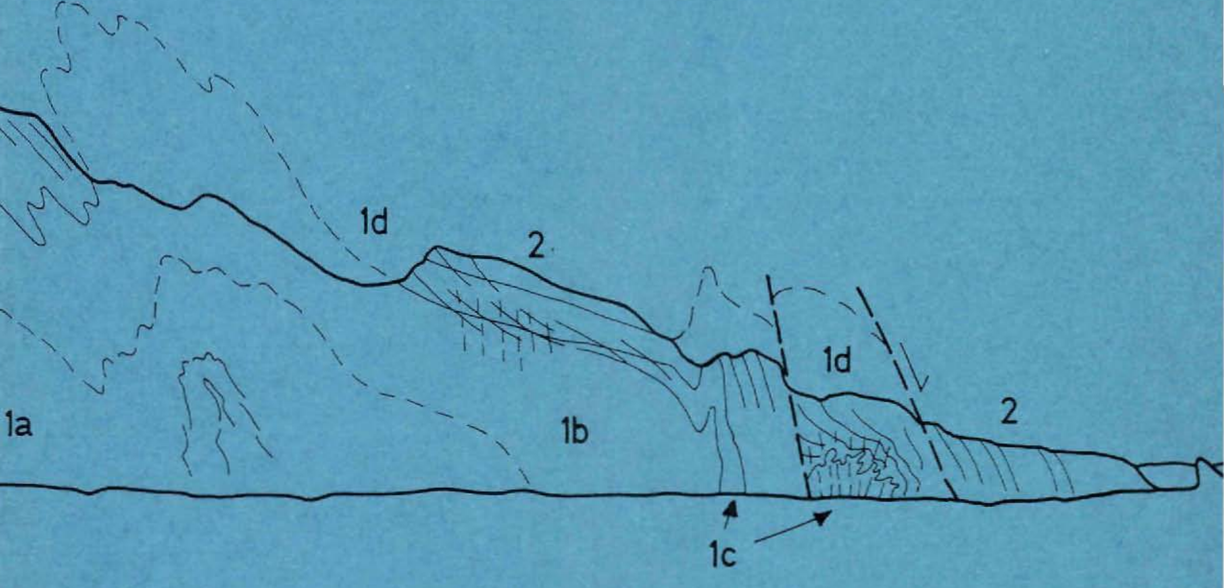
Structural and stratigraphic framework of the North Greenland fold belt in Johannes V. Jensen Land, Peary Land

by

Peter R. Dawes and N. J. Soper



GRØNLANDS GEOLOGISKE UNDERSØGELSE
RAPPORT Nr. 93
1979

Grønlands Geologiske Undersøgelse
(The Geological Survey of Greenland)
Øster Voldgade 10, DK-1350 Copenhagen K

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Abstract

Structural and stratigraphic details collected during reconnaissance field work in northern Peary Land in 1969 are presented to substantiate the rather general accounts of the North Greenland fold belt hitherto published. The structural detail, largely in the form of graphic profiles sketched in the field, is referred to a structural framework in which three main deformation phases are recognised.

The fold belt displays a roughly E–W zonation based on the progressive northerly increasing intensity of deformation and metamorphic effects that culminate along the northern coast in amphibolite-facies mineral assemblages in complexly folded schist lithologies. It is stressed that, while the conspicuous structural character of the fold belt is its northerly vergence seen particularly in the northernmost part, the detailed structural make-up of the fold belt is complex. Fold style and vergence vary considerably and the southern margin of the fold belt, autochthonous with respect to the platform, is characterised by south-verging folds.

Some stratigraphical data is presented particularly from the Lower Palaeozoic sequence at the southern part of the fold belt that illustrates the basinal clastic facies at the shelf-basin margin.

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Fig. 1. General view of the central Roosevelt Fjelde looking east towards Helvetia Tinde (1920 m) from peak 1433 m, north of A. Harmsworth Gletscher. August 8th, 1969.

INTRODUCTION

In this report we present field results of the geological survey of the North Greenland fold belt carried out in 1969 in northern Peary Land. The main aim of the report is to provide the structural details to supplement the general description of the fold belt that was presented to the 2nd International Symposium on Arctic Geology in San Francisco in 1971 (Dawes & Soper, 1973). That account, as part of a regional review paper dealing with the whole of northern Greenland, was necessarily a brief synopsis, as essentially are all descriptions of the fold belt included in other review papers (e.g. Dawes, 1971, 1976; Dawes & Peel, in press).

With this background and in view of the systematic mapping of the fold belt to be undertaken in the coming years by GGU, it seems appropriate to elucidate the structural and stratigraphic details that formed the basis of the published descriptions referred to above. All the material presented here results from the 1969 field work and several of the structural profiles figured here were prepared for the San Francisco meeting but were omitted by space restrictions (Soper, 1971).

Some general results of the field work have been given in a short preliminary paper (Dawes & Soper, 1970). Isotopic age determinations of material collected have been discussed in several accounts (e.g. Dawes & Soper, 1971; Larsen *et al.*, 1978) while the Lower Palaeozoic fold belt faunas collected were reported on by Bjerreskov & Poulsen (1973).

Field work, physiography and logistics

The 1969 geological work was carried out during the British Joint Services Expedition that operated from May to August in the northern peninsula of Peary Land, Johannes V. Jensen Land, an area of about 10 000 km^2. This 12-man military expedition, to which the authors were attached as geologists, had a varied scientific programme in which the main aims were a tellurometric-cartographical survey, and geological studies (Peacock, 1972).

Johannes V. Jensen Land is characterised by an alpine mountain range that contains several peaks over 1500 m. The mountains are cut by numerous valley glaciers, and upland consists of ridges usually culminating in sharp peaks (fig. 1). The western and central part of the mountain range – the Roosevelt Fjelde – contains Helvetia Tinde, which at about 1920 m is the highest peak in North Greenland. Here the mountains have steep walls and sharp outlines that generally expose excellent structural profiles. Farther east in the H. H. Benedict Bjerge, mountains have a lower altitude, ridges are rounded with long smooth, heavily mantled slopes leading to poorer exposures. This alpine topography contrasts markedly with the region south of Frederick E. Hyde Fjord which is generally plateau terrain of lower altitude etched out of homoclinal strata.

Large ice-free areas occur around Frederick E. Hyde Fjord and Frigg Fjord while an

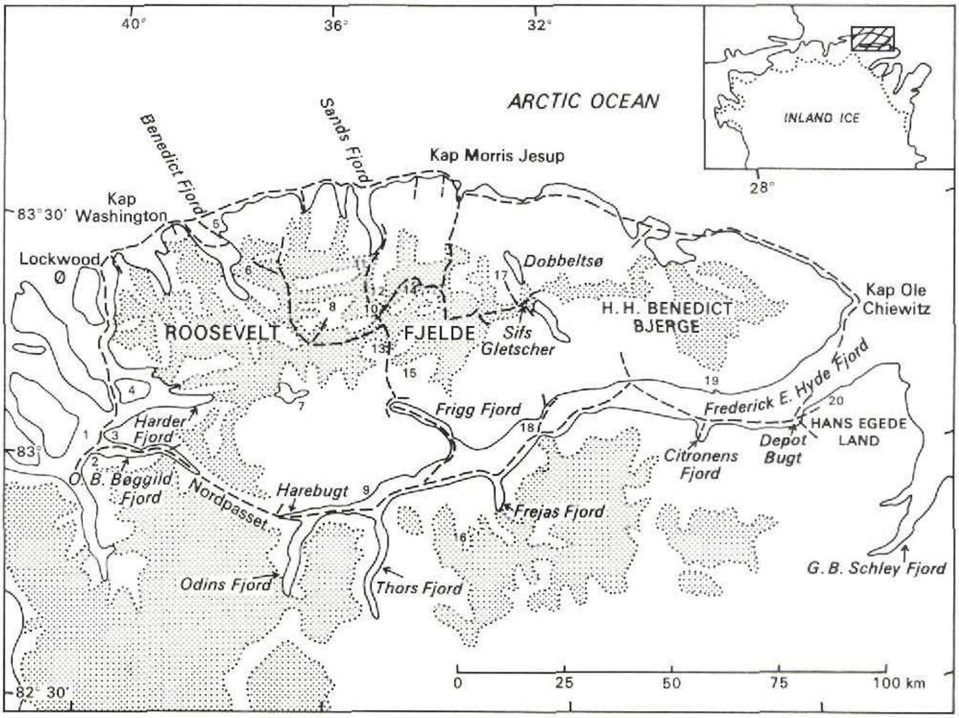

Fig. 2. Index map of Johannes V. Jensen Land showing place names and the 1969 travelling route. 1: Dilemmasund; 2: Kap Bopa; 3: Kap Holger Danske; 4: Moa Ø; 5: Kap Cannon; 6: A. Harmsworth Gletscher; 7: Columbus Sø; 8: Helvetia Tinde; 9: Kap Mjølner; 10: Polkorridoren; 11: Nordgletscher; 12: Paradisfjeld; 13: Sydgletscher; 14: Mary Peary Tinde; 15: Nysne Gletscher; 16: Nordkronen; 17: Birgit Koch Tinde; 18: Midtkap; 19: Flammens Fjord; 20: Hundeskrænten.

extensive flat, low-lying area covered by varied Quaternary deposits forms the entire outer coast east of Kap Morris Jesup.

In North Greenland, ice-locked throughout the year, logistics are generally difficult, and particularly so in the most northerly mountainous terrain of Johannes V. Jensen Land. Transport for the 1969 field work was by motor skidoo and sledge on the sea-ice in May and June and on ski and foot with pulka inland later in the season. The main expedition routes and the areas visited by one or both authors are summarised in fig. 2.

The geological investigations were essentially of a reconnaissance nature and in many cases, because of other priorities or lack of time, observations were necessarily cursory. During the first phase of the expedition – a 1000 km long, anticlockwise sea-ice traverse around Johannes V. Jensen Land – observations were mainly restricted to coastline localities but with several inland traverses. During the 2nd phase – overland exploration of the central Roosevelt Fjelde – stratigraphic and structural details were obtained by studying sections across the fold belt and it was during this phase that the main tectonic-metamorphic framework was erected in the central Roosevelt Fjelde (Soper & Dawes, 1970; Dawes & Soper, 1973).

Other geological exploration

Geological investigations in Johannes V. Jensen Land have been sparse. The early U.S. expeditions led by A. W. Greely and R. E. Peary reached the northern coast of Peary Land but recorded little geological information. The deformed and metamorphic rocks of the fold belt were noted and sampled by J. P. Koch and A. Bertelsen at the mouth of Frederick E. Hyde Fjord during the Danmark Expedition (1906–1908) (Bøggild 1917; Ellitsgaard-Rasmussen, 1955). Lauge Koch on his sea-ice traverse in 1921, during the Danish Bicentenary Jubilee Expedition (1921–1923) established the structural unity of a 'Caledonian' E–W trending belt of folding and metamorphism across northern Greenland. He noted various structural details, the high-grade mica-schist lithologies at, and west of, Kap Morris Jesup and the presence of younger volcanics and basic dykes (Koch, 1923, 1925).

During the Danish Peary Land Expedition (1947–1950) a rock and sand collection from the Frederick E. Hyde Fjord area provided lithological information from the southern margin of the fold belt although the main structural study was carried out in Nansen Land farther to the west (Ellitsgaard-Rasmussen, 1950, 1955).

The first mapping work in Johannes V. Jensen Land was carried out during a S–N foot traverse across the central Roosevelt Fjelde by E. Fränkl & F. Müller in 1953. Fränkl (1955) described the main rock lithologies and erected a lithostratigraphic subdivision of the central fold belt sequence. He stressed the northerly overturning of folds, and interpreted the tectonic development in terms of intense superficial thrusting and northerly-directed nappes.

The only other geological field work prior to 1969 consisted of scattered observations, mainly of Quaternary geology, made by W. E. Davies and associates in 1960 during helicopter reconnaissance in search of ice-free emergency landing sites (Davies & Krinsley, 1961).

During Greenarctic Consortium's field work in northern Greenland between 1969 and 1973 (mainly on the southern platform terrain) only sparse information was collected in northern Peary Land and this is incorporated into regional photo-geological maps (personal communication to GGU). In 1978, a fully airborne 3-year mapping programme was initiated by GGU in Peary Land and some structural and stratigraphic work was carried out in the southern margin of the fold belt in the Frederick E. Hyde Fjord region (Pedersen, 1979; Hurst, 1979).

