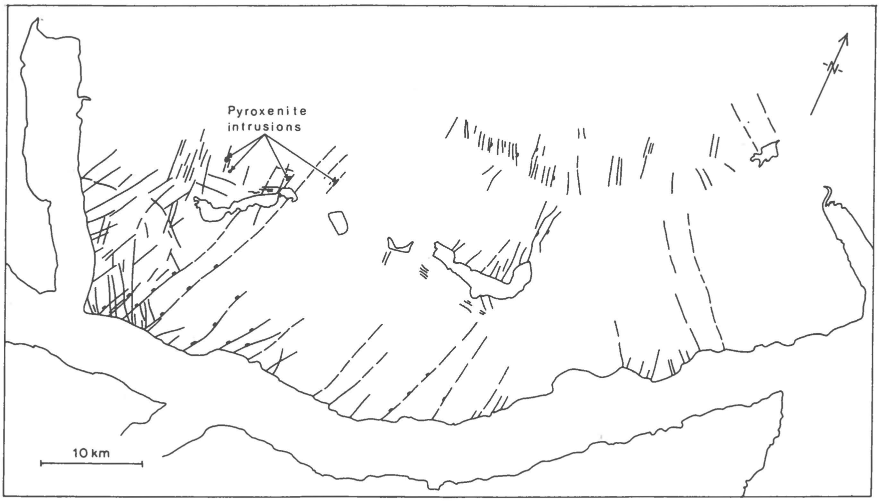

Fig. 27. Prominent topographic lineaments in south Renland; downthrow side of faults marked with bar. Pyroxenite intrusions of Tertiary age controlled by fractures.

downthrow to the west appear to pass north into the faults in the area of Edward Bailey Gletscher with downthrow east, but the relation between the fault sets is not clear.

The north-north-east normal faults with downthrow east and west are broadly parallel to the fault boundary on the west of the trough containing Permo-Carboniferous molasse-type sediments in the Rypefjord –Rødefjord region (Collinson, 1971) and the more distant fault boundary to the east between the Stauning Alper and late Palaeozoic–Mesozoic sediments in the Jameson Land trough. These relations and their distribution suggest the normal faults in south Renland were initiated during the formation of late Palaeozoic intramontane troughs and the area of Renland and parts of Milne Land formed part of a horst-like structure.

SYNTHESIS

The principal conclusions concerning the evolution of structures in south Renland in relation to metamorphism and other plutonic activity are summarised in table 1. The timing of these events is currently uncertain in view of the mixed radiometric ages obtained by Hansen & Steiger (1971), Hansen, Steiger & Henriksen (1972) and Steiger & Henriksen (1972). Indeed much of what has hitherto been regarded as the result of Caledonian activity in East Greenland may in fact be to a large extent the result of Grenvillian activity with a weak Caledonian metamorphic overprint, particularly in the inner fjord area of Scoresby Sund. Support for this view has come recently from a preliminary indication of a Rb/Sr whole-rock isochron of 1194 m. y. obtained by Hansen *et al.* (1973) for three samples of mica schist from the Krummedal sequence in the inner fjord area. Nevertheless, in the light of the certain Caledonian deformation of late Precambrian and early Phanerozoic sediments in the inner fjord complex north of Stauning Alper (Haller, 1971) and on the coast to the east (Caby, 1972), coupled with the lithological similarity between paragneisses in south Renland and the Eleonore Bay Group, a comparison and not a definite correlation, there remain grounds for regarding the tectonometamorphic phenomena in south Renland as Caledonian. Of particular relevance to this problem are the current views of the structure and isotopic ages of events in the Moinian and Dalradian rocks of the Caledonides of Scotland and Ireland summarised by Dunning (1972). Although late Precambrian isotopic ages, including one of 1200 m.y. for zircons, have been obtained from the Moinian, "the field evidence for Precambrian orogenic events is still lacking, while much other field evidence continues to point to a post-Arenig age for the earliest tectonic structures in the Moinian", (Dunning, 1972, p. 188). He also points out that whereas the Dalradian sedimentation is regarded as lasting from about 700 m.y. ago until Lower Ordovician times, the main folding and metamorphism took place around 500 m.y. ago.

