Sedimentary basins of North Greenland

edited by
John S. Peel and Martin Sønderholm

GRØNLANDS GEOLOGISKE UNDERSØGELSE

Bulletin 160

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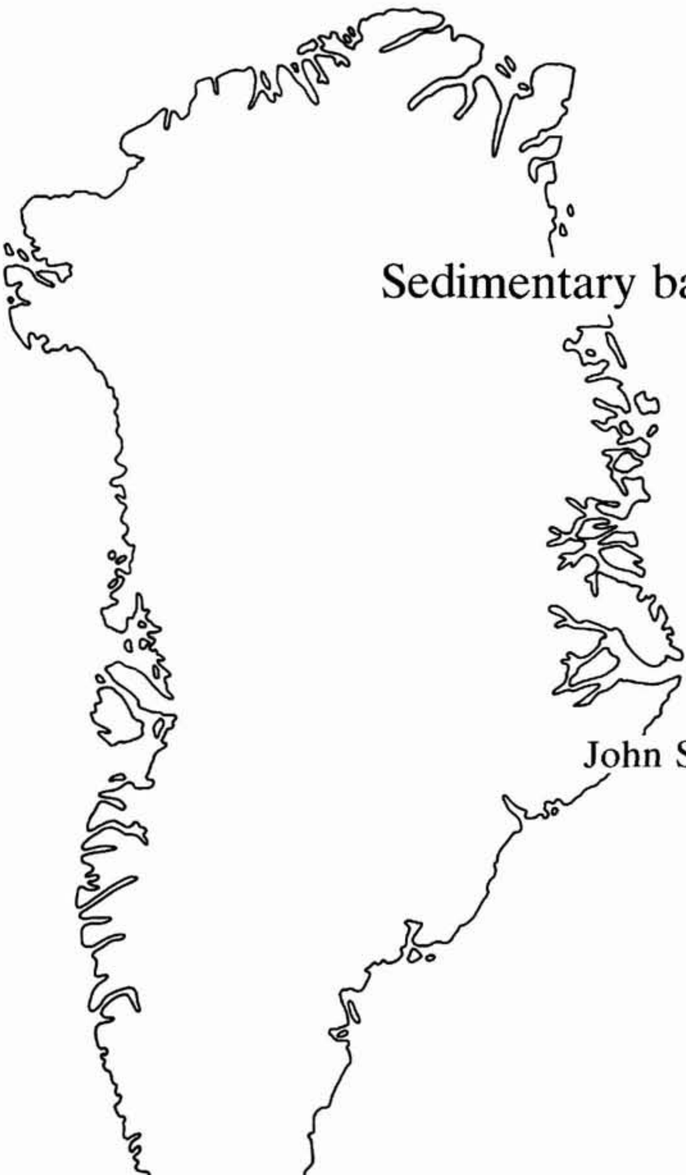

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Peel, J. S. and Sønderholm, M. (ed.) 1991: Sedimentary basins of North Greenland. *Bull. Grønlands geol. Unders.* **160**, 164 pp.

This bulletin presents a synthesis of the sedimentological and stratigraphic data collected mainly during the Geological Survey of Greenland's North Greenland Project (1978–80, 1984–85).

The history and logistics of this project are described by N. Henriksen and A. K. Higgins. This paper forms the background for 5 papers dealing with the development of the sedimentary basins in North Greenland.

In their account on the Proterozoic basins, M. Sønderholm and H. F. Jepsen recognise three main sedimentary basin events: a Middle Proterozoic interior sag (Independence Fjord Basin), Middle Proterozoic rifting (Midsommersø/Zig-Zag Dal volcanic event) and a Late Proterozoic passive margin (Hagen Fjord Basin). Problems concerning correlation of the sediments of the Hagen Fjord Basin and the glaciogenic Morænesø Formation with other Late Proterozoic sediments in East Greenland are also discussed.

The main part of North Greenland is occupied by sediments of the Early Palaeozoic Franklinian Basin which is described by A. K. Higgins, J. R. Ineson, J. S. Peel, F. Surlyk and M. Sønderholm. The evolution of the basin is elucidated in terms of seven stages of which the later are strongly influenced by the closure of the Iapetus Ocean and the formation of the East Greenland Caledonian orogenic belt. The effects of the Ellesmerian Orogeny on the Franklinian Basin deposits in North Greenland are also summarised.

The Late Palaeozoic to Cenozoic evolution of North Greenland is complex and characterised by different tectonic regimes related to the opening of the North Atlantic Ocean. L. Stemmerik and E. Håkansson describe the Early Carboniferous – Middle Permian rifting event which forms the northern continuation of the East Greenland rift basin. The Mesozoic to Cenozoic evolution, outlined by E. Håkansson, C. Heinberg and L. Stemmerik, is characterised by extensional oblique slip tectonics between eastern North Greenland and Svalbard, and rifting related to the opening of the Eurasia Basin.

A synthesis of these four papers from a tectonostratigraphic point of view is given by F. Surlyk who recognises 14 major events of plate reorganisation during the 1200 million years of sedimentary record in North Greenland, from the Middle Proterozoic to the Tertiary.

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Grønlands Geologiske Undersøgelse
Kalaallit Nunaanni Ujarassiortut Misissuisoqarfiat
Geological Survey of Greenland

The Geological Survey of Greenland (GGU) is a research institute affiliated to the Mineral Resources Administration for Greenland (MRA) within the Danish Ministry of Energy. As with all other activities involving the non-living resources in Greenland, GGU's investigations are carried out within the framework of the policies decided jointly by the Greenland Home Rule Authority and the Danish State.