Regional geological setting

The rocks of Johannes V. Jensen Land form the easternmost part of a regional, generally E–W trending basin flanking to the north the Precambrian craton and stable platform region. This basin represents the Franklinian miogeosynclinal segment of the Innuitian orogenic system that stretches through the Arctic Islands of Canada and across northern Greenland (Thorsteinsson & Tozer, 1970; Haller, 1970).

In Greenland the basin forms a fold belt that occupies the entire northern coast facing the Arctic Ocean. The southern margin of this North Greenland fold belt occurs south of Johannes V. Jensen Land and is traceable some 600 km westwards to Hall Land and the Nares Strait. It is continuous with the central Ellesmere Island fold belt of Canada that displays similar lithological character but shows some variance in tectonic composition (Kerr, 1967; Dawes, 1973).

The homoclinal platform sequence south of the North Greenland fold belt consists of Precambrian to Silurian (possibly Devonian), dominantly carbonate strata which pass northwards, into basinal clastics of the fold belt. A late Palaeozoic–Mesozoic–Tertiary cover sequence (Wandel Sea Basin) overlies the south-eastern part of the fold belt in eastern Peary Land. No strata of this sequence have been recorded in Johannes V. Jensen Land. In Peary Land the fold belt terminates to the north against a major Tertiary thrust (Kap Cannon thrust) beneath which are volcanics and associated sediments of presumed late Phanerozoic age. Several generations of basic dykes, at least some of which are of Cretaceous age, cut the fold belt.

The structural and metamorphic pattern of the fold belt is the product of both Palaeozoic (presumably mainly Devonian) and late Phanerozoic (Cretaceous–Tertiary) diastrophism. The effects of these two orogenies have yet to be fully unravelled. The key to this may lie in the presence of Mesozoic dyke swarms which, if correctly dated, must cut structures attributable to the earlier orogeny but are affected by the later tectonic and thermal events.

STRATIGRAPHY

The following stratigraphic notes describe some of the main lithologies of the fold belt and for descriptive convenience the fold belt is divided into three regions. Much of the new information given here comes from the southern region at the margin of the fold belt.

The southern region

In this region sections were examined at various localities from Kap Bopa and O. B. Bøggild Fjord in the west through Nordpasset and Frederick E. Hyde Fjord to the area around Depot Bugt in the east. Three main successions are described.

Carbonate and psammite succession

Two fault-separated sequences, both containing meta-igneous rocks, outcrop in the area to the east and south of Depot Bugt in eastern Frederick E. Hyde Fjord. A drift-filled major valley, interpreted as the eastern extension of the Harder Fjord Fault, divides a dominantly carbonate sequence in the north, forming the spectacular cliffs of Hundeskrænten, from a southern sequence of psammitic rocks that form the range of hills south-east of Depot Bugt. The coast west of Depot Bugt towards Citronens Fjord is composed of rocks of another succession – the Silurian basinal clastic rocks described later.

The *northern sequence* was investigated in the multicoloured cliffs of Hundeskrænten immediately east of Depot Bugt. It is severely deformed and composed of dark grey and buff limestones and calcareous shales, white to cream coloured quartzites, conglomerates and units of meta-igneous rock. Southwards towards the Harder Fjord Fault, poor exposures of younger? brown-weathering calcareous sandstone and pebbly sandstone occur.

The limestones, often brown to orange weathering, are well exposed in the steep cliffs of Hundeskrænten, where large-scale fold closures with some dislocations are depicted by repetition of conspicuous dark and light coloured limestone units (fig. 3). Cleavage is well developed and fine-grained carbonate lithologies are slates and in places calcareous phyllites. Calcite veining is common.

The quartzites are typically brown to grey-weathering, many have a sugary texture and in places concentration of mafic minerals produces a crude banding. The conglomerates, several metres thick, are polymict containing rounded pebbles of quartzite and chert with some shale. Many have a red colouration and display thin hematite veining.

The meta-igneous rocks are green 'metabasalts' containing chlorite, epidote and amphibole and they are apparently concordant layers, the largest noted being 15 m thick. These rocks pre-date the development of the main cleavage that severely affected the limestone and shale lithologies. Their formation as either sills or extrusives remains an open question.

Fig. 3. Coastal cliffs at Hundeskrænten showing a major fold closure in the carbonate-sandstone-shale sequence. Cliffs about 350 m high.

The *southern sequence* is composed of folded, thin to medium bedded, light brown weathered, white to cream quartzites of rather homogeneous lithology with some ripple marks, containing dark green 'metabasalt' rocks. This sequence makes up distinctive terrain of dark and light coloured ridges that forms the lower part of a south-east trending range of hills. The summits of these hills, composed of buff weathering, rather flat lying, presumably younger strata, were not visited in 1969.

The meta-igneous rocks form both cross-cutting dykes as well as concordant layers but the age relationship between these two forms is unknown. The igneous rocks are of similar type and show the same type of alteration and age relationship to the main cleavage development, as in the northern sequence. In several places transitions exist between meta-gabbro with preserved igneous texture, through foliated rock to, at the margin of some bodies, basic amphibole-bearing schist. Although much of the meta-igneous material seen in 1969 was of intrusive aspect, Christie & Ineson (1979) record units of volcanic rocks in the sequence between Depot Bugt and G. B. Schley Fjord.

Age, stratigraphic relations and faulting

The age and stratigraphic relationship of the two sequences are unknown. No fossils were found. From regional considerations a Proterozoic age was suggested for the southern sequence that stretches towards G. B. Schley Fjord and that has similar lithological characters to those of the psammitic-igneous sequence that occurs at the base of the platform succession in the south (Dawes, 1976). This age has been confirmed by Christie & Ineson (1979) who record strata of the Cambrian? Portfjeld Formation overlying the quartzite-igneous rocks between Depot Bugt and G. B. Schley Fjord. If the meta-igneous rocks in the northern sequence are of similar age to those to the south, then a Proterozoic age for at least part of the Hundeskrænten sequence is evident. Moreover, the carbonate sequence of Hundeskrænten shows general lithological similarity to the Paradisfjeld Group of the central Roosevelt Fjelde (see below) which is considered to form the base of the exposed succession in the central part of the fold belt and which must contain Cambrian or even older strata (Table 1).

Table 1. Stratigraphical schemes for the three regions of Johannes V. Jensen Land

	Southern region O. B. Bøggild Fjord – Frederick E. Hyde Fjord	Central region	Roosevelt Fjelde – Polkorridoren	Northern region Sands Fjord – Kap Morris Jesup
DEV. / SILURIAN	Flysch	SYDGLETSCHER GROUP	? 3e Sydgletscher Sandstone (calc-sandstone) 3d Upper Sydgletscher Shales (calcareous and graphitic slates) 3c Sydgletscher Quartzite (black quartzite) 3b Lower Sydgletscher Shales (calcareous and graphitic slates) 3a Nysne Gletscher Mudstones (purple and green mudstones)	?
SILURIAN / ORDOVICIAN	Formation C	POLKORRIDOREN GROUP	2b Polkorridoren Psammite (arkosic psammite) 2a Rusty, green quartz phyllite	Sands Fjord Quartz phyllites
ORDOVICIAN	Formation B			– – – – – –
CAMBRIAN	Formation A ? Hundeskrænten carbonates and clastics	PARADISFJELD GROUP	1d Yellow limestone 1c Green calcareous phyllite 1b Dark grey limestone 1a Graphitic and calcareous phyllites	Ulvebakkerne Marbles Kap Morris Jesup Quartz phyllites
PROT.	? Depot Bugt clastics and igneous rocks		?	?

An age assignment of the strata recognised in the southern region is attempted; elsewhere ages are unknown and thus any correlation between the regions is speculative. Stratigraphy of the central region is from Dawes & Soper (1973), the southern region is modified from Dawes (1976) and the units of the northern region are from Fränkl (1955).

The Depot Bugt region is characterised by prominent block faulting and several WNW-trending faults parallel to the Harder Fjord Fault traverse the country. Although all the strata noted in the northern sequence appear to be in stratigraphic order, the presence of such faults makes it uncertain at the present stage of investigation whether all the lithologies are part of a single sequence.

Small but spectacular features seen to the west and south-east of Depot Bugt are bright orange and yellow-weathering gossan areas, containing sulphur, iron compounds and sulphates, as well as thermally heated brittle shales, sometimes rusty-weathering. These features show affinities to the 'solfataras' described from Jørgen Brønlund Fjord (Troelsen, 1949). At Depot Bugt they are aligned on important faults and their presence may well have regional volcanic significance (Dawes & Peel, in press).

Basinal clastic succession

A thick and varied sequence of Lower Palaeozoic rocks, characterised by limestone conglomerate and breccia is exposed on both sides of O. B. Bøggild Fjord and Nordpasset and

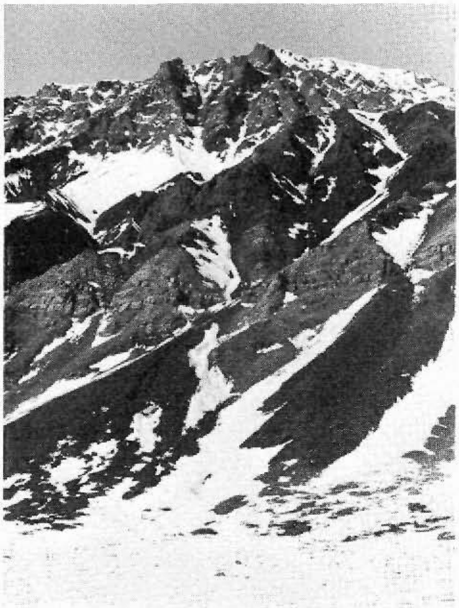

Fig. 4. View of coastal cliffs, north side of O. B. Bøggild Fjord showing tripartite division in mainly Ordovician clastic succession (see fig. 5).

throughout much of Frederick E. Hyde Fjord, where in many places, particularly in Nordpasset, steeply inclined sections exist. Some general remarks on the succession have been given by Dawes (1976).

In the field the succession was divided into three un-named formations and these are retained here (figs. 4 & 5). The lower two form the light and dark banded outcrops that are particularly conspicuous as a zone on the northern side of inner O. B. Bøggild Fjord, stretching continuously along Frederick E. Hyde Fjord to Frigg Fjord. Sections were measured through formations on the northern sides of O. B. Bøggild Fjord and Harebugt. The upper formation is a grey to brown-weathering sequence of more monotonous aspect and it was studied at various localities, particularly on the south coasts of O. B. Bøggild Fjord and Frederick E. Hyde Fjord as far east as Depot Bugt.

Formation A

This formation consists mainly of yellow-weathering, generally thin bedded, grey quartzitic sandstone with interbedded dark grey to black, often rusty, shales and parallel laminated siltstones. Some sandstones are calcareous and show ripple drift cross lamination. The sandstones vary from fine to coarse grained and a few thin conglomerate beds contain shale and siltstone fragments.

The formation is characterised by several massive and resistant, often clast-supported, limestone breccio-conglomerate units that can be up to 10 m or so thick. The clasts, up to 1 m in size, are composed of a variety of subrounded to angular limestone and dolomite types

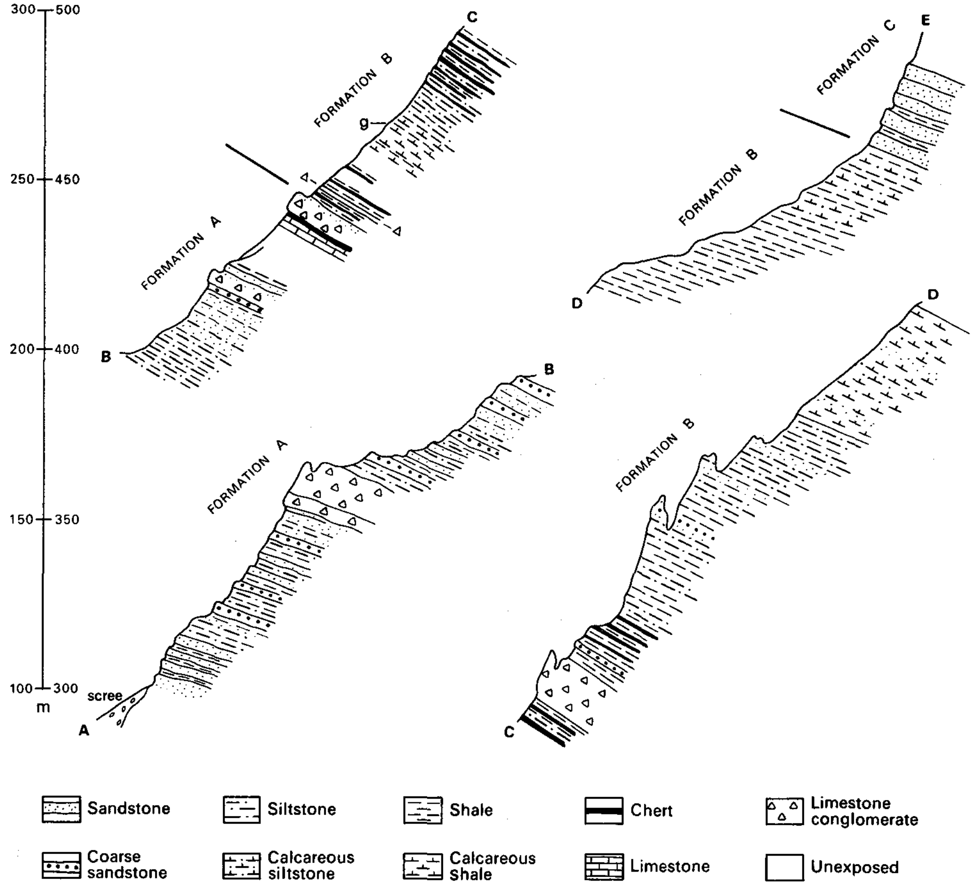

Fig. 5. Sketch profile on the north side of O. B. Bøggild Fjord showing formations A, B and C. Section is continuous from A to E. Figures on vertical scale are altitude in metres above sea level. g = locality of early Ordovician graptolites (GGU 53488) described in Bjerreskov & Poulsen (1973).

with many elongate blocks. At O. B. Bøggild Fjord near the top of the formation, thin beds of yellow and grey, striped to banded limestone occur and several limestone conglomerates with chert fragments grade upwards into calcarenite (fig. 6).