In south Renland the great thickness of alternations of thin psammites and pelitic rocks, locally with cross-bedding, suggests regular subsidence of a large basin of sedimentation to accommodate relatively shallow-water deposits, but little is known of the influence of palaeogeography or sedimentation represented by the allochthonous rocks in south Renland

Table 1. *Summary of the principal events in the structural evolution of south Renland*

		Faults; intramontane graben filled with late Palaeozoic molasse-type detritus; Renland and Milne Land formed horst-like area
		Injection of pegmatites and microgranites as the final manifestations of plutonic activity
Climactic tectono-metamorphic episode	High-grade metamorphism (?)	Warping on upright folds parallel trend of main monzonite sheet in south-east Renland; superimposed on earlier nappe structures to give domes and basins
		Grey granites of 'younger' generation formed in central Øfjord and Milne Land
		Migmatisation and granitisation of monzonites and earlier migmatites above the extensive monzonite sheet in south-east Renland; generation of grey-pink granites; probable K-metasomatism of originally more basic monzonites
		Injection of hypersthene monzonite or more basic parent as sheets in migmatised paragneisses and possible Flyverfjord-type basement gneisses in south-east Renland; lopolithic form of principal intrusion initiated warping (?)
	Maintained high-grade metamorphism	Small-scale shear belts
		Constrictional deformation of rocks sandwiched between rising mass at head of Rypefjord and nappes advancing from south-east; intensification of linear fabrics, locally extreme; fanning of schistosity and regional folding, including back-folds
		Rise of granite and mobilised basement in north-west; initiation of linear fabrics
		Evolution of regional nappes; advance from south-east to north-west; overthrusts; continued evolution of schistosities
		Migmatisation under granulite or transitional amphibolite-granulite facies conditions; generation of augen granites and emplacement; initial schistosity formation as protoclastic product; deformation of lamprophyres and aplites; intrafolial folds in paragneisses as nappes evolve

on the subsequent evolution of regional structure in the principal orogenic compressive episode in the inner fjord complex.

The earliest plutonic event in south Renland, and one of the most profound, was the migmatisation of the paragneisses and formation of the concordant sheets of augen granites, mobilisate in the gneisses and biotite-garnet-feldspar textures in the granites suggesting high temperature conditions giving rise to relatively dry melts. Protoclasis combined with vertical flattening gave rise to the schistose fabrics in the granite. Metamorphic mineral assemblages indicate that migmatisation took place under low pressure granulite or transitional amphibolite-granulite conditions over the whole of south Renland. On the grounds of provisional estimates of cordierite stability (TURNER, 1968), a mineral of local occurrence in south Renland and the Bjørneøer (KALSBEEK, 1969), the migmatisation probably took place under conditions of high heat flow at depths of no more than 15 km. The thickness of overburden, including higher-level nappes, in south Renland is unknown although a minimum thickness of 8–9 km might be inferred from estimates by HALLER (1971) for the metamorphism of kyanite schists adjacent to migmatites in Kejser Franz Joseph Fjord, which are similar to the non-migmatised kyanite schists west of Rypefjord.

Injection of the sheets of augen granite into the high-temperature paragneisses as buoyant, low density material may have initiated the nappe movements which culminated in the regional structures of the inner fjord complex. Schistose fabrics in the granites and migmatite foliation in the paragneisses are folded by the nappes, but intrafolial folds and boudinaged quartzites in the gneisses and folded lamprophyres and aplites in the granites with axial surfaces parallel to schistosity suggest a complex relation between migmatisation and the evolution of regional and small-scale structures. Mobilisate occurs locally in planes parallel to nappe axial surfaces indicating the persistence of high-grade conditions throughout the nappe episode.