ISSN 0105-3507

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Cover

Cambrian platform margin sequence at the head of Nordenskiöld Fjord, Freuchen Land, central North Greenland. Outer shelf sandstones and mudstones of the Buen Formation forming the lower talus-covered slopes are overlain by slope carbonates and debris flow units of the Brønlund Fjord Group, with conspicuous olistoliths. Succeeding platform margin carbonate grainstones also assigned to the Brønlund Fjord Group form the upper part of the 700 m cliff which is topped by platform carbonates and siliciclastic sediments of the Ryder Gletscher Group.

Dansk sammendrag

Nordgrønland udgør det største sammenhængende område af sedimentære bjergarter i Grønland. Her findes en følge af sedimentære bassiner af proterozoisk til kænozoisk alder blottet i et bredt bælte mellem Indlandsisen og det Arktiske Ocean. Det mest fremtrædende af disse bassiner er en fortsættelse af det Franklinske Bassin i Arktisk Canada og består af et system af nedre palæozoiske shelf- og trug-aflejringer, der kan følges fra Inglefield Land mod vest til Kronprins Christian Land i øst.

Planlægningen og udførelsen af Nordgrønlandsprojektet (1978–80, 1984–85), det største i GGU's historie, er i dette bind gennemgået af N. Henriksen og A. K. Higgins og danner baggrunden for de fire artikler, der i det efterfølgende beskriver udviklingen af de individuelle bassiner. De proterozoiske bassiner, der hovedsageligt er blottet i det østlige Nordgrønland, er beskrevet af M. Sønderholm og H. F. Jepsen, og problemerne omkring korrelationen med andre proterozoiske sedimenter i Østgrønland bliver diskuteret. A. K. Higgins, J. R. Ineson, J. S. Peel, F. Surlyk og M. Sønderholm har beskrevet det nedre palæozoiske Franklinske Bassins udvikling og har inddelt denne i 7 stadier, hvoraf de senere er stærkt præget af lukningen af Iapetus Oceanet og dannelsen af den kaledone bjergkæde. Den sen-palæozoiske og mesozoiske til kænozoiske udvikling af Nordgrønland er kompleks og præget af forkastnings-betinget tektonik i forbindelse med dannelsen af det Atlantiske Ocean. Dette bliver gennemgået af L. Stemmerik og E. Håkansson samt E. Håkansson, C. Heinberg og L. Stemmerik i to artikler . Disse beskrivelser er sammenfattet af F. Surlyk i et bidrag om Nordgrønlands tektono-stratigrafiske udvikling.

Denne bulletin danner således sammen med GGU Bulletin **158** (*Petroleum geology of North Greenland*) en syntese af al tilgængelig information fra verdens nordligste kompleks af sedimentære bassiner.

Imaqarnersiuineq

Avannaarsua Kalaallit Nunaanni kinnganernik tiggusimasunik ujaraqarfiit annersaraat. Tamaani iterlassuit kinnganerit kiviorarfigisimasaat ukiut 600 milliunit sinnerlugit ukiullu 60 milliunit akornanni angullugit pisoqaassuseqartut nunami isorartoqisumi Sermersuup Issittullu Imarpissuata akornanni siumorneqarsinnaapput.

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Una nalunaarusiaq GGU Bulletin **158** (*Petroleum geology of North Greenland*) ilanngullugu nunarsuarni iterlassuaqarfiit avannarpasinnerpajusunik paasissutissanik tamanik katersorneqarsimasunik saqqummiussineruvoq.

Introduction

North Greenland is overwhelmingly dominated by sedimentary rocks which outcrop in a broad belt between the permanent central ice cap of Greenland (the Inland Ice) and the Arctic Ocean (Figs 1–3). A succession of sedimentary basins contains strata of Proterozoic to Cenozoic age, forming the largest contiguous area of sedimentary rocks in Greenland. Most prominent is a tract of Lower Palaeozoic shelf and trough deposits, representing the continuation of the Franklinian Basin of the Canadian Arctic Islands (Trettin, 1989), which can be traced from Inglefield Land in the west to Kronprins Christian Land in the east.

The first geological study of this remote area is little more than a century old (Feilden & De Rance, 1878; Etheridge, 1878). However, the general inaccessibility of ice-bound shores kept subsequent visitors to a trickle of hardy explorers, despite the fact that more than 100 000 km^2 of land area are free of ice and snow in the two months comprising the summer season. The Danish geologists Lauge Koch and Johannes C. Troelsen may be singled out for their contributions to sedimentary geology in North Greenland, although many of their observations were never fully published.

The advent of aircraft to arctic exploration heralded a new age in North Greenland geology. Exactly 45 years elapsed from the time that Lauge Koch first conducted airborne reconnaissance over eastern North Greenland until the Geological Survey of Greenland (Grønlands Geologiske Undersøgelse, GGU) launched the major regional geological programme, the North Greenland Project (1978–80, 1984–85), which has provided the bulk of the geological information upon which this present volume is based.

Fig. 1. The south-eastern margin of the Franklinian Basin in Greenland. Pale weathering Cambrian siliciclastic and carbonate sediments overlying darker Precambrian crystalline basement at Marshall Bugt, Inglefield Land. Aerial photograph looking north across Nares Strait toward Ellesmere Island. Copyright, Kort- og Matrikelstyrelsen, Denmark.