Thickness and age

The thickness of the formation at O. B. Bøggild Fjord is at least 200 m but the base was not seen. Apart from possible worm traces, no fossils were discovered. However, in view of the early Lower Ordovician age for part of the overlying formation (see below) it seems probable that this formation is partly Cambrian.

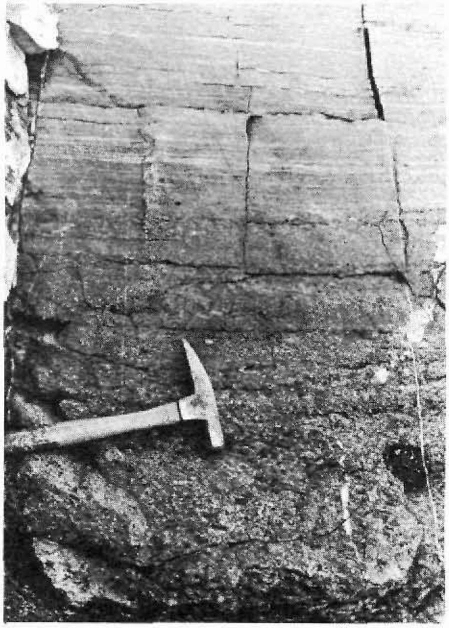

Fig. 6. Graded-bedded unit from uppermost part of formation A; limestone conglomerate at base grading upwards into calcareous sandstone. O. B. Bøggild Fjord.

Formation B

At O. B. Bøggild Fjord this formation overlies conformably Formation A (fig. 5). It consists of dark-weathering, grey to black shales, laminated siltstones that show a varying intensity of silicification, and thin beds of black chert. Some yellow-weathering, grey calcareous mudstone beds and several thin beds of calcareous sandstone of fine to coarse grain size occur.

Talus beds of limestone conglomerate and breccia, showing chaotic arrangement of clasts, are common. These units vary in thickness laterally; at Harebugt (fig. 7) regularly spaced beds reach up to 10 m thick but elsewhere prominent ridges of carbonate breccio-conglomerate reach perhaps several tens of metres thick. Many of the breccio-conglomerates are

Fig. 7. Thin-bedded silicified siltstone and black cherts with limestone conglomerate beds. Formation B, Harebugt.

polymict and some contain black chert and calcarenite clasts, as well as various limestone lithologies. Grading from conglomerate to calcarenite occurs in some beds.

Thickness and age

At O. B. Bøggild Fjord the formation is approximately 230 m thick but farther east, despite structural complications, up to 400 m of strata was estimated to occur.

Graptolites, collected near the base of the formation at O. B. Bøggild Fjord and at Harebugt, contain a fauna referable to the *Tetragraptus approximatus* Zone, indicative of an early Ordovician (early Arenigian) age (Bjerreskov, *in* Bjerreskov & Poulsen, 1973). At Harebugt and at Kap Bopa, the presence of the graptolite *Isograptus caduceus* referable to the *Isograptus caduceus* Zone, indicates a somewhat younger age of Lower Ordovician (uppermost Arenigian) strata.

Formation C

This formation consists of well-bedded, grey to brown and yellow-weathering sandstone, interbedded with siltstone and shales and in which several mappable limestone breccio-conglomerate units occur. The formation shows considerable lateral lithological variation and generally becomes more sandy upwards.

The sandstones, mainly calcareous turbidites, are fine to medium grained that vary to occasional coarse-grained, angular pebbly sandstone. They form tabular, often graded sheets with erosive bases. In coastal sections between Thors Fjord and Frejas Fjord certain graded units reach over 20 m in thickness.

The thin-bedded shales and siltstones are characteristically interbedded with the sandstones but occasionally thick shale units occur (fig. 8).

The limestone breccio-conglomerates appear to be more common in the lower part of the formation and they reach several tens of metres in thickness and contain carbonate clasts up to several metres in diameter.

Thickness and age

At O. B. Bøggild Fjord the formation overlies formation B, apparently conformably, and in the immediate coastal area it must be at least 250 m thick. From sections elsewhere in Frederick E. Hyde Fjord, the composite thickness must be at least 600 m. The formation is a facies equivalent to part of the Ordovician and possibly the whole of the platform carbonate sequences of the south. It passes upwards into the main flysch sequence that south of Frederick E. Hyde Fjord forms a broad belt of relatively undisturbed strata representing the youngest rocks of the platform. According to Christie & Peel (1977) the flysch sequence in central Peary Land approaches 1 km in vertical thickness.

Several localities, e.g. Citronens Fjord, east of Thors Fjord (figs 8 & 12) and west of Depot Bugt, shelly faunas (mainly brachiopods, corals, trilobites and gastropods) were collected from limestone breccio-conglomerate. The most extensive fauna from Thors Fjord, suggests a general Lower Silurian (late Middle Llandovery) age (Poulsen, *in* Bjerreskov & Poulsen, 1973). However, the presence of certain brachiopods may indicate a somewhat

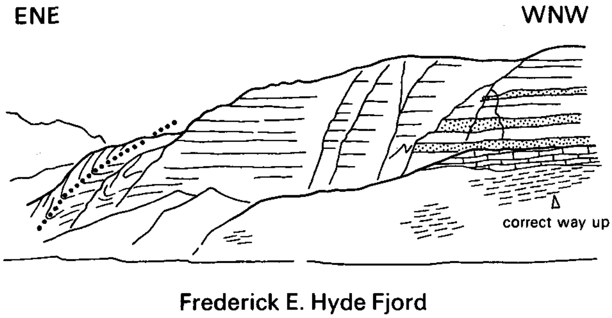

Fig. 8. View south of coastal cliffs between Thors Fjord and Frejas Fjord showing fossiliferous Silurian limestone and conglomerate unit overlying a shale unit (formation C). Main cliffs are composed of graded-bedded calcareous greywacke in which a large-scale south-verging fold is visible at the margin of the fold belt.

wider range of Lower Silurian strata (A. J. Boucot, personal communication; see Dawes, 1976). Faunas collected recently from the Thors Fjord locality by J. M. Hurst (personal communication) suggest that the lowest outcrops at the coast at that locality are uppermost Ordovician whilst graptolites from shales about 150 m above indicate strata as late as middle Upper Llandovery.

Facies significance

North Greenland provides an excellent example of a major fold belt that, because of its autochthonous margin, allows more or less continuous stratigraphic outcrop from the platform into the shelf and basin region of the geosyncline. From rock samples collected by early expeditions (Ellitsgaard-Rasmussen, 1955) it was known that a predominantly clastic succession characterised the southern margin of the fold belt in the Frederick E. Hyde Fjord region. This was confirmed by the 1969 field work when faunal proof of an Ordovician and Silurian age was obtained for the widespread sandstone-shale-chert succession that contrasts markedly with the classical Lower Palaeozoic carbonate platform sequence of the south (Troelsen, 1949).

A notable feature of the Lower Palaeozoic succession is the presence of frequent carbonate conglomerates and breccias that occur as discrete units and show lateral thickness variation. One important type is breccia in which the clasts show complete disorganisation and which have been interpreted as olistrostrome deposits derived from the edge of the carbonate platform (Dawes, 1976). Many of these deposits are characterised by large blocks of carbonate and although clast size can vary considerably within a single bed, some beds have smaller and more uniform clasts. A second major type is bedded carbonate units which show grading from carbonate conglomerate, often polymict, into calcareous sandstone, while a third type comprise intraformational conglomerates and breccias derived by fragmentation of nearby carbonate material.

Similar fragmental carbonate deposits have been recorded worldwide in Palaeozoic successions bordering carbonate shelves and banks (McIlreath & James, 1978). Striking examples are the Cow Head breccia of Newfoundland (Hubert *et al.*, 1977), the Sekwi Formation of the Mackenzie Mountains (Krause & Oldershaw, 1979) and the Ancient Wall complex of Rocky Mountains, Alberta (Cook *et al.*, 1972). While the conglomerate types recognised in the O. B. Bøggild Fjord – Frederick E. Hyde region must differ in mode of formation, from presumably allochthonous debris flows to more distal forms with finer clast size and graded bedding, to more or less autochthonous intraformational beds, their presence is an indication of the conditions and relationship to the platform-shelf edge in Ordovician–Silurian time.

In Peary Land, the northernmost exposures of undisturbed platform carbonates are the Silurian limestones in Odins Fjord that underlie the main Silurian flysch development (Hurst, 1979). Thus the basinal clastic succession accurately fixes the basin margin to the south of Frederick E. Hyde Fjord.

Strata akin to the Peary Land succession, characterised by redeposited limestone units, presumably mark the basin–shelf margin throughout much of the Franklinian geosyncline. For instance, a strikingly similar and undoubtedly equivalent succession occurs in the Hazen Trough in north-eastern Ellesmere Island, Canada (Trettin, 1971). Particularly noteworthy is the Hazen Formation composed of bedded chert, graptolitic shale, siltstone, breccia and redeposited limestone of early Lower to late Middle Ordovician age, that is a close correlative of formation B in Peary Land. The more quartz-rich facies of the underlying strata (formation A) suggests correlation with the Grant Land Formation of early Ordovician and older age while the calcareous greywacke, siltstone and shale turbidite facies forming the uppermost part of the succession in northern Greenland and representing a major regional event, correlates with the Imina Formation of Ellesmere Island.

Multicoloured shale succession

Red and green shales exposed at the head of Frigg Fjord were referred to as the Frigg Fjord Mudstones by Fränkl (1955). These rocks can be traced in an E–W trending belt south of the Harder Fjord Fault both to the west and east of the type area. Exposures at Frigg Fjord are generally poor but the hills surrounding the fjord reveal several conspicuous purple shale outcrops together with subsidiary green and buff shales.

This sequence outcrops also in Frederick E. Hyde Fjord, and at Midtkap and coast to the east, a highly contorted and in places fractured sequence contains in addition, yellow-weathering calcareous siltstones and intercalated shales, often in graded units. The Harder Fjord Fault separates this sequence from a typically banded sequence of alternating yellow- and grey-weathering limestone with some siltstone and shale in which green metamorphosed basic igneous material exists.

Age, stratigraphic relations and faulting

Stratigraphic relations of the two sequences are uncertain because of faulting. No determinable fossils were encountered although a rodded structure in tectonically compressed dark bluish grey and pale grey limestones from the sequence north of the fault may be organic.

Fränkl (1955) correlated the Frigg Fjord Mudstones south of the Harder Fjord Fault with certain shales north of the fault in the Sydgletscher area. However, because of the intervening fault this correlation was questioned by Dawes & Soper (1973) and the shales north of the fault were referred to as the Nysne Gletscher Mudstones and placed at the base of the

Sydgletscher Group. (It should be mentioned that in fig. 6 of that paper, the Frigg Fjord Mudstones were erroneously given the same ornament as the Nysne Gletscher Mudstones). The age of the restricted Frigg Fjord Mudstones is more uncertain since relation to the fossiliferous basinal clastic Lower Palaeozoic succession of Frederick E. Hyde Fjord is as yet unknown. However, in view of the regional structural pattern with strata as old as early Ordovician being brought up by large-scale folds at the fold belt margin (see later) the presence of Cambrian and even Proterozoic rocks in the area north of Frederick E. Hyde Fjord is likely.