As the nappes evolved and advanced north-west areas of basement made buoyant by regional heating and intrusion of granite masses were elevated to form obstructions to the nappe progress. Such a mass north of the head of Rypefjord and extending at least as far as the granitic rocks at the head of Edward Bailey Gletscher is regarded as causing the constraint that produced the east-north-east synforms in south-west Renland and the associated back-folding. Relief of stresses took place in the form of constrictional deformation with greatest finite elongation parallel to fold axes and concomitant formation of the prominent biotite, sillimanite and feldspar augen lineations. The structures swing round to the north-east in the area of Edward Bailey Gletscher, suggesting the east–west trends are effects of shape and site of elevated basement and granite masses. East–west structures reported further north of Scoresby Sund by HALLER (1970) may be the result of similar effects. That high-grade metamorphic conditions were maintained during this phase is indicated by the crystallisation of sillimanite and local mobilisate.

Discordant relations in the area of the southern spur of Edward Bailey Gletscher and Øfjord show that intrusion of hypersthene monzonites, which bear resemblance to the mangerite-jotunite suite (STRAND, 1960; DE WAARD, 1968), took place after the principal nappe movements in south-west Renland. Concordant intrusion of sill-like masses, the largest being 500 m thick and possibly with a lopolithic form, probably took place under continued high-grade metamorphic conditions. To this extent crystallisation of these igneous rocks may have taken place under granulite or transitional amphibolite-granulite conditions suggesting they have a charnockitic affinity (DE WAARD, 1968). Textures show that biotite and K-feldspar are late-stage minerals and may have formed as a result of regional potash metasomatism associated with a later phase of migmatisation and granitisation that disrupted monzonites and migmatised paragneisses within the basin outlined by the extensive, 500 m monzonite sheet. In the event of such metasomatism the original parent of the present hypersthene monzonite may have been more basic, perhaps noritic. Regional warping on north-north-west trends which is manifested by the spectacular arches and troughs along central Øfjord is broadly parallel to the trend of the extensive monzonite sheet in south Renland. This relation suggests the warping is associated with the basin development in the south-east, although late-stage north–south warps further north (HALLER, 1970) appear not to be related to any intrusions. The limitation of later migmatisation and granitisation to the area circumscribed by the main sheet of hypersthene monzonite indicates progressive retreat of regional thermal effects to the east and south-east during the course of the orogeny. Pegmatites and microgranites cutting transversely across the whole of the region appear to be the final manifestations of the waning plutonism.

The structural complexity and high grade of metamorphism in south Renland place this part of the inner fjord complex within the infrastructure (Unterbau) of the *stockwerke* envisaged by WEGMANN (1935) for the Caledonides of East Greenland. This scheme has been elaborated by HALLER (1955, 1970, 1971) who believes that the nappes in this level were produced by rising *migmatite bodies* which were constrained to spread laterally under the pile of rocks forming the superstructure (Oberbau). In areas north of Scoresby Sund, HALLER has recognised nappe-like structures with forms including domes, foreheads and mushrooms. The early structures in south Renland may have cores of either augen granite as in the closures in Rypefjord or migmatised paragneisses as in the large north-west facing closure extending from central Øfjord to upper Catalinadal. In this respect the nappes in south Renland differ from those described by HALLER and may not be directly attributable to lateral spreading of rising migmatites, but may involve migration of the augen granites. The synformal basins and related structures which formed during the high-grade metamorphism are geometrically similar to infrastructural elements north of Scoresby Sund, but the structures in Renland are regarded as products of 'synchronous refolding' of the type described from the Grenville province of Canada by WYNNE-EDWARDS (1963).

The later domes and basins whose profiles are exposed in central Øfjord and in the southern spur of Edward Bailey Gletscher differ significantly from the domal nappe-type structures described by HALLER, because they are late-stage products of superimposed folding.