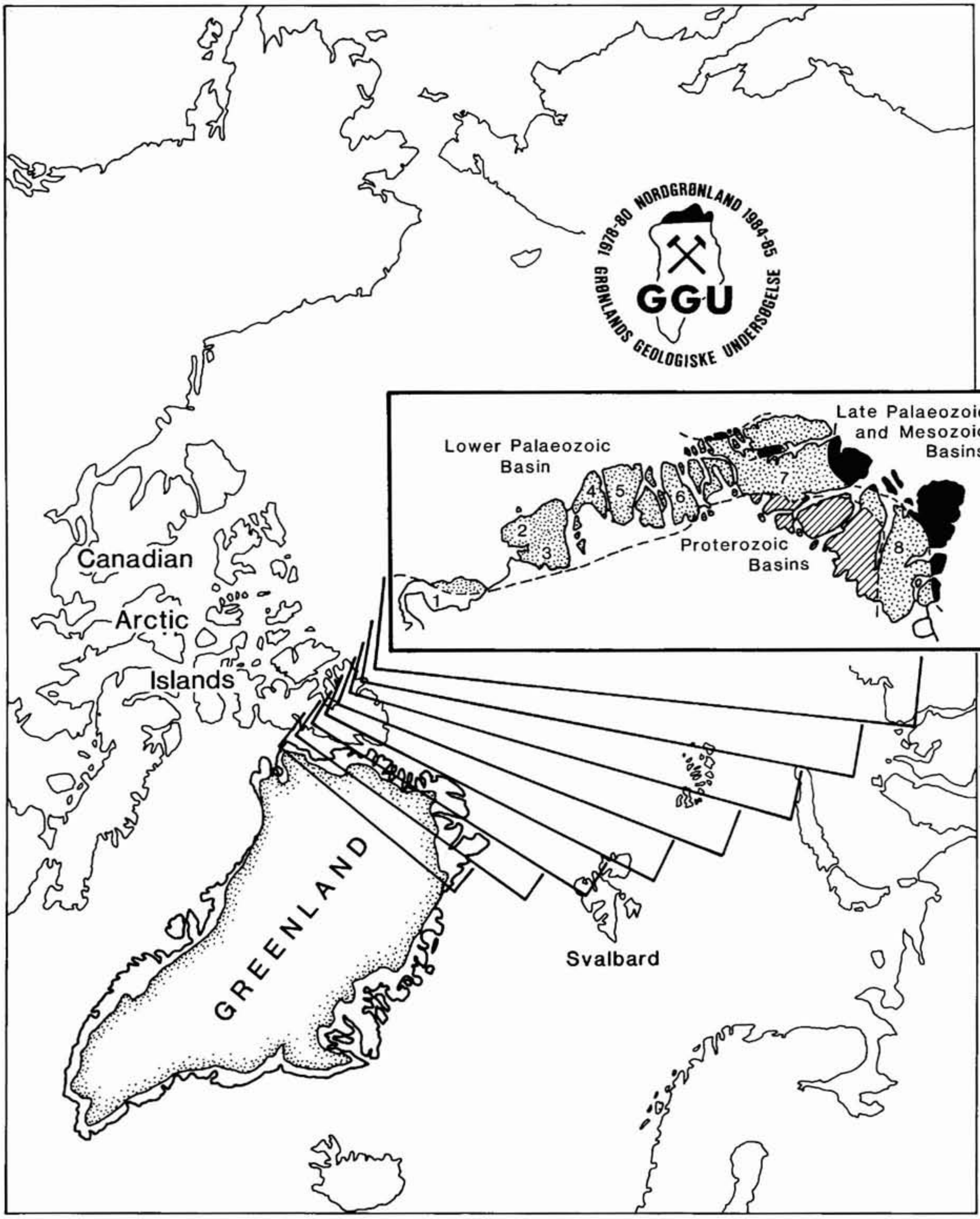

Fig. 2. Greenland viewed in polar projection showing the general distribution of sedimentary basins in North Greenland, based on present outcrops. Much of the geological information synthesised in the present volume was obtained during the North Greenland Project of the Geological Survey of Greenland; the project logo is reproduced in the upper right. 1, Inglefield Land; 2, Washington Land; 3, Daugaard-Jensen Land; 4, Hall Land; 5, Nyeboe Land; 6, Wulff Land; 7, Peary Land; 8, Kronprins Christian Land.

Fig. 3. The Navarana Fjord Escarpment, representing the juxtaposition of Cambrian-Silurian shelf carbonates against Silurian deep-water trough turbidites, is one of the principal tectonostratigraphic features within the Franklinian Basin succession of North Greenland. Cliffs approach 1000 m in height. Aerial photograph of the eastern side of J. P. Koch Fjord looking eastward across Peary Land. Copyright, Kort- og Matrikelstyrelsen, Denmark.

The planning of the North Greenland Project and its development into the largest programme ever mobilised by GGU are recounted in this volume by Niels Henriksen and A. K. Higgins, as a background to four papers describing the development of individual sedimentary basin successions – Proterozoic, Lower Palaeozoic, Upper Palaeozoic, and Mesozoic-Cenozoic. Finn Surlyk integrates these separate discussions into an overview of the geological evolution of North Greenland.

Sedimentary basins of North Greenland forms a companion volume to *Petroleum Geology of North Greenland* (Christiansen, 1989), providing a synthesis of all available information from the world's northernmost complex of sedimentary basins.

Acknowledgements. Many fellow participants in field work in North Greenland under the auspices of the Geological Survey vey of Greenland have generously contributed information incorporated into the individual papers in this volume and reviewed the manuscripts of their colleagues. Esben W. Glendal, Bodil Sikker Hansen, Bente Thomas and Jakob Lautrup have provided technical assistance in the final compilation of the text and illustrations.