The Harder Fjord Fault is a zone composed of several fault and crush planes. At Midtkap, an interesting feature in the zone is the presence of altered acidic and basic igneous rocks, possibly intrusive plugs, while at Frigg Fjord several E–W trending dolerite dykes (of possible Cretaceous age) are conspicuously aligned in the fault zone. Some post-dyke crushing can be determined. At Midtkap, certain orange, green, yellow and white colouration of shales, that are often rusty, suggests mineralisation associated with the fault zone, perhaps akin to the mineralisation already described from Depot Bugt.

The central region

Description of the main succession of central Roosevelt Fjelde between Frigg Fjord and Sands Fjord has been presented elsewhere (Dawes & Soper, 1973). The tripartite group subdivision is summarised in Table 1. The formations so far recognised are considered to be sequential units with normal stratigraphic relations, although in places boundaries are tectonised and slide zones exist. This stratigraphy was mapped on the ground between the Benedict Fjord – A. Harmsworth Gletscher area in the west through the classical Polkorridoren area of Fränkl (1955) and towards Døbbeltsø.

The Polkorridoren Group forms a prominent central clastic belt with many of the high alpine summits of the Roosevelt Fjelde, including Helvetia Tinde. It is of unknown but substantial thickness and is a resistant, brown-weathering sequence of arkosic arenites typically developed in upward fining units many metres in thickness that in many places show sulphide mineralisation. This group must also constitute much of the eastern part of the region – the H. H. Benedict Bjerge – as well as stretching far to the west. It is a turbidite sequence and although its age is as yet undetermined, it may well represent the initial expression of the extensive development of flysch that occurs across northern Greenland and that is known to have a Silurian–Devonian age range (Dawes, 1976; Christie & Peel, 1977).

Age and stratigraphic relations

The actual contact between the Polkorridoren Group and the Sydgletscher Group has not been observed but from structural evidence the latter group in considered the youngest. While this relationship needs testing in the field, it is more certain that the dominantly carbonate and calcareous phyllite rocks of the Paradisfjeld Group underlie the clastic sequences of the Polkorridoren and Sydgletscher Groups (fig. 27).

From regional considerations the succession is considered to be of mainly Lower Palaeozoic age, with possible Proterozoic strata, and it probably reaches into the Devonian. Poorly preserved fossils (crinoid and brachiopod remains) were noted in a shale-limestone section on the south side of Sifs Gletscher (presumably part of the Sydgletscher Group) while the Sydgletscher Sandstone, the suppposed youngest formation of the succession, has yielded unidentifiable graptolite remains in the Sydgletscher area.

The northern region

Mappable units recognised along the northern coast region are all metamorphic lithological units of unknown sedimentary thickness. Fränkl (1955) originally established three groups in the region between Kap Morris Jesup and the head of Sands Fjord. In 1969, these rocks were investigated during two traverses south from the northern coast and they were found to contain mappable units of diverse lithology.

Kap Morris Jesup Quartz phyllite group

This group contains several units of light to dark weathering chlorite-mica phyllites and schists, some of which are intercalated with light coloured quartzite and quartz schists, units of dark coloured pelitic schists and slates, as well as psammitic units in places intercalated with mica phyllites. In some psammitic lithologies cross bedding and pebbly beds are preserved. Garnet occurs sporadically and was noted concentrated in several chlorite schists layers. Thinner and less common are calcareous phyllites and thin-bedded limestones.

Ulvebakkerne Marble group

This group characteristically forms a southerly-dipping scarp and shows spectacular internal folding (fig. 29 & 30). The main rock type is a light grey-weathering crystalline marble, often quartz bearing, and often displaying a colour banding. Some fine-grained slaty marbles occur. In addition several intercalated and thin units of brown-weathering quartz phyllites and psammitic rocks exist.

Sands Fjord Quartz phyllite group

This group is dominantly psammitic, composed of a variable succession of quartz-rich phyllites and arenaceous rocks characterised by a high proportion of feldspar. Several units of coarse arkosic arenite and feldspar clast conglomerate were noted.

Age and stratigraphic relations

The ages of the three rock groups are unknown. From structural considerations it seems likely that at least part of the succession represents high-grade correlatives of the stratigraphic units recognised in the central part of the Roosevelt Fjelde. Hence, it is deemed probable that the arkosic meta-arenites of the Sands Fjord group are equivalents to the less-metamorphic Polkorridoren Group of the south.

STRUCTURE AND METAMORPHISM

Structural-metamorphic pattern

In this account we adopt the structural-metamorphic zonation used by Dawes & Soper (1973) as a convenient framework for describing the northwardly increasing structural complexity and metamorphic grade of the fold belt (fig. 9). It should be stressed that the boundaries of these zones are defined only in areas examined during the 1969 reconnaissance.

The most conspicuous and much published regional structural feature of the fold belt in Peary Land is its northerly vergence (i.e. away from the platform to the south). This is characteristic of the central part of the fold belt and is particularly evident in the northernmost high-grade segment of the belt flanking the Arctic Ocean (fig. 31; see also Dawes, 1976, fig. 261). This tectonic feature was stressed by the earlier workers (Ellitsgaard-Ras-

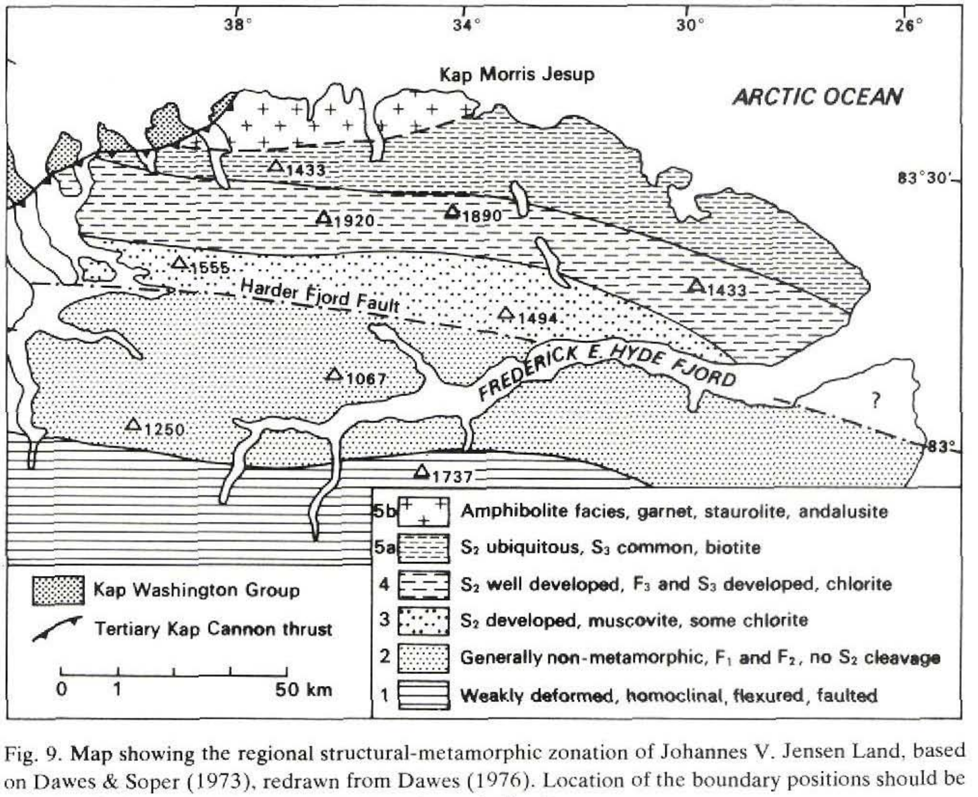

Fig. 9. Map showing the regional structural-metamorphic zonation of Johannes V. Jensen Land, based on Dawes & Soper (1973), redrawn from Dawes (1976). Location of the boundary positions should be seen in relationship to the travelling route shown in fig. 2.

mussen, 1955; Fränkl, 1955) and has been illustrated graphically by the present authors. It must be of utmost signifiance in regional geotectonic reconstructions (Dawes & Soper, 1973; Dawes, 1973).

Nevertheless, while this remarkable fabric catches the eye in regional tectonic appraisals, fold styles seen in detail are quite varied and complex. A whole range of fold attitudes from southward verging through upright folds to the characteristic northward verging structures exist within the fold belt and oppositely verging folds can occur in close association. The detailed relationship of the different fold styles to the regional chronology is not yet fully understood but the 1969 field work enabled at least three main, fold-producing phases of deformation to be recognised and to be correlated across Johannes V. Jensen Land. For convenience we follow the assignment in Dawes & Soper (1973) and refer to the three fold phases as F_1 to F_3 with the associated planar fabrics as S_1 to S_3. It is emphasised that it has not yet proved possible to fully differentiate elements developed in the earlier (Palaeozoic) and later (Cretaceous–Tertiary) orogenies within this tectonic sequence.

Zone 1

This comprises the non-metamorphic, tilted and faulted, generally homoclinal Lower Palaeozoic platform that in the south is composed of Cambro-Silurian carbonates and in the north at the present level of exposure, by the Silurian–Devonian shale and greywacke flysch sequence. The regional dip of the platform strata is shallowly northward so that younger rocks of the carbonate sequence of the south disappear progressively northwards under the younger clastic cover. Inclination of beds is generally under 5° but large areas of uniformly homoclinal rocks, particularly in the flysch region are characterised by extremely shallow dips from flat-lying to a couple of degrees (Dawes, 1976, fig. 249). Certain areas of steeper inclined strata appear due to fault tectonics.

Several open, long wavelength, small amplitude folds were noted from the air in 1969, particularly in the northernmost part of the zone and several structures of this type are illustrated in Koch (1940). These folds have a trend that is crudely parallel to Frederick E. Hyde Fjord; thus in the west, fold axes are ENE to E–W trending but to the east of Frejas Fjord towards Citronens Fjord structural trends swing towards the south-east.

A detailed structural analysis of this zone has been recently undertaken by Pedersen (1979).

Zone 2

The southern margin of the fold belt was observed in the Odins Fjord – Thors Fjord – Frejas Fjord region where it is quite abrupt. These fjords provide good structural profiles across the regional strike; the most illustrative of these was recorded in Frejas Fjord (fig. 10). Here the fold belt margin is marked by several small buckles, perhaps of box style, followed immediately by a large south-verging, upwards-facing syncline, with an inverted northern limb. The steeply inclined beds of this inverted limb form the bold spectacular eastern cape of Frejas Fjord that in the field we appropriately referred to as 'Kap Hinge'. Similar south-verging folds noted along the coast to the west towards Thors Fjord (fig. 8) are presumably the strike continuation of this structure or *en echelon* equivalents. The

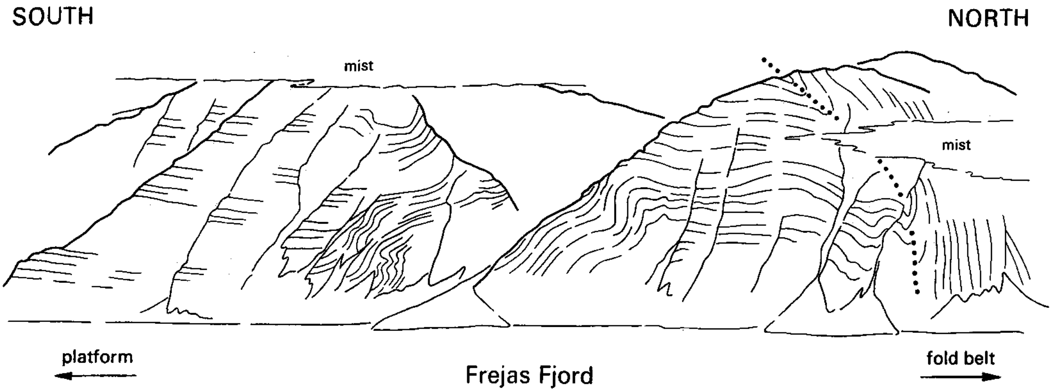

Fig. 10. View south-west to the western side of Frejas Fjord from Frederick E. Hyde Fjord showing the transition from platform (zone 1) to the fold belt (zone 2) in the Silurian calcareous greywacke, flysch sequence. The first major fold (not seen quite in profile) is a south-verging syncline with an inverted northern limb. Length of section is about 2 km.

south-verging folds, characteristic of this part of the margin, are thought to be early (F_1) structures, more or less unaffected by later deformation. The folds appear to be of buckle type, apparently generated by flexural slip, so that accomodation thrusts and faults are common.