The structures in south-west Renland also bear comparison with those illustrated in the dramatic sections across the Pennine nappes of the Western Alps (HEIM, 1922), but in spite of the many geometrical similarities, such as nappe forms and back-folding, the differences in basement-cover components and incidence of metamorphism are very marked. The Pennine nappes are cored by basement (pre-Mesozoic) rocks, whereas no basement is involved in the nappes in Renland although basement of Flyverfjord-type occurs in thrust sheets further west and north-west. Furthermore, whereas in the Penninic terrain blueschist facies metamorphism may have been contemporaneous with nappe emplacement, the principal metamorphism (Lepontine phase) of the Lower Pennines took place after the nappe movements (BEARTH, 1962; WENK, 1962). The Lepontine phase has Barrovian affinities whereas in Renland the metamorphism, which began very early in, or before, the nappe emplacement, is of low-pressure type.

Barrovian metamorphism has been described by STECK (1971) in the Charcot Land supracrustal sequence in the north-west of the inner fjord complex, and the abundance of kyanite west of Rypefjord suggests similar high-pressure conditions. STECK suggests that the metamorphism in the north-west took place in close association with the movements on the Hinks Land thrust which carried rocks of the Krummedal sequence and its basement over the Charcot Land sequence (figs 1 & 26). Following the thrusting and metamorphism, the Charcot Land complex was intruded by pegmatites which STECK relates to dome-like uplift of the basement. This history of events, although different in terms of metamorphic conditions, is broadly similar to the series of events in south-west Renland where uplift of basement occurred after the principal nappe translations and gave rise to constrictional deformations.

Aside from the detail of the structural evolution of south Renland in relation to metamorphism and other plutonic activity, one of the most significant conclusions arises from the comparison of these events with the climactic orogenic activity in the Caledonides of Scotland. There are many geometrical similarities, for example the reversals of nappe facing, and both Barrovian and low-pressure facies series are well-known as the principal components of the climactic episode of metamorphism in Scotland. Effects of blueschist metamorphism are also known in south-west Scotland where they are regarded in a plate tectonic model by DEWEY & PANKHURST (1970) as being contiguous, if not contemperaneous, with the climactic metamorphic effects in the Dalradian rocks. However, in great contrast to the association of the climactic metamorphism with events *after* the emplacement of the Moine and Dalradian nappes in Scotland (JOHNSON, 1963), the incidence of the climactic episode in Renland, whether it was Grenvillian or Caledonian, extended for a relatively longer period in relation to deformation beginning prior to, or very early in, the nappe phase and persisting through subsequent deformation and plutonic intrusion. A similar contrast exists between climactic events in Renland and the Western Alps.

TERTIARY IGNEOUS ROCKS

Minor intrusions related to the Tertiary igneous activity in the Scoresby Sund region are represented in south Renland by a few dykes of olivine dolerite and some plugs of pyroxenite which locally contain large blocks of host gneisses. The largest dyke of olivine dolerite is 15 m thick and outcrops in the cliffs of west Øfjord. It is equigranular with chilled margins and dips steeply north-west. The north-east trend of the dyke suggests intrusion was controlled by pre-existing fractures related to the set of late Palaeozoic normal faults. Other dykes with east–west trend were noted in the central parts of Catalinadal.

The pyroxenite intrusions outcrop north of the 920 m lake in Catalinadal (fig. 27). Like the dykes, it appears that the emplacement of the pyroxenites was also controlled by pre-existing fractures trending north and north-east. The pyroxenites are dark green-brown, medium grained, equigranular and nodular in weathered outcrop, commonly reducing to a loose gravel. The principal constituent is optically positive, colourless enstatite with exsolved micro-lamellae of clinopyroxene parallel to (100). Subhedral prisms of diopsidic augite occur in accessory proportions. Both pyroxenes show uralitic alteration on grain boundaries with rare development of colourless prismatic amphibole. Accessory biotite also formed at a late stage along pyroxene grain boundaries. Large grains of plagioclase which occur locally in excess of 10 % total mode may enclose smaller grains of pyroxene.