Aerial photographs are reproduced with permission (No. A.200/87) of Kort- og Matrikelstyrelsen, Denmark.

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John S. Peel and Martin Sønderholm, June 1991.

Contrasts in North Greenland geology: southern Warming Land (above) and northern Peary Land.

The North Greenland Project

Niels Henriksen and A. K. Higgins

The background for the North Greenland Project, one of the largest and most ambitious geological programmes undertaken by the Geological Survey of Greenland, is outlined. Aspects of the physiography and history of research are briefly recounted prior to a discussion of the cartographic and logistic problems associated with field work along the northern coast of Greenland. The principal scientific results of the project are enumerated.

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The first areas to be investigated when the Geological Survey of Greenland (Grønlands Geologiske Undersøgelse, GGU) was established shortly after the Second World War were the more easily accessible parts of West and South-West Greenland (Fig. 1). These regions are part of the Precambrian Shield which dominates Greenland and, as a consequence, GGU initially developed into an institution specialised in 'hard rock' geology. From the mid-1950s a systematic programme aimed at the production of 1:100 000 geological maps was begun in South-West Greenland. A complementary 1:500 000 mapping programme was initiated in 1964 with the aim of establishing a general geological overview of the entire ice-free part of Greenland within the foreseeable future (Fig. 2). This work began in West Greenland and continued in East Greenland after 1:100 000 mapping (1968–72). By the early 1970s North Greenland had also come into focus as a 1:500 000 mapping target.

A primary aim of the 1:500 000 programme is to establish a geological foundation which will facilitate the exploitation of mineral resources in Greenland. In some areas, such mapping can be based on information derived from the existing 1:100 000 programme. In other areas, special ship-based or helicopter-supported field programmes, supported by photogeological interpretation, are necessary to provide the required geological data to supplement existing information.

North Greenland presented a special catalogue of problems. Unlike the Precambrian crystalline terranes of West Greenland, North Greenland is dominated by Proterozoic and Phanerozoic sedimentary basins, variously affected by mid-Palaeozoic and Tertiary orogenies (Map 1). The area had been little visited since a brief early period of exploration, although all available geological information and a large-scale reconnaissance photo-interpretation had been integrated to provide a synthesis of the regional geology (Dawes, 1971; 1976). A new approach to the 1:500 000 mapping programme was necessary in terms of logistics in the remote areas of North Greenland and, in formulating the North Greenland Project, GGU came to adopt and adapt techniques used by geologists in the adjacent Canadian Arctic to cope with the investigation of large tracts of sedimentary rocks.

The growth of the North Greenland Project into one of the largest and most ambitious work programmes ever undertaken by GGU was influenced by the increasing interest in economic exploitation of the Arctic. Activities by government and commercial agencies in the high Arctic of Canada had earlier reached parts of North Greenland. In 1965–66 two GGU geologists joined the Geological Survey of Canada 'Operation Grant Land' which worked in Ellesmere Island and the Washington Land – Wulff Land area of western North Greenland (cf. Dawes, 1984; Dawes & Peel, 1984).

Commercial activity in the Innuitian region of northern Canada was extended to Greenland in 1969 when the Canadian organisation of J. C. Sproule and Associates commenced a regional geological survey of northern Greenland for Greenarctic Consortium, a programme that included a regional aeromagnetic survey.

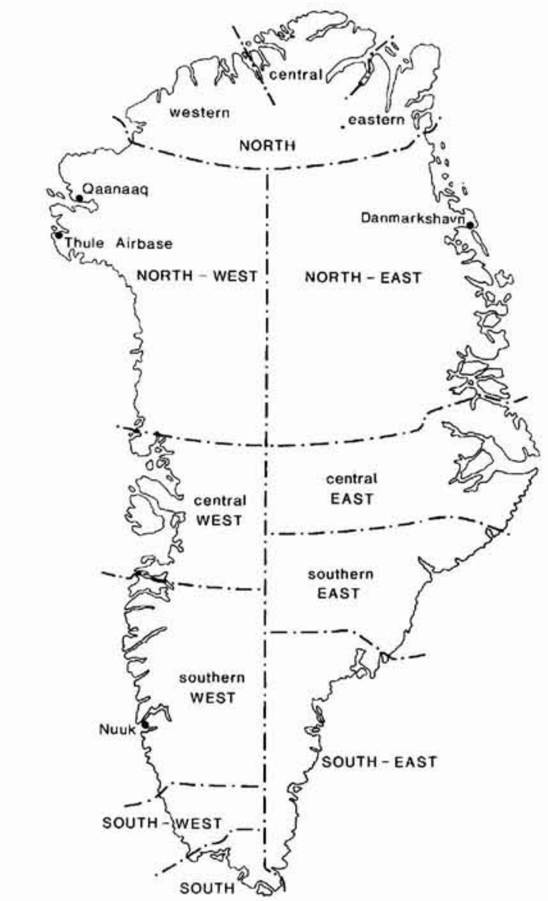

Fig. 1. Locality map.

Field work undertaken by GGU as a preliminary to the North Greenland project was initiated in 1974 with reconnaissance in Peary Land (Peel & Christie, 1975; Christie & Peel, 1977). From 1975 to 1977 field teams worked in Daugaard-Jensen Land and Washington Land, with short visits to Hall Land and Inglefield Land (Henriksen & Peel, 1976; Peel, 1977, 1978).