Detailed recent work by Pedersen (1979) stresses the importance of thrust planes and bedding plane glides in the regional tectonic pattern that in the case of the Frejas Fjord fold are said to create "a complex deformation pattern". Most important is the discovery in the Frederick E. Hyde Fjord region of a series of southerly-directed regional thrust units.

Southerly-verging folds were noted in 1969 also farther away from the margin between Kap Bopa in the west (fig. 11) and Citronens Fjord (fig. 12) (perhaps at Hundeskrænten, fig.

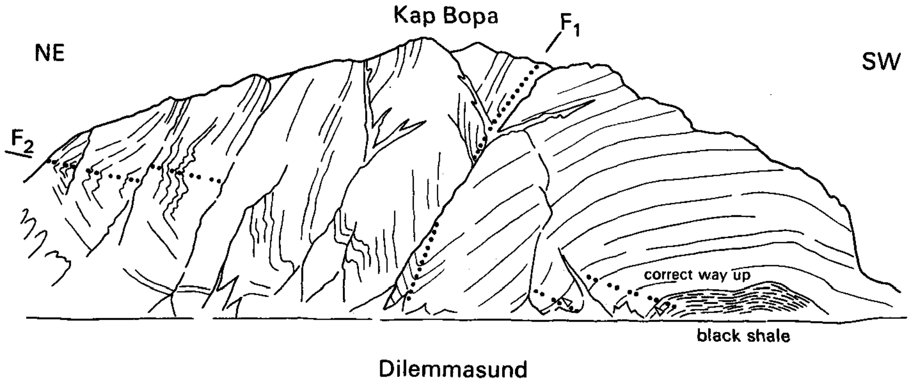

Fig. 11. View south-east of Kap Bopa from Dilemmasund. A major south-verging F_1 syncline with steeply inverted northern limb, refolded by F_2 reclined folds (zone 2). Height of the cliff is about 450 m. Ordovician-Silurian sandstone-shale lithology; black shales from the eastern side of the massif yielded graptolites of early Ordovician age.

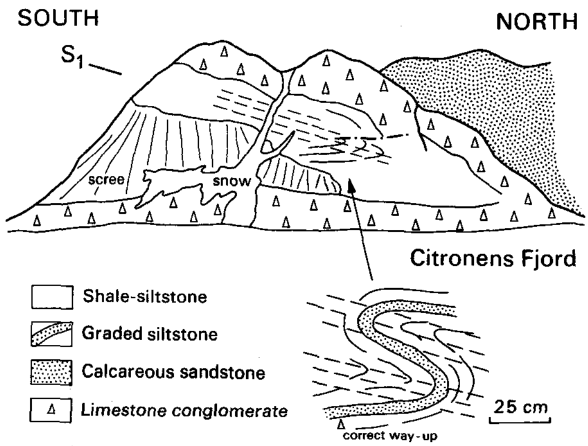

Fig. 12. View of locality on west coast of Citronens Fjord showing a south-verging fold depicted by a limestone conglomerate bed in the Silurian greywacke-shale sequence. Height of cliff about 50 m.

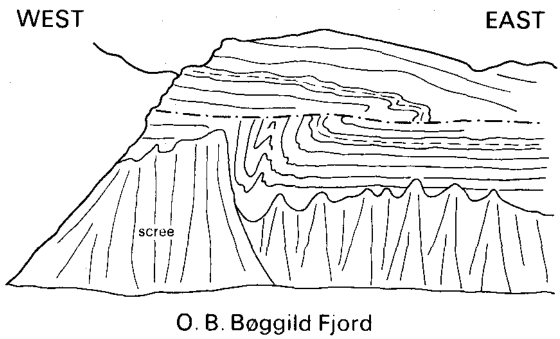

Fig. 13. A thrust disrupted monocline in the Ordovician-Silurian clastic sequence, in zone 2 on the north side O. B. Bøggild Fjord, east of Kap Bopa. Height of cliff perhaps 350 m.

3) in the east, suggesting that true (not induced) southerly vergence characterises the margin of the fold belt in a tract probably as much as several tens of kilometres wide. This implies southerly displacement of the mobile region with respect to the platform. Although certain dislocation planes were recorded in the region (e.g. fig. 13) no regional thrusts or major nappe structures were observed by the authors; on the contrary the fold belt margin is essentially autochthonous.

The large-scale southerly verging structures at the fold belt margin, where Silurian rocks form the main stratigraphic thickness at the present exposure level, have an important effect on the regional stratigraphic outcrop pattern in that older rocks (Ordovician, and probably Cambrian or older) are brought up on the northern side of the inverted limbs.

The interior to northern part of zone 2 contains what appear to be large northward-verging monoclines with vertical or steep inverted common limbs (figs 14 & 15). Towards the north these folds become tighter, the inverted middle limbs having moderate southerly dips (fig. 16). Thus, northwards in this part of the zone, axial planes of these folds become progressively more gently inclined to the south; this holds true not only in the northern part of zone 2, but northwards throughout the metamorphic terrain of the fold belt.

These asymmetric, north-verging folds are assigned to the second main phase of deforma-

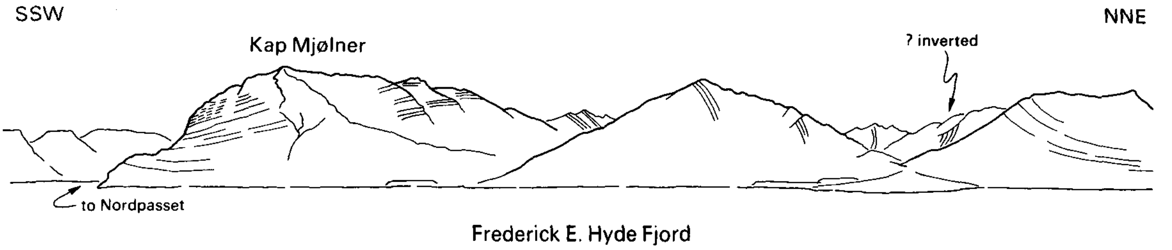

Fig. 14. View west along Frederick E. Hyde Fjord to Kap Mjølner to illustrate a major structure interpreted as a north-facing monocline with vertical or steeply inverted middle limb, assigned to F_2 (zone 2). Lower Palaeozoic (Ordovician-Silurian) basinal clastic lithologies, including sandstone, shale, chert and limestone conglomerate.

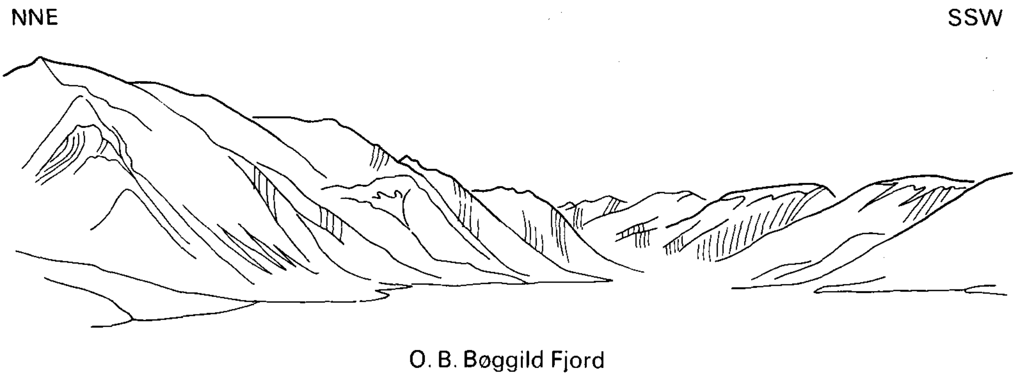

Fig. 15. View up O. B. Bøggild Fjord to Nordpasset showing steeply inclined and inverted beds composed of Lower Palaeozoic clastic basin-margin deposits. Overall structure is possibly referable to a north-verging F_2 monocline although some invertion of beds in south may be due to a major south-verging structure of type seen in fig. 10.

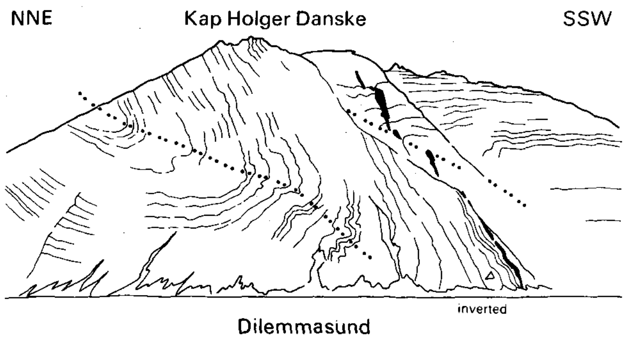

Fig. 16. View of Kap Holger Danske from Dilemmasund. Major F_2 north-verging fold pair with inverted common limb in Ordovician-Silurian clastic sequence (zone 2). Black = basic dyke. (cf. Dawes, 1976, fig. 264).

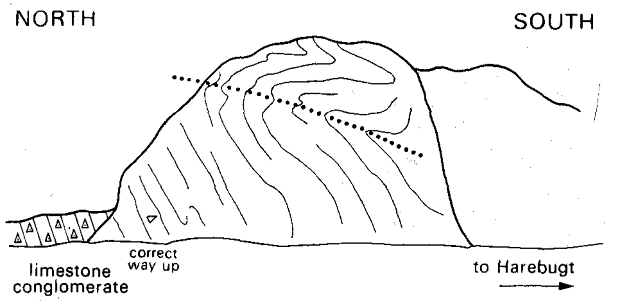

Fig. 17. Fold structure in Lower Ordovician shales and siltstones, interpreted as a south-verging fold pair with an induced southerly-dipping axial plane (zone 2). Height of cliff is uncertain, perhaps 40 m. Harebugt.

tion (F_2) because they clearly refold more upright, often south-verging folds, as at Kap Bopa (fig. 11). Both sets, where observed, trend between E and SE and thus the refolding is roughly coaxial. Their effect on the first folds is to induce both northerly and southerly vergence. Fold styles can be complicated, for example such structures that appear essentially to be south-verging, yet have southerly-dipping (?induced) axial planes of variable dip (fig. 17). The ground between Nordpasset and Frigg Fjord, appears to be structurally complicated, where perhaps due to fold interference or dislocations, or both, the regional strike swings markedly to the south.

Cleavage is generally absent in zone 2 although due to the rather arbitrary northern boundary of the zone at the Harder Fjord Fault (see below), some areas of cleaved rocks fall into the zone as presently defined. For example at Citronens Fjord and towards Depot Bugt, cleavage can be well developed and associated with S-verging folds that are assigned to F_1 (fig. 12). In zone 2 quartz and carbonate veining are common and there is local mineralisation although the sediments generally are little recrystallised and effectively non-metamorphic.

Zone 3

The southern edge of zone 3 is defined by the incoming of cleavage in argillaceous lithologies. For convenience the southern boundary has been drawn at the Harder Fjord

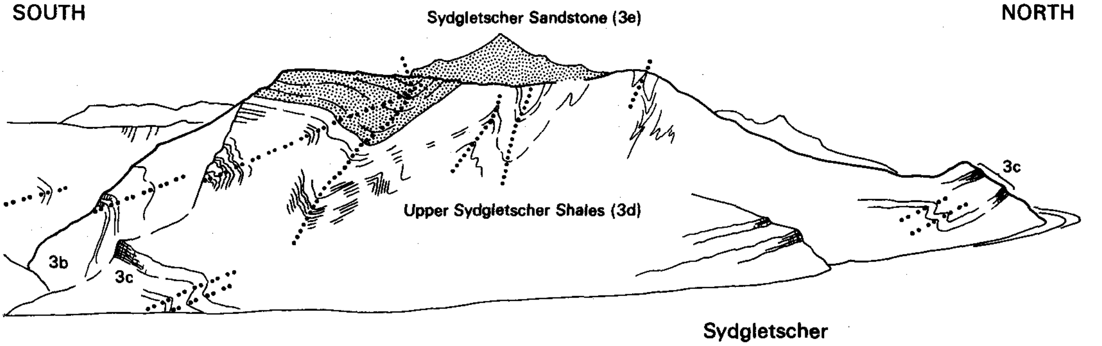

Fig. 18. View west across Sydgletscher showing refolding of upright F_1 folds in Sydgletscher Group sediments by weak reclined F_2 north-verging folds (zone 3). Length of the section about 3 km.