A coarse breccia on the west of the southern spur of Edward Bailey Gletscher, described by Chadwick (1971, fig. 1), is similar to large outcrops of breccia north of the 920 m lake in Catalinadal. The blocks of gneiss in these outcrops are angular, range from 2–50 m in size, and are contained in a matrix of pyroxenite. Boundaries of the intrusions with surrounding host gneisses are sharp and parallel to prominent fractures. The angularity of the included blocks suggests stoping along pre-existing fractures played an important part in the intrusion of the pyroxenites.

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Zusammenfassung

Renland liegt im Kern des südlichsten Teils der kaledonisch gefalteten Zone Ostgrönlands, zwischen 70° und 82° nördlicher Breite. Im südwestlichen Renland kommen migmatisierte Paragneise vor, die aus Sedimenten, ähnlich der spät pre-kambrischen Lower Eleonore Bay Gruppe, bestehen. Sie bilden eine vielfach verschuppte Folge von wenigstens 1500 m Mächtigkeit. Diese Migmatite werden von mächtigen konkordanten granatführenden Augen-Graniten durchsetzt. Man kann ihre Entstehung mit Faciesbedingungen der niedrig-Druck Granulite oder des Amphibolit-Granulit Überganges verknüpfen, die durch Migmatisierung der Paragneise erreicht wird. Diese Bedingungen dauerten an, während die Granite und die Paragneise zusammen gefaltet wurden und sich als regionale Decken mit nördlicher bis nordwestlicher Vergenz entwickelten. Wiederfaltung der Decken unter andauernden hochgradigen Bedingungen liess Strukturen entstehen, die lokal mit den Decken co-axial sind. Rückfaltung zeigt sich in Umkehrung des "facing" der Decken. Linearstreckungen von Sillimanit und Biotit sowie gestreckte Feldspataugen liegen parallel zu den Faltenachsen und zeigen, dass während späterer Stadien der Deckenphase und der Wiederfaltung Kompressionsdeformation herrschte. Die gerichtete Kompression wird erklärt durch das Ein-

zwängen der Gesteine Südwest-Renlands zwischen Decken, die von Süden vordrangen, und einer Grundgebirgsmasse im Norden, bestehend aus Granit und Gneis.

In Südost-Renland folgte der Deckenverformung das Eindringen konkordanter Lagen von Biotit-reichem Hypersthen-Monzonit (Mangerit). Die 500 m mächtige Hauptlage bildet den Rand eines Teils eines lopolithischen Beckens. Weniger mächtige Monzonitlagen, die in die Migmatite des Beckeninneren eingedrungen sind, sind durch andauernde Migmatisierung und Granitisierung weiter zerrissen worden. Stabile Vergesellschaftungen in Pyribolit-Restit weisen darauf hin, dass während dieses letzten Ereignisses, welches hauptsächlich auf das Becken beschränkt war, Bedingungen der Hornblende-Granulit Fazies erreicht waren. Offene Verbiegungen, die man der Monzonit-Injektion zuschreibt, sowie die Beckenbildung werden auf die Decken überlagert, die westlich der Hauptdecke liegen.

Abschiebungen nach Osten un Westen sind mit der Entwicklung der spät-paläozoischen und mesozoischen Sedimentbecken im Scoresby Sund Gebiet verbunden. Die Verteilung der Verwerfungen deutet darauf hin, dass Renland in spät-paläozoischer Zeit ein Horst war. Tertiärer Vulkanismus in Süd-Renland zeigt sich in seltenen Olivin-Dolerit Gängen und vereinzelten Pyroxinit Stöcken. Diese enthalten hier und da grosse Blöcke des Wirt-Gneises.