The North Greenland Project itself was divided into two phases, the first phase from 1978 to 1980 covered the Peary Land to Kronprins Christian Land region, and the second (1984–85) concentrated on the area from Petermann Gletscher to J. P. Koch Fjord (Map 1). This corresponds to the area covered by 1:500 000 maps sheets 7 and 8 (Fig. 2), although field investigations were carried out in areas adjacent to the map sheet areas as geological problems dictated. Acquisition of a regional geological understanding sufficient for the production of these map sheets was a primary goal of the project, although a variety of other activities were also encompassed. Yearly summaries of project activities are given in volumes **88, 99, 106, 126** and **133** of *Rapport Grønlands geologiske Undersøgelse*. A summary of the many papers and maps resulting from the project is given below

Physiography and climate

Geological activities associated with the North Greenland project extended from northern Washington Land in the west to southern Kronprins Christian Land in the east, a distance of more than 1000 km. The region, north of the Inland Ice, is up to 250 km wide from north to south with a land area of about 130 000 km^2. The physiography varies widely, reflecting both the high Arctic setting and the influences of geology.

The Arctic Ocean and the fjords of North Greenland are ice-covered all the year round, although the innermost parts of a few fjords may be ice-free in August and early September. Open-water leads form in the

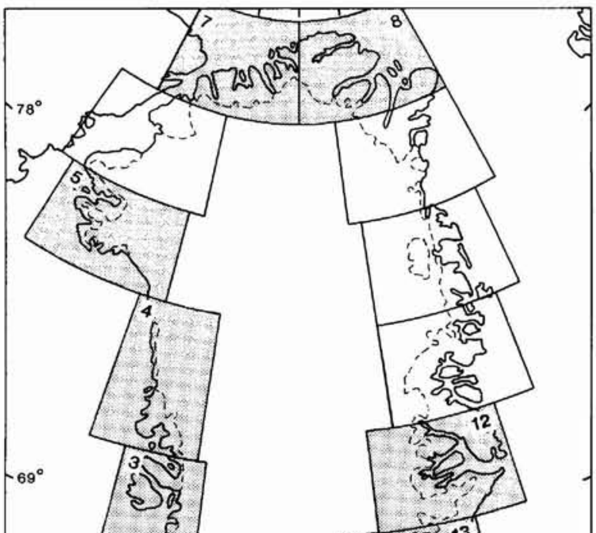

Fig. 2. Index to the 1:500 000 geological map series of Greenland. Ten of the 14 sheets are published or in press. Sheets 7 (Nyeboe Land) and 8 (Peary Land) cover most of the area surveyed by the North Greenland Project.

Fig. 3. Plateau landscape with local ice caps formed in gently dipping Cambrian–Silurian sediments; the plateau surface rises to more than 1000 m. View looking north across Lauge Koch Land and Ekspedition Bræ (centre left), down J. P. Koch Fjord which is covered with semi-permanent sea ice.

summer in the Arctic Ocean ice, notably at the contact between the stationary fjord ice and the drifting ice pack. Hydrographic conditions in the fjords are poorly known, although some geophysical information exists for Nares Strait and parts of the continental margin facing the Arctic Ocean (Dawes, 1990).

The Inland Ice, the major glaciers which drain it, and the many local ice caps are prominent features of the region. The Inland Ice margin can be traced as an undulating line across the region, and has an altitude of generally 600–800 m where it abuts against the ice-free ground to the north. The numerous glaciers draining from the Inland Ice to the heads of the fjords range up to 15 km in width (Map 1), and the larger glaciers have velocities mainly in the range of 300–500 m per year; Petermann Gletscher has advanced 17 km in 19 years, an average annual velocity of almost 900 m (Higgins, 1988).

Independent local ice caps are promiment in Peary Land, Freuchen Land and Kronprins Christian Land. They occur at altitudes of about 1000 m and may be more than 70 km across. Alpine glacier systems are conspicuous in Nansen Land, Johannes V. Jensen Land and parts of Kronprins Christian Land.

The topography of the ice-free areas of North Greenland clearly reflects the influence of the former ice cover during the last glacial maximum (Funder & Hjort, 1980; Kelly & Bennike, 1985; Bennike & Kelly, 1990). Glacier-eroded U-shaped valleys cut through the landscape, radiating out from the Inland Ice or local glaciation centres. Relief in these valleys varies from a few hundred metres to over 1000 m. Glacial deposits are widespread. Moraine occurs at all altitudes, whereas fluviatile Quaternary deposits are confined to valley floors.

In areas to the south, where the geology is characterised by flat-lying, mainly sedimentary sequences, geomorphological expression generally takes the form of a plateau landscape with summits reaching 800–1200 m, dissected by steep-sided valleys or fjords (Fig. 3). Plateau forms vary from place to place, depending on the local rock types. Alternating sandstone and siltstone sequences of the Silurian turbidite succession and massive Cambrian–Silurian carbonate units have extensive outcrops; in the south-east Proterozoic basalts and associated carbonate and siliciclastic sediments are conspicuous.

Areas formed by folded and metamorphosed rocks, such as Nansen Land and Johannes V. Jensen Land in the North Greenland fold belt and parts of Kronprins Christian Land in the East Greenland Caledonian fold belt, are characterised by alpine relief and support inde-

Fig. 4. Alpine landscape in the North Greenland fold belt, western Johannes V. Jensen Land. Mountain summits approach 2000 m.

pendent valley glacier systems (Fig. 4). The highest peak in the area, Helvetia Tinde in Johannes V. Jensen Land, reaches an altitude of 1930 m.