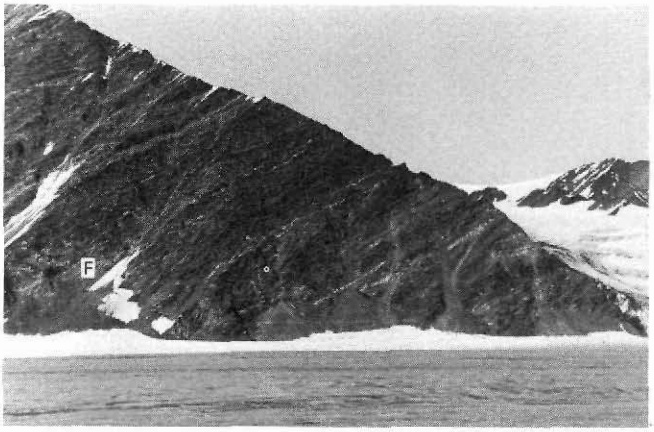

Fig. 19. A series of northerly-overturned folds assigned to F_1 in Polkorridoren Group lithologies. Small isoclinal closure seen above 'F' (boundary, zones 3–4). North of Columbus Sø. Height of the cliff above glacier ice at the left is perhaps 400 m.

Fault although this structure is only crudely parallel to the 'slate front' (fig. 9). In the northern part of the zone metamorphic muscovite appears in appropriate lithologies and the recrystallisation of sedimentary fabrics becomes widespread. The cleavage is of spaced type, probably of pressure solution origin. In places cleavage is weak or even absent and massive lithologies at least in the central Roosevelt Fjelde remain for the most part uncleaved.

The main cleavage of zone 3 is associated geometrically with F_2 folds and is designated S_2. Normally, therefore, it is inclined southward and in many localities it is seen to be superimposed on variably oriented F_1 limbs. However, in some places, for example on the north side of Frederick E. Hyde Fjord between Midtkap and Flammens Fjord, and on Moa Ø, northerly-dipping cleavage is recorded. At the former locality the cleavage is superimposed on an earlier, more steeply dipping cleavage, perhaps S_1, which implies original S-vergence for the F_1 folds thereabouts.

Clearly, many complexities of the fold phase interference geometry are not yet understood. Nonetheless, the general disposition of the stratigraphic units of the zone is mainly

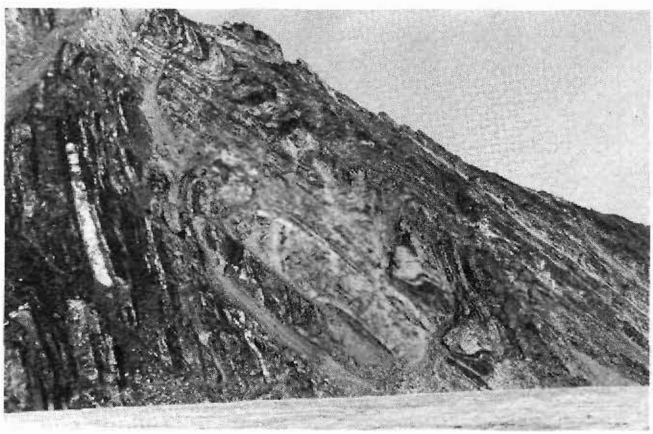

Fig. 20. Northerly-overturned folds assigned to F_2 in metasediments of the Polkorridoren Group (boundary, zones 3–4). North of Columbus Sø. Height of the cliff above glacier ice to the left is perhaps 150 m.

controlled by approximately coaxial F_1/F_2 interference as is well illustrated in the central region around Sydgletscher (fig. 18). Here a broad E–W trending F_1 syncline with an almost horizontal axis exists, having several medium-scale, slightly northerly overturned F_2 folds superimposed across it. Towards the northern boundary of the zone both F_1 and F_2 folds are northerly verging (figs 19 & 20). Here F_1 folds are rather long limbed and in places isoclinal, whilst the later folds are characterised by a more open style and have in places rather angular chevron-type hinge zones. In the western Roosevelt Fjelde in the region east of Moa Ø and in the interior of Harder Fjord, several large-scale fold closures with moderate to shallow southerly dipping axial planes were observed in prominent mountain summits. These structures are interpreted as north-verging, predominantly F_2 folds.

A somewhat anomalous area exists at Hundeskrænten, on the south-east side of Frederick E. Hyde Fjord, where a thick and diverse sequence contains varied limestones and calcareous shales as dominant ductile lithologies. These lithologies have developed, at least locally, a penetrative cleavage and are slates and in places phyllites, and as such can be assigned to zone 3 or to zone 4. Large-scale folds, depicted by thick, yellow-weathering carbonate beds characterise the steep coastal cliffs at Hundeskrænten (fig. 3). One major southerly closing

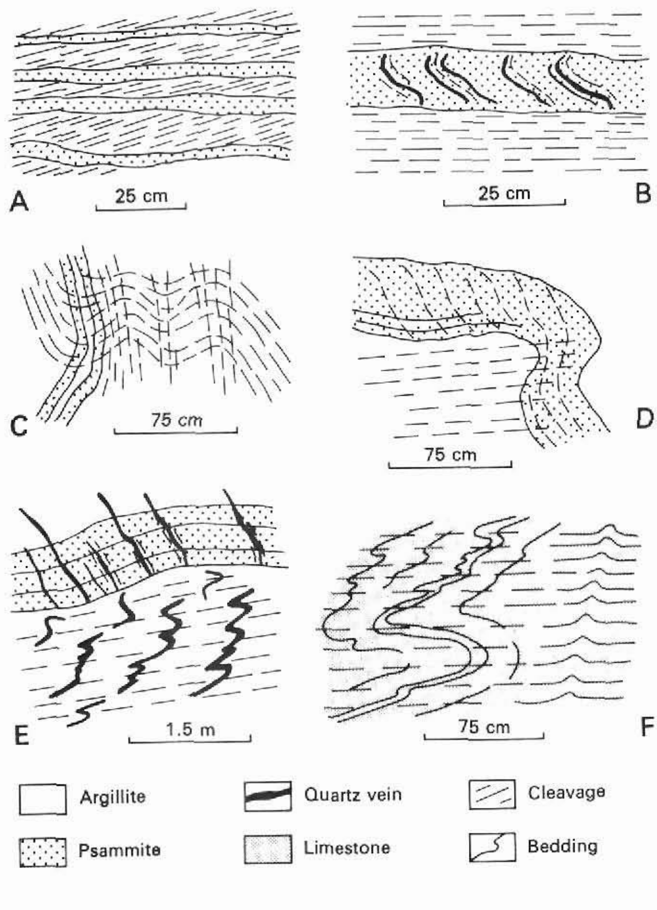

Fig. 21. Sketches of small-scale structures to show the relationship between cleavage (S_1 and S_2), bedding and folds in structural-metamorphic zone 4. A-E: Sifs Gletscher and Døbbeltsø, F: Hundeskrænten. A – selective S_2 cleavage, B – relict S_1 in psammite, penetrative S_2 in ductile lithology, C – penetrative S_1 deformed by F_2 folds that have S_2 developed in ductile lithology, D – deformed S_1 in psammite with penetrative S_2, E – penetrative S_2 in folded ductile lithology with weak S_1 in psammite, F – penetrative ?S_1 in limestone slate deformed by ?F_2 kink band.

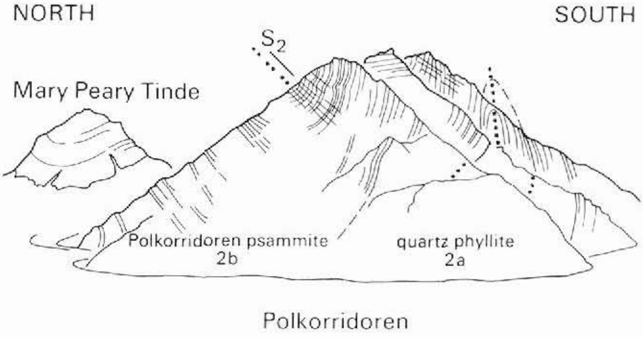

Fig. 22. View east from Polkorridoren to Mary Peary Tinde (1585 m) showing folds in metasediments of the Polkorridoren Group. Upright F_1 interpreted as refolded by north-verging F_2 with weak S_2 cleavage in some units (zone 4). Height of cliff at least 400 m.

fold to the east of Depot Bugt (?south-verging F_1 anticline or north-verging F_2 syncline?) has an associated cleavage. This planar fabric is deformed by small-scale folds and kink bands (fig. 21, F).

It is in this region that the projection of the metamorphic-structural zonation of Johannes V. Jensen Land becomes speculative, as shown in Dawes & Soper (1973). Moreover, eastern Hans Egede Land is known to be structurally complex, characterised by fault tectonics and the area was omitted from the later zonation (Dawes, 1976). Some structural details from this area are now available from recent field work (Christie & Ineson, 1979).

Zone 4

This zone is defined by the stronger development of S_2, which becomes penetrative in micaceous lithologies giving rise to chlorite phyllites. In arenite lithologies it is usually of spaced type. The chlorite isograd is not precisely defined as pelitic lithologies are of limited occurrence. The dominant rock types of the zone are arkosic and calcareous, i.e. the Polkorridoren and Paradisfjeld lithologies respectively.

F_1/F_2 interference dominates the zone (figs 22, 25 & 27). F_2 folds are the dominant

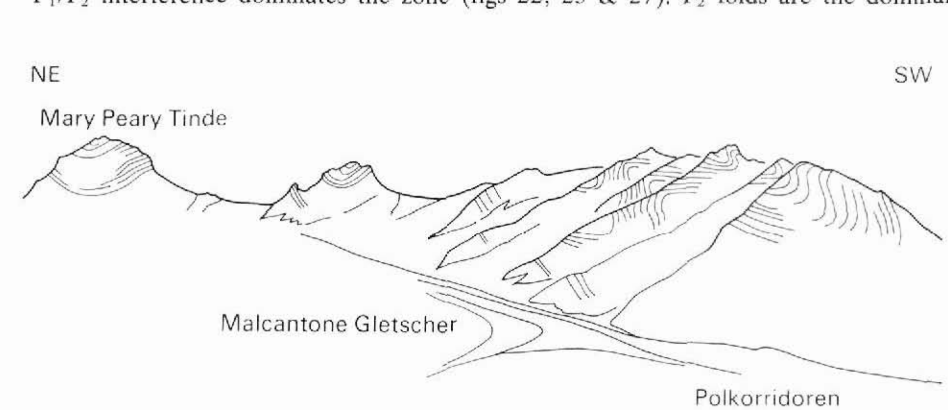

Fig. 23. Northerly overturned F_2 folds on a ridge on the east side of central Polkorridoren in metasediments of Polkorridoren Group (zone 4). Mountain summits in the area are characteristically etched out of major synforms. For detail of western end of ridge see fig. 22.

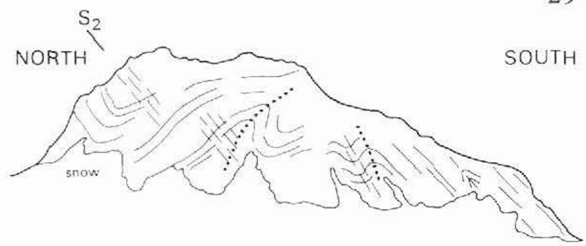

Fig. 24. Interpretive view of a nunatak to the west of Birgit Koch Tinde showing an apparent south-verging (?F_1) fold with southerly inclined axial plane cleavage (S_2) superimposed non-congrously across it (zone 4). Height of cliff perhaps 150 m.

structures controlling the outcrop pattern and these are north-verging (fig. 23). F_1 folds have variable vergence in the southern part of the zone being originally upright or verging to the north or south. For example, in fig. 22 a quartz-phyllite formation (2a of Table 1) occupies the core of an almost isoclinal anticline (F_1) on which is superimposed a north-verging F_2 fold, so that the F_1 axial plane dips alternatively south and north. This suggests that prior to the second deformation, the F_1 folds at this locality were more or less upright in nature. On south-eastern Lockwood Ø and elsewhere several folds with steep northward-inclined axial planes were noted (fig. 24). Generally it is possible to distinguish folds of F_1 and F_2 generations by the manner in which the S_2 cleavage is superimposed noncongruously across F_1 hinges (figs 24 & 25). F_2 folds in places approach a 'similar' style, consistent with their origin as flexural folds subsequently shortened across the cleavage. In places F_2 folds develop a fanning but congruous S_2 cleavage (fig. 26).