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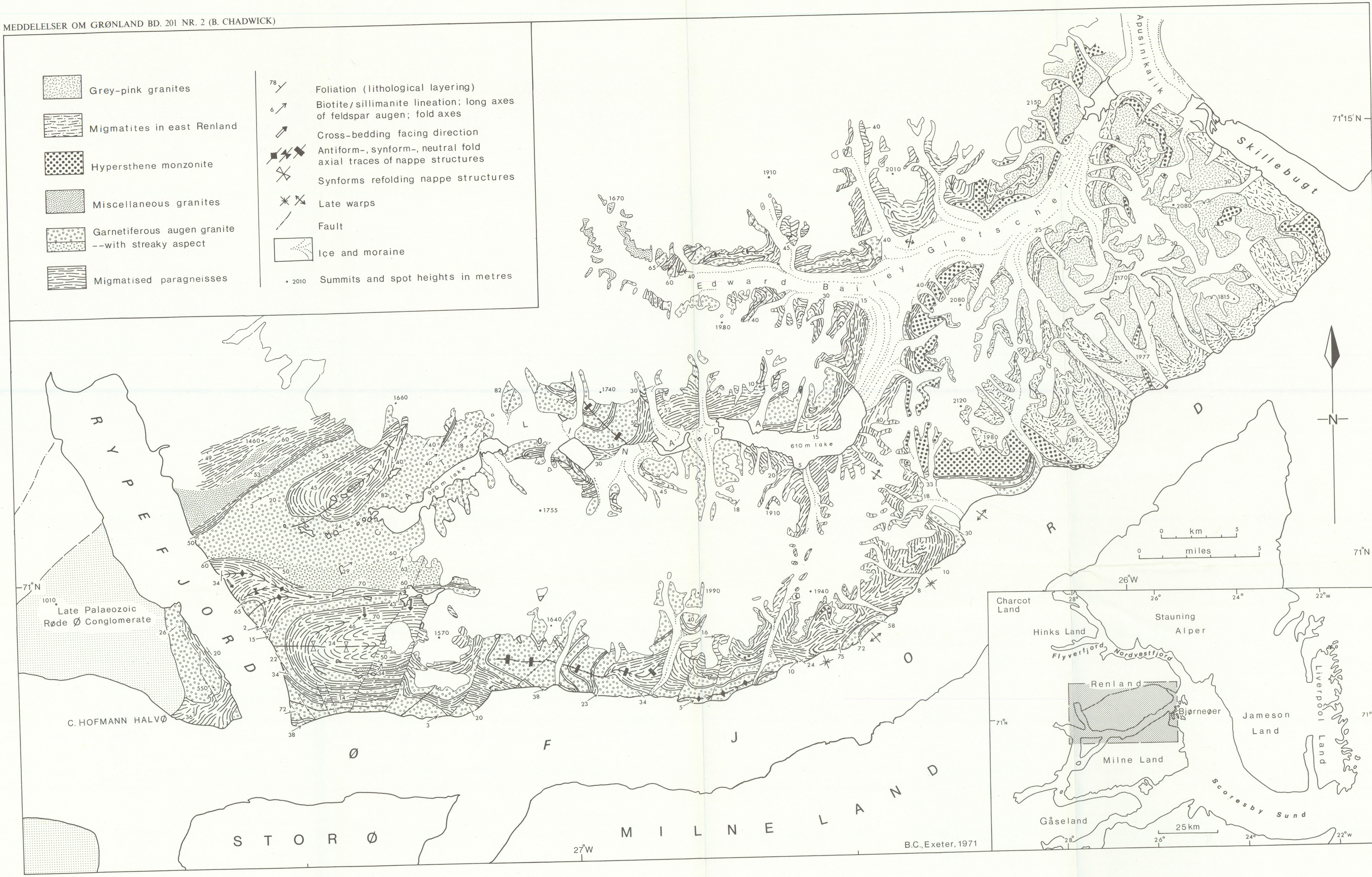
Færdig fra trykkeriet den 31. januar 1975.