Climatic records for North Greenland include those made at stations at Jørgen Brønlund Fjord (1948–52) and Kap Harald Moltke (1973–87) by the Danish Peary Land expeditions, and more continuous records made at Station Nord (1950–72). In recent years, the establishment of five unmanned automatic weather stations in North Greenland by the Danish Meteorological Institute has provided better regional control and continuous records of basic weather data. The latter show the annual mean temperature for the region to range from −20°C to −17°C, with average winter temperatures as low as −40°C and average summer temperatures of up to +5°C. Annual precipitation, mainly as snow, is estimated at 100–200 mm (P. Frisch, personal communication, 1990).

Winds are mainly katabatic, and are strongest in a 30 km wide zone near the Inland Ice margin. In coastal areas summer winds are sea breezes formed due to temperature contrasts between the land and ice-covered sea, and fog developments are common. There is midnight sun from mid-April to early September, and total darkness from late October until late February.

Working conditions during the project's summer field seasons were generally very favourable, with stable weather and little precipitation. Coastal fog was the most usual cause of lost working days. At the beginning of some seasons the thaw of local extensive snow cover could produce the practical difficulty of very wet conditions.

History of research

Summaries of the geology of North Greenland and its history of exploration prior to the start of the North Greenland project include those of Dawes (1971, 1973, 1976, 1987), Dawes & Christie (1982), Dawes & Haller (1979), Dawes & Soper (1973) and Christie & Dawes (in press). A geological map at a scale of about 1:1 500 000 accompanies Dawes (1976).

North Greenland is uninhabited, apart from a handful of military personnel maintaining the gravel airstrip at Station Nord (Fig. 5). The nearest permanent civilian settlement is at Qaanaaq, near Thule Air Base in North-

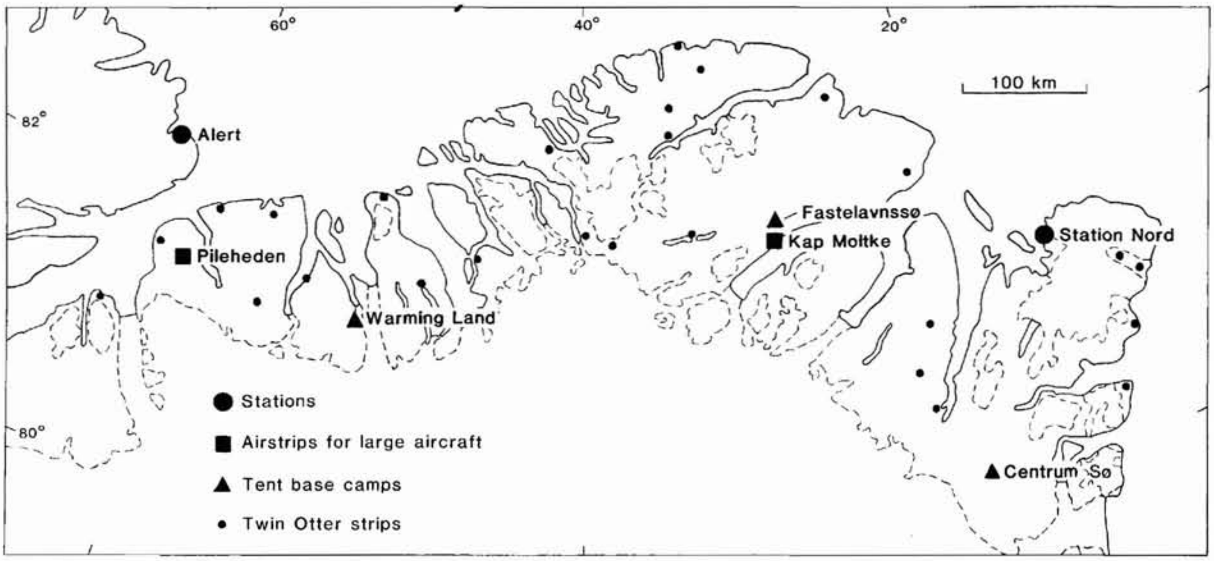

Fig. 5. Map of North Greenland and adjacent Ellesmere Island showing the location of permanently manned stations capable of receiving large aircraft, tent base camps established by GGU in connection with the North Greenland Project and natural landing strips.

West Greenland, the principal point of access to the region (Fig. 1). North Greenland, however, was inhabited by palaeo-Eskimos as far back as 4300 years ago (Independence I culture), and a succession of cultures (Independence II, 700 B.C.; Dorset, 100 B.C. – A.D. 700; Thule, A.D. 900 – A.D. 1200) indicate a long history of Inuit habitation.

The earliest written records and geological observations concerning North Greenland relate to late 19th century voyages of geographical discovery in pursuit of the North-West Passage or the North Pole. In the early decades of this century Danish dog-sledge expeditions assumed a leading role in the exploration of North Greenland. The activities of one man – Lauge Koch (1892–1964) – are pre-eminent in providing the geological and cartographical framework upon which subsequent studies of North Greenland geology have been based. The considerable scientific results of expeditions in which he was a participant include a series of topographic maps at 1:300 000 (Koch, 1932), five geological maps (see summary by Dawes & Haller, 1979) and several geological syntheses (Koch, 1925, 1929, 1935).

The introduction of aircraft-support for expeditions in the years immediately following the Second World War marked the beginning of the modern age of North Greenland geology, although it was first during 'Operation Groundhog' in 1958–60 that aircraft were integrated into daily geological field work (Davies *et al.*, 1959, 1963). The true potential of aircraft-based logistics was fully exploited by the North Greenland Project, with two helicopters and a fixed-wing Twin Otter continuously supporting the expedition in the field.