Towards the northern part of zone 4 folds of both sets become isoclinal and long limbed (fig. 27). They become increasingly difficult to discern, but are revealed by the symmetrical repetition of lithological sequences and changes in direction of younging, as well as actual observations of hinge zones. It is even more difficult to differentiate F_1 and F_2 hinges since

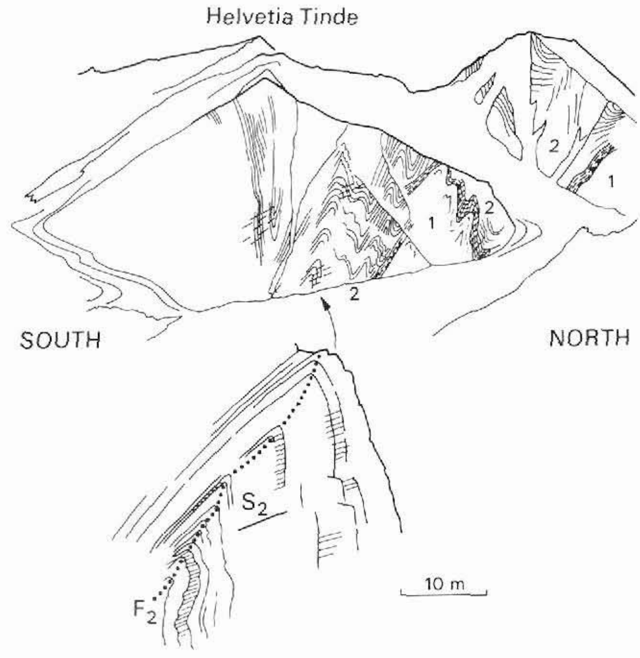

Fig. 25. View west from the summit of Paradisfjeld across Polkorridoren to Helvetia Tinde (1920 m) illustrating interfolding of Paradisfjeld Group (1) and Polkorridoren Group (2) in zone 4. Mainly F_1 folds to the left of profile, as indicated by non-congruous S_2 cleavage (shown in detailed sketch). Mainly F_2 folds to the right of section.

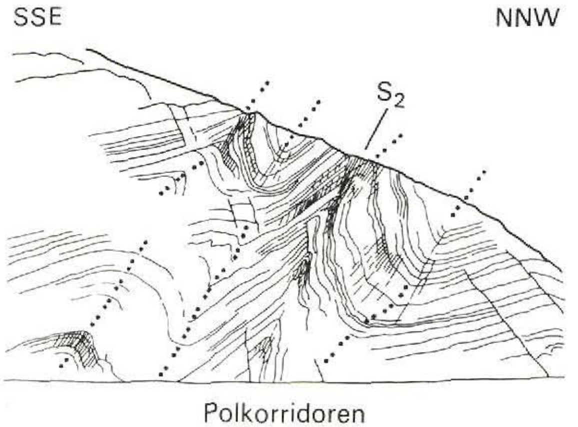

Fig. 26. View of a cliff section on the west side of central Polkorridoren showing profile view of F_2 folds with congruous, often fanning S_2 cleavage. Height of cliff perhaps 400 m. Polkorridoren Psammite in zone 4.

S_2 becomes sub-parallel to the axial planes of both fold sets. However, in Paradisfjeld (fig. 27) one isoclinal syncline upon which S_2 cleavage is superimposed obliquely can be designated F_1. Disruption of the sequence by slide zones becomes important but the formations in Table 1 can be seen to have normal stratigraphic contacts; they do not comprise separate nappe units as envisaged by Fränkl (1955).

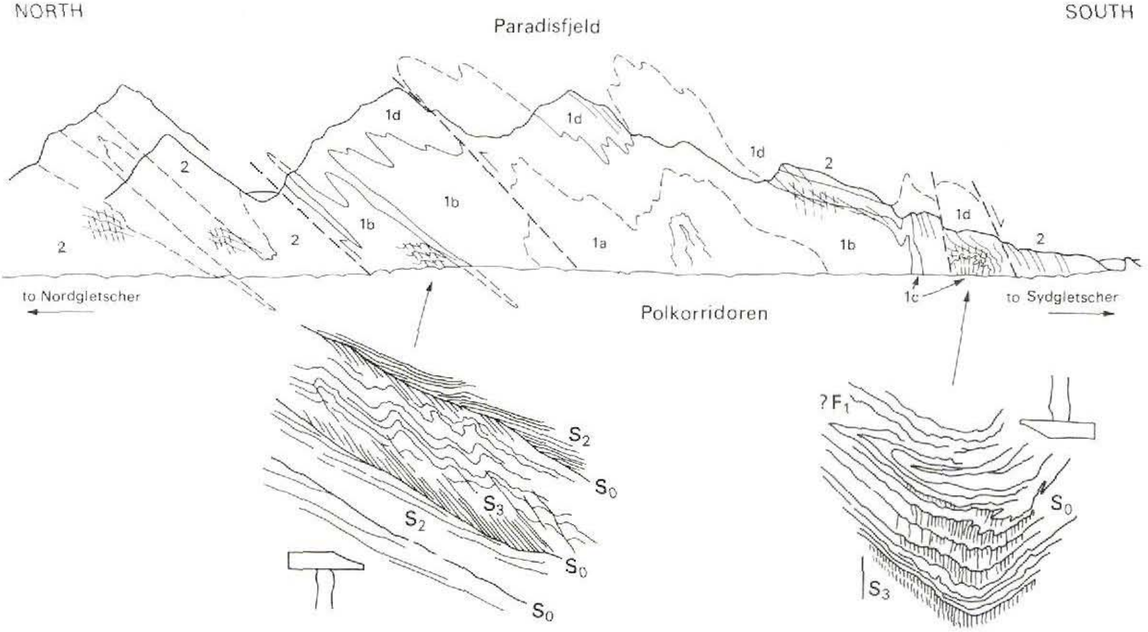

Fig. 27. Interpretative profile of western face of Paradisfjeld showing interfolding of various units of the Paradisfjeld and Polkorridoren Groups in which numbers refer to stratigraphic units listed in Table 1. Major folds are probably of both F_1 and F_2 generations, becoming isoclinal, long-limbed and affected by sliding to the north. Detailed sketches show superimposed F_3 minor folds and S_3 cleavage. Length of section is about 7 km, zone 4–5.

Fig. 28. Calcareous phyllites of formation 1c of Paradisfjeld Group showing F_3 folds with some leucocratic veins along axial planes. The synform under the hammer (center left) is the same fold as shown in the detailed sketch in fig. 27. Zone 4.

In the southern part of Paradisfjeld (fig. 27) small-scale F_3 folds were recorded and these become more important northwards. These are generally small-scale, upright, more or less E–W trending folds accompanied by a crenulation cleavage (S_3) along which bedding and S_2 becomes transposed in ductile lithologies. Thin, leucocratic, carbonate-quartz veins can occur in the axial planes of F_3 folds (fig. 28). Muscovite and chlorite aligned in the main cleavage (S_2) is deformed by this crenulation fabric.

While the main tectonic synthesis of zone 4 outlined above was established in the central Roosevelt Fjelde, particularly in Polkorridoren, another extensive cross-section exists to the east, in the Døbbeltsø valley, the central part of which was visited in 1969 by way of Sifs Gletscher (fig. 2). The section at Dobbeltsø is composed predominantly of variable psammitic and argillaceous sequences of the Polkorridoren Group and Sydgletscher Group, although exposure is not so spectacular as in Polkorridoren. However, the section is illustrative as a reminder that the relationship of fold phases to planar fabrics, in places involving at least three ages of cleavage, is complex and as presently known in that area is difficult to reconcile completely into an all embracing tectonic framework. Moreover, frequent dislocations affect the continuity of the structure thus adding to the difficulty of interpretation. Suffice it to report here that in the Døbbeltsø section both north-verging and south-verging fold series exist, fold style varies considerably, and, as well as examples of refolded isoclines, other fold interference patterns are reminiscent of 'wild folding' involving planar surfaces of variable intensity and attitude.

Zone 5

The southern edge of this zone is marked by the incoming of biotite although it is of sporadic occurrence and does not define an adequate mapping line. The metasediments are completely recrystallised and a thoroughly penetrative schistosity becomes the dominant fabric of all rock types. At about this point in a northward traverse, the normal techniques of structural mapping, using the criteria outlined above to define F_1/F_2 interference, became too time consuming to employ satisfactorily during the 1969 reconnaissance. However, correlation with zone 4 demonstrates that the dominant planar fabric is, at least in the southernmost part of the zone, F_2 and it is thus so interpreted throughout the zone. This dominant schistosity characteristically dips at varying degrees to the south and gives to the fold belt its conspicuous northward-directed tectonic style.

The stratigraphic sequence becomes unclear as 'way up' evidence fails, but distinctive lithologies permit the definition of good mapping units. Some units erected by Fränkl (1955), i.e. Kap Morris Jesup Quartz phyllites, Ulvebakkerne Marbles, Sands Fjord Quartz phyllites, Nunatak Quartzitic Slates, and the Sortevæg Marbles and Phyllites, must at least in part represent the higher grade correlatives of the stratigraphy established in the south (Table 1).

Sub-zone 5a

The S_2 fabric becomes a pervasive schistosity along which bedding is largely transposed. Nevertheless, early folds (F_1 & F_2) can be recognised and they are characteristically isoclinal and often recumbent, and have extremely attentuated limbs (fig. 29). Small- and medium-scale F_3 folds become increasingly important northwards typically verging to the north and accompanied by an intensification of the S_3 fabric which has high to moderate southerly dips. This fabric is clearly superimposed across the dominant F_2 schistosity.

Sub-zone 5b

The metamorphism attains amphibolite facies on the north coast in an area extending westwards from Kap Morris Jesup to Benedict Fjord (fig. 9). Garnet is common and is locally accompained by staurolite, andalusite and cordierite. Thin, often irregular, quartz

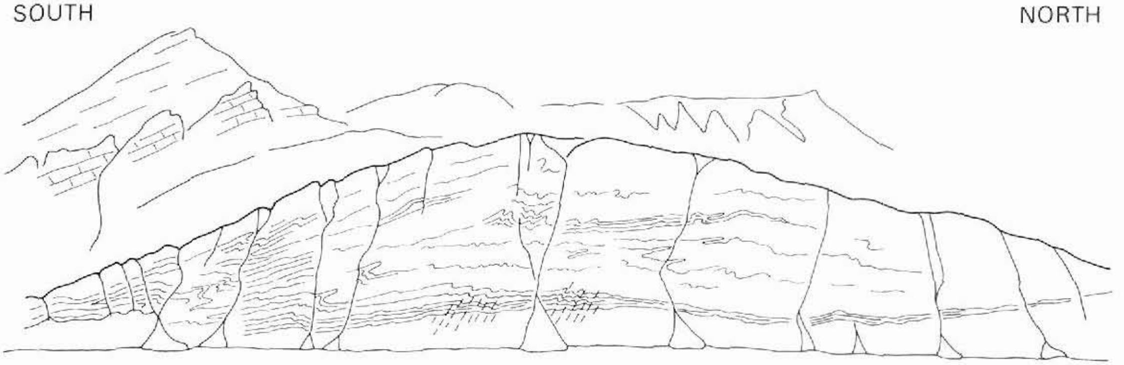

Fig. 29. Cliff section on the west side of Sands Fjord in zone 5 (cf. Fränkl, 1955, fig. 16). Very long-limbed recumbent isoclines, probably both F_1 and F_2 in psammite, quartz phyllite and carbonate of the Ulvebakkerne Marble group, with superimposed F_3 folds and cleavage. Length of section is about 2 km.

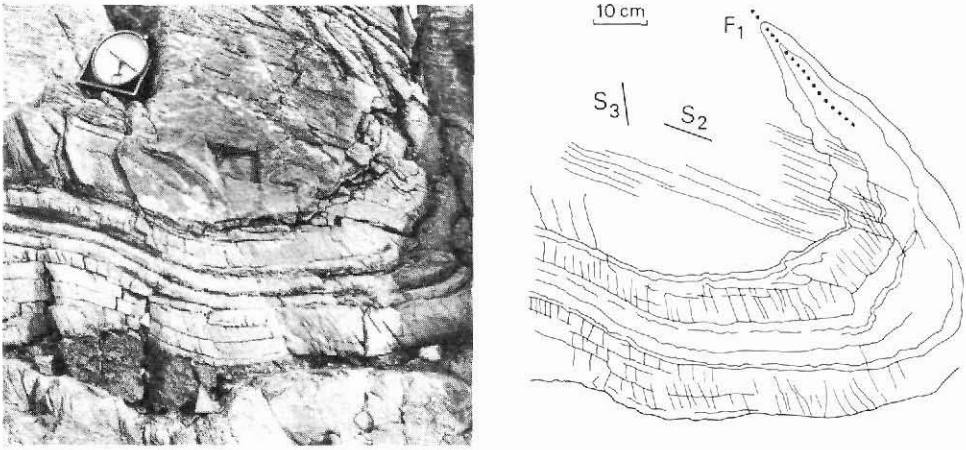

Fig. 30. Fold interference pattern in calcareous rocks of the Ulvebakkerne Marble group in sub-zone 5b. A refolded isocline (assumed F_1) with two sets of southerly-dipping cleavage. The steeper cleavage (S_3) is superimposed incongruently across the F_2 fold limb. South of Kap Morris Jesup. Interpretative sketch from Dawes & Soper (1973).

and quartz-feldspathic veins and segregations are common in the schists. These have been deformed by at least two fold phases; isoclinal (?F_2) and open folds (?F_3).