GRØNLANDS GEOLOGISKE UNDERSØGELSE

THE GEOLOGICAL SURVEY OF GREENLAND

PLATE I

MEDDELELSER OM GRØNLAND BD. 201 NR. 2 (B. CHADWICK)



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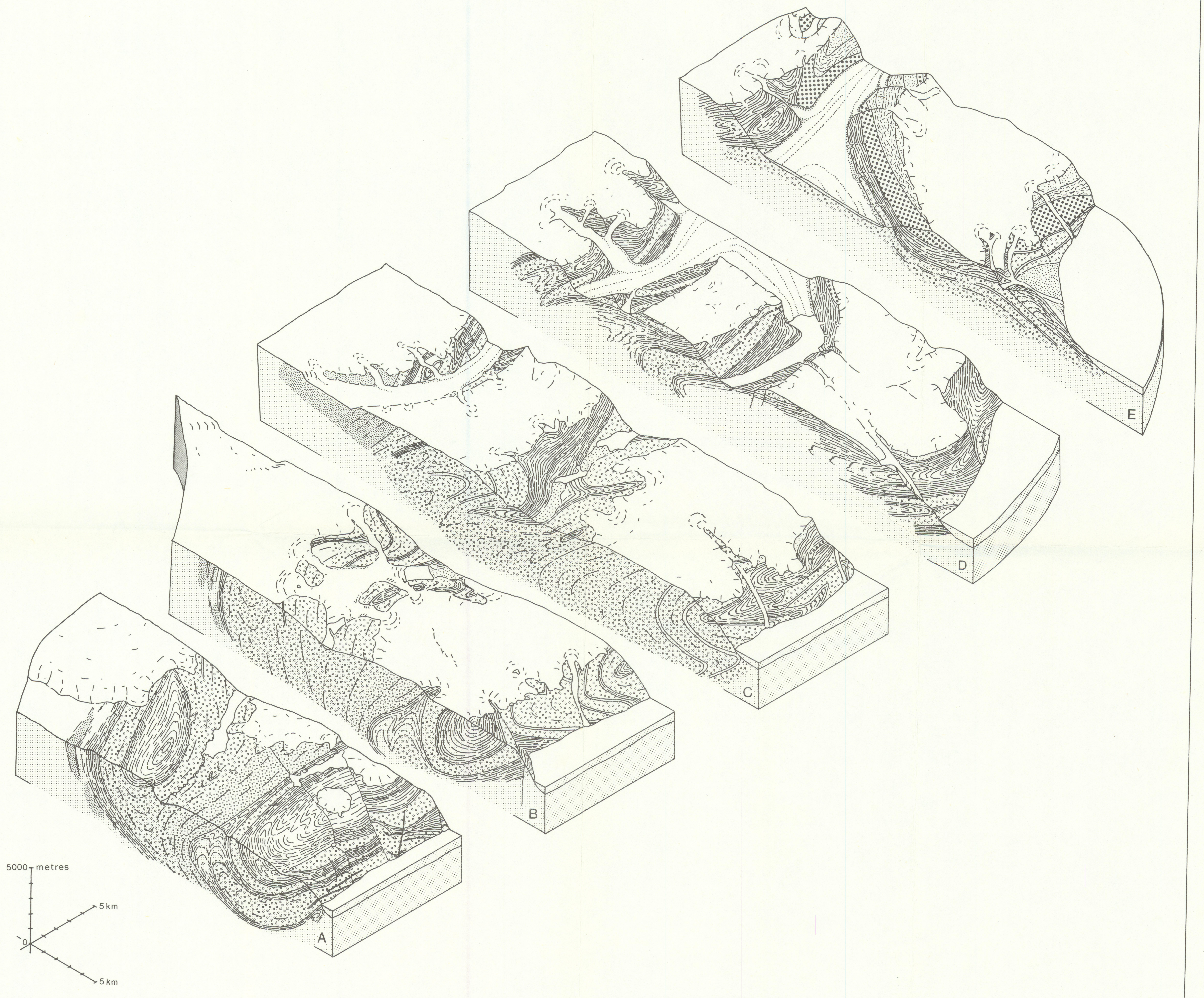
THE GEOLOGICAL SURVEY OF GREENLAND



B.C., Exeter, 1971