Project formulation and preparation

Survey field activities in North Greenland commenced in 1974 with a four-man expedition to southern Peary Land. A 3000 m thick succession of Cambrian to Silurian carbonate and clastic sediments exposed in the Børglum Elv region was described but formal stratigraphy was not proposed (Peel & Christie, 1975; Christie & Peel, 1977).

In 1975 attention was turned to western North Greenland, where reconnaissance studies of the Lower Palaeozoic succession in Daugaard-Jensen Land (Henriksen & Peel, 1976) were followed in 1976 and 1977 by similar studies in Washington Land and Inglefield Land. Standard profiles through the sequence were investigated as a preparation for the main phase of the North Greenland project (Peel, 1978, 1979; Hurst, 1980).

In 1975, a research project led by K. S. Dueholm (Institute of Surveying and Photogrammetry, Copenhagen) was initiated to investigate the coordination of topographical and photogeological interpretation, particularly in remote and essentially unmapped regions. The project was supported by GGU, with P. R. Dawes undertaking a primary study of Hall Land (Dawes, 1977, 1987). The success of this venture was a major factor in influencing the establishment by GGU of a photogeological laboratory in 1978 (see below), with North Greenland as the first major region of study.

Detailed planning of the North Greenland Project progressed rapidly throughout the early 1970s, with much discussion of the topographic map base of North Greenland and logistical problems. The defects of existing topographic maps were such that an entirely new topographic base map seemed essential (Lillestrand *et al.*, 1968; Lillestrand & Johnson, 1971). This eventually became possible with the enthusiastic support of the Geodetic Institute (GI; since 1988 part of Kort- og Matrikelstyrelsen, the National Survey and Cadastre) which led to the formulation of GGU/GI cooperation, combining geological and geodetic field work in North Greenland. Logistical problems were linked to the total dependency on air support for transportation of equipment, personnel, food and fuel supplies for aircraft. These necessitated negotiations with the military authorities of Denmark, the United States of America and Canada to permit use of the base facilities at Station Nord, Thule Air Base and Canadian Forces Station Alert, respectively. Practical details associated with base maps and logistics are discussed below.

The 1978–80 phase of field work during the North Greenland Project was carried out from a base camp at Fastelavnssø, a few kilometres north of Kap Harald Moltke in southern Peary Land (Fig. 5). The aim of the GGU work was to undertake regional geological investigations and field mapping throughout the area covered by the Peary Land map sheet (1:500 000 series, sheet 8; Fig. 2). However, field activities extended beyond this area in response to the scientific demands of the developing field work and as a result of reconnaissance activities prior to the second phase of the project (1984–85).

Participation by the Geodetic Institute was concentrated in the period 1978–80, with the aim of establishing new survey ground control points throughout northern Greenland. This work was undertaken from three base camps, at Fastelavnssø (shared in 1978 with GGU), Centrum Sø in Kronprins Christian Land, and in south-east Warming Land (Fig. 5). The new ground control points were to be used in conjunction with new aerial photographs taken in 1978 for the production of orthophotographic maps (see also below).

GGU field work in 1984–85 was carried out from the base in southern Warming Land, and extended throughout the ice-free land areas between Washington Land in the west to Nansen Land and Lauge Koch Land in the east; this corresponds approximately to the boundaries of the Nyeboe Land map sheet (1:500 000 map series, sheet 7; Fig. 2). A special element in this phase of the North Greenland Project was cooperation with 'Projekt Nordolie', a GGU-manned enterprise financed by the Danish Ministry of Energy and aimed at the assessment of the hydrocarbon potential of the Lower Palaeozoic Franklinian Basin in North Greenland (Christiansen, 1989).

Cartography and photogeology

Lauge Koch's early field work was a major step forward in the surveying of northern Greenland, leading to the publication of a set of 19 map sheets at 1:300 000 by the Geodetic Institute (Koch, 1932). Koch used a theodolite for the measurement of angles, while astronomical determinations were measured by Zenith distances of the sun (Koch, 1922).

The first aerial surveys for the purpose of map making were carried out by the U.S. Air Force in 1947 and the resulting trimetrogon photography taken at 6000 m formed the basis of the 1:250 000 map series published in the 1950s by the U.S. Army Map Service (AMS) and the U.S.A.F. Aeronautical Chart and Information Center (ACIC). Both the ACIC and AMS map series covering northern Greenland are characterised by poor absolute map accuracy, mainly due to lack of a ground control net and reliance on the same astronomical position fixes incorporated into Koch's maps of 1932. The largest single error in absolute location is about 23 km and the highest proven map scale error about 20% (Lillestrand *et al.*, 1968; Lillestrand & Johnson, 1971). Information content is poor, and altitude errors of several hundred metres lead to poor representation of topographic features. For representation of detailed geological documentation the AMS and ACIC maps are thus a totally inadequate base.

When the North Greenland Project was being planned the AMS/ACIC 1:250 000 series provided the only map coverage for all of northern Greenland. Excellent 1:50 000 maps prepared by the Geodetic Institute existed for a small area immediately around Jørgen Brønlund Fjord, and the same institute had also prepared 1:100 000 uncontoured photomosaics for much of Peary Land using 1:54 000 vertical aerial photographs taken in the period 1959–61. Much of GGU's early planning concerned assessment of the existing map coverage and evaluation of ways in which map material might be modified in order to produce an acceptable base map for geological documentation. An evaluation of photointerpretation techniques was made with a view to the construction of maps by untraditional methods (see discussion in Dawes, 1987).