In 1969, this area was examined before the less complex ground to the south had been visited. As a result it has not proved easy to interpret our observations in terms of the three-phase deformation sequence outlined above. Lithological units and schistosity are inclined uniformly to the south at variable but low angles. As suggested above, the main fabric is probably S_2 and the prograde mineral assemblages appear to have developed during and immediately after the F_2 phase. Retrogressive assemblages are widespread and chlorite, commonly associated with garnet, is a typical paragenesis of the schists, for example, as south of Kap Morris Jesup. We speculate that this retrogression may be associated with the later (Tertiary) orogeny.

In this sub-zone major fold closures have not been identified and such lithological groups as can be mapped, i.e. the Kap Morris Jesup Quartz phyllites and Ulvebakkerne Marbles of Fränkl (1955), are purely structural units of unknown sedimentary thickness. Nevertheless, it is still possible in this high-grade terrain to recognise minor interference patterns, in places involving three deformation phases that appear to be controlled by a similar tectonic regime to that of the structures further south. It is this fact that suggests that the polyphase deformation sequence recognised in the central Roosevelt Fjelde may provide the key to the structural understanding of the entire fold belt. An illustrative example (fig. 30) south of Kap Morris Jesup, indicates an isocline (assumed F_1) refolded by F_2 with a congruous S_2 schistosity and a southerly-inclined S_3 schistosity locally developed.

The northern margin

The folded and metamorphic schists, phyllites and marbles of zone 5 reach the outer coast in much of Johannes V. Jensen Land but to the east of Kap Morris Jesup they are overlain by extensive areas of Quaternary deposits. In the north-west the fold belt terminates to the north against the Kap Cannon thrust, beneath which is a thick sequence of volcanic rocks, dominantly rhyolitic in the east, named the Kap Washington Group (fig. 31). These have recently yielded a Rb/Sr age close to the Cretaceous–Tertiary boundary (Larsen *et al.*, 1978). The Kap Cannon thrust is therefore of Tertiary age and so is the associated mylonitisation and greenschist retrogression of the overlying Palaeozoic metasediments. The northward displacement of these rocks is unknown, but by analogy with similar marginal thrust zones, it is likely to be at least several tens of kilometres. The underlying volcanic rocks have developed a southerly-inclined cleavage parallel to the thrust zone. Tectonic and metamorphic effects die out rapidly southwards from the outcrop of the thrust plane but aerial extent of the retrogression is unknown. In the vicinity of the thrust severely deformed rocks show some recrystallisation of the constituent mineral fragments, with the development of minute but unstrained grains of sericite and chlorite. Less-severely deformed amphibolites interbanded in the metasediments show the destruction of a hornblende-epidote-plagioclase-ilmenite assemblage and the crystallisation of actinolitic amphibole, chlorite, sericite, carbonate and leucoxene (Dawes & Soper, 1973).

Basic dykes

Basic dykes of three main trends (N–S, E–W and NE–SW) cut across the folded Lower Palaeozoic succession in Johannes V. Jensen Land (Dawes & Soper, 1970); basic dykes also traverse the platform sequence to the south. The dykes are dolerites or olivine dolerites with

Fig. 31. The local northern margin of the fold belt at Benedict Fjord. The Kap Cannon thrust (dashed line) separates the weakly-deformed Kap Washington Group volcanics from overlying garnet-grade metasediments and basic rocks. View is towards the north-east from near the summit of Kap Washington, with volcanics in the foreground. The southerly dipping tectonic fabric of the fold belt is illustrated.

preserved igneous textures; some are biotite-bearing and vesicular. Chemical analyses reveal a SiO_2 content between 45 and 48 per cent but certain NE-trending dykes in the central Roosevelt Fjelde are ultramafic with silica content down to 42 per cent.

The importance of the dykes in the context of this paper is their relationship to the structural and metamorphic chronology already outlined. The dykes are cross-cutting and post-date the main deformation that produced the F_1 and F_2 folds and presumably also the F_3 structures. Two K/Ar ages of 72 m.y. and 66 m.y. respectively from NW and E–W trending dykes, are taken to indicate a Cretaceous age of intrusion (Henriksen & Jepsen, 1970; Dawes & Soper, 1971). Other hitherto unpublished K/Ar ages, that include dates of 82 ± 3, 119 ± 4 and 130 ± 5 m.y. (D. C. Rex, personal communication) suggest an extended period of Cretaceous igneous activity. What is significant here is that some dykes in the northern part of the fold belt in zone 5, have been affected by post-intrusion deformation and metamorphism. Particularly noteworthy are dykes in the area west of Sands Fjord, which,while preserving their discordant relation to the metasediments, show outcrop forms and sheared contacts that indicate appreciable deformation. In addition, a gradation from ophitic-textured dyke rock, through foliated metadolerite to basic schist occurs, culminating in total amphibolitisation. One small amphibolite body, several metres across, within the schists and phyllite succession to the south-west of Kap Morris Jesup, may have been derived from intrusive material of similar age.

These deformation and metamorphic effects seen in the dykes are probably of Tertiary, or conceivably late Cretaceous, age. The regional assessment and detailed relation of this activity to the regional overprinting and to the Tertiary thrusting described above, must await further field information.

Palaeozoic and Tertiary chronology

Perhaps the most important open questions in the chronology of the fold belt are the nature and extent of the Late Phanerozoic (Cretaceous and Tertiary) diastrophism and metamorphism. From the available metamorphic evidence it appears that the thermal maximum coincided with, or outlasted, the second main phase of deformation. This is known to pre-date basic dykes of Cretaceous age. The F_2 folds have been assumed to be of Palaeozoic age (Dawes & Soper, 1973). The metamorphic mineralogy associated with F_2 and F_3 developed under a northerly-increasing temperature regime and although the grade achieved during F_3 was lower (chlorite and muscovite associated with F_3 microfolds), it seems illogical to separate radically the S_3 metamorphism from the Palaeozoic development.

Thus, it has been argued that the three main deformation phases so far recognised are best considered to be of Palaeozoic age, i.e. late Silurian to late Devonian (Dawes & Soper, 1973). However, this Palaeozoic metamorphism still remains to be isotopically dated. Attempted Rb/Sr age determinations on metamorphic rocks indicate considerable isotopic redistribution of the Palaeozoic Rb/Sr system. K/Ar mineral dates have given an age range of 42 to 84 m.y. (Dawes & Soper, 1971). These results testify to regional Tertiary overprinting of the Palaeozoic metamorphic mineral assemblages.

The Tertiary greenschist metamorphism associated with the Kap Cannon thrust clearly post-dates the metamorphic maximum but its relationship to the deformation producing F_3 is uncertain. Similarly the extent of the Tertiary regional retrograde (and indeed prograde) metamorphism in the fold belt is unknown. Furthermore, apart from the Kap Cannon thrust that resulted in northerly transport of the fold belt, and other late faults, major tectonic structures of Tertiary age have yet to be identified. This leads to the tantalising question as to the parts played by Palaeozoic and Tertiary diastrophism in the fold belt make-up and particularly, how much of the northerly-directed tectonic character of the fold belt is of Palaeozoic origin. Conversely, how far has the Tertiary (and perhaps Mesozoic) deformation accentuated or modified the presumed northerly overturned aspect of the belt? Answers to these questions are of utmost importance in any geotectonic consideration of the northern margin of Greenland.

CONCLUSIONS

The following statements summarise the main structural and stratigraphic results of the 1969 field work.

1. In the fold belt the intensity of deformation and metamorphism increases progressively northwards from the non-metamorphic stable platform to the border of the Arctic Ocean where amphibolite facies is attained.

2. Three main deformation episodes have been recognised but further work will no doubt reveal a more complex picture. Structures (folds and planar fabrics) attributable to the three episodes make their appearance sequentially across the fold belt from south to north.

3. The most impressive regional tectonic feature of the fold belt is the northerly-directed structural pattern. This is largely attributable to the northerly vergence of the second phase folds. In the northern high-grade part both second and third phase folds verge north and southerly inclined schistosities are associated with them.

4. The southern margin of the fold belt is essentially autochthonous; no regional-scale thrusts separate the fold belt from the platform.

5. The southern margin of the fold belt is marked by southerly-verging folds assigned to the first phase. In the central part the first phase folds appear to have had originally steep axial planes; to the north their original attitude is unknown.

6. The local northern margin of the fold belt is allochthonous. The metamorphic rocks are thrust northwards over cleaved but essentially non-metamorphic volcanic and sedimentary rocks of presumed latest Cretaceous age.

7. The northerly thrusting is of Tertiary age and involves mylonitisation and greenschist retrogression of the metasediments. The thrusting has had the important effect of accentuating the earlier northerly-directed structural pattern.

8. Mesozoic basic dykes, that cut across the folded metamorphic lithologies of the fold belt, show the effects of late Phanerozoic (Tertiary and possibly Cretaceous) metamorphism and deformation.

9. The main structural and metamorphic evolution of the fold belt is of Palaeozoic (probably Devonian) age. It has not yet proved possible to entirely differentiate the Tertiary and Palaeozoic effects.

10. Ordovician and Silurian faunas from the southern margin of the fold belt define the age of the thick clastic sequence which marks the shelf edge-basin transition. Successions of Proterozoic and probable Cambrian ages were also recognised at the southern margin.

11. The metamorphic succession in the central part of the fold belt can be divided into three stratigraphic groups of uncertain age that must represent stratigraphic equivalents of the Lower Palaeozoic and presumably Proterozoic essentially non-metamorphic strata of the south.

12. The structural analysis strongly suggests the correlation of the high-grade metamorphic lithostratigraphic groups of the northern coast region with the less metamorphic stratigraphic units of the central part.

Acknowledgements

The authors wish to thank Col. John D. C. Peacock, leader of the Joint Services Expedition 1969, for help and excellent cooperation in accommodating, often in difficult circumstances, the geological work into the general expedition programme. We thank all other members of the expedition for support and assistance.

A. K. Higgins and J. M. Hurst are thanked for critical reading of the text.

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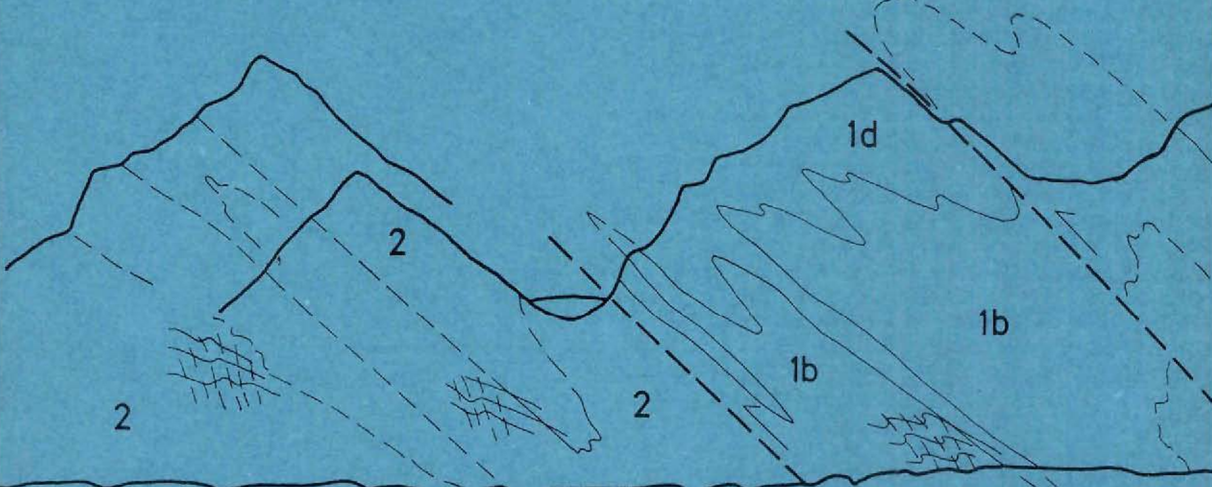

ISSN 0418–6559
AiO Tryk as, Odense