These considerations led to formulation of the research project led by K. S. Dueholm (as noted above), aimed particularly at the coordination of topographical and geological mapping, and the development of methods for increased extraction of geological information from aerial photographs (Dueholm, 1979). Two GGU geologists were attached to the project, P. R. Dawes from 1975 with Hall Land as a study area (Dawes, 1977, 1987), and later H. F. Jepsen in the Washington Land area (Jepsen & Dueholm, 1978). It was clear that most of North Greenland was well suited to photogeological interpretation, with vegetation being scarce and with large areas comprising well exposed and laterally continuous rock units.

The dilemma with respect to the inaccurate existing maps was resolved with formulation of the work in North Greenland as a joint venture with the Geodetic Institute (see above). As producing maps of North Greenland from the existing 1:54 000 vertical photographic coverage would require photogrammetric work on 8000 stereoscopic pairs of photographs, an almost insurmountable task, it was decided to undertake new super-wide angle aerial photography at a scale of 1:150 000 which would reduce the photogrammetric work to a more manageable 1300 pairs (Bengtsson, 1983). Ground control points were established throughout North Greenland in the summer seasons 1978–80 using a doppler satellite position system combined with barometric and triangulation measurements; this permitted a precision of 1 m in all three dimensions (Madsen, 1979; Bengtsson, 1983). A regional gravity network was established at the same time; preliminary Bouguer anomaly maps have been compiled (Forsberg, 1979, 1981; Weng, 1980) and a geoid prediction established (Forsberg & Madsen, 1981).

The new aerial photographs were taken in 1978 from a Lear Jet 25 C aircraft, operating out of Thule Air Base and from Svalbard. Flight altitude was 14 km. A set of super-wide angle photographs was taken in black and white at 1:150 000 with 40% lateral overlap and 80% overlap in the flight direction. A set of infrared, false colour, wide angle photographs was taken at 1:87 000 with 67% overlap in the flight direction, but without side overlap. On the basis of the 1:150 000 photographs and

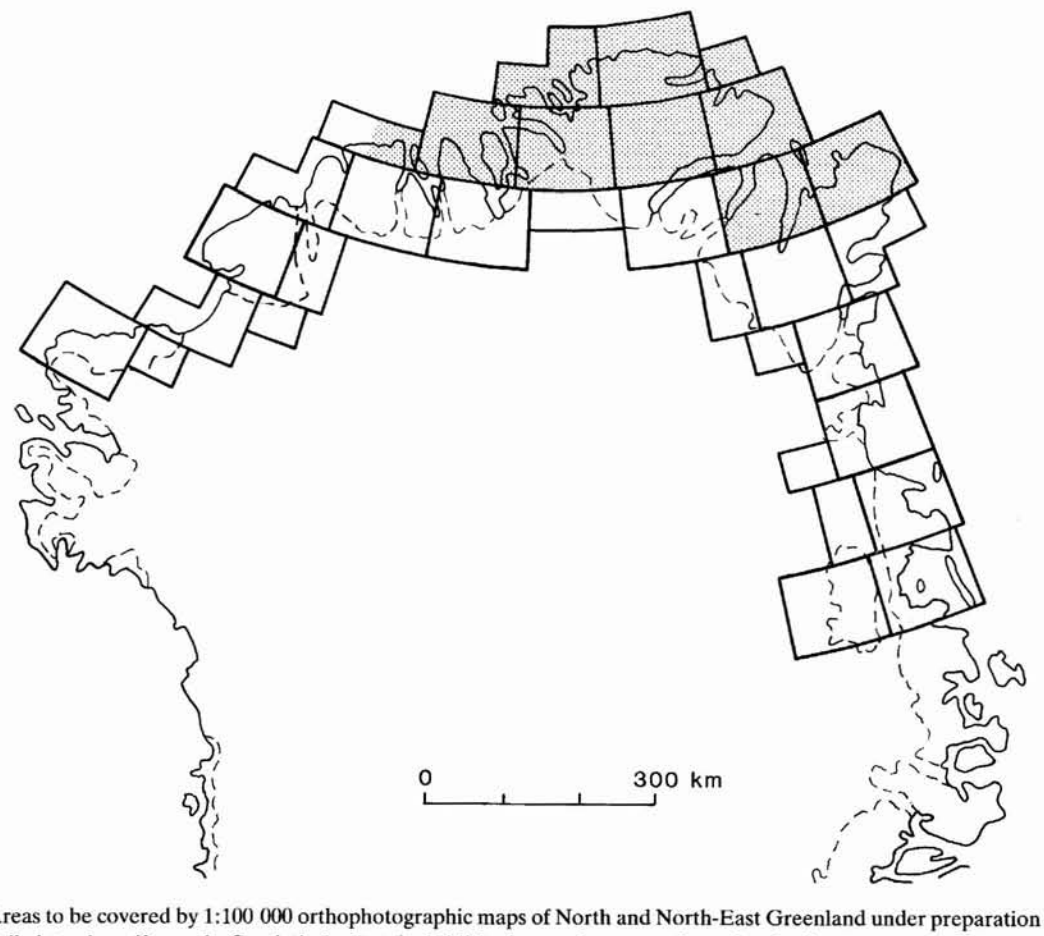

Fig. 6. Areas to be covered by 1:100 000 orthophotographic maps of North and North-East Greenland under preparation by Kort- and Matrikelstyrelsen (formerly Geodetic Institute). Published map sheets are shown by shading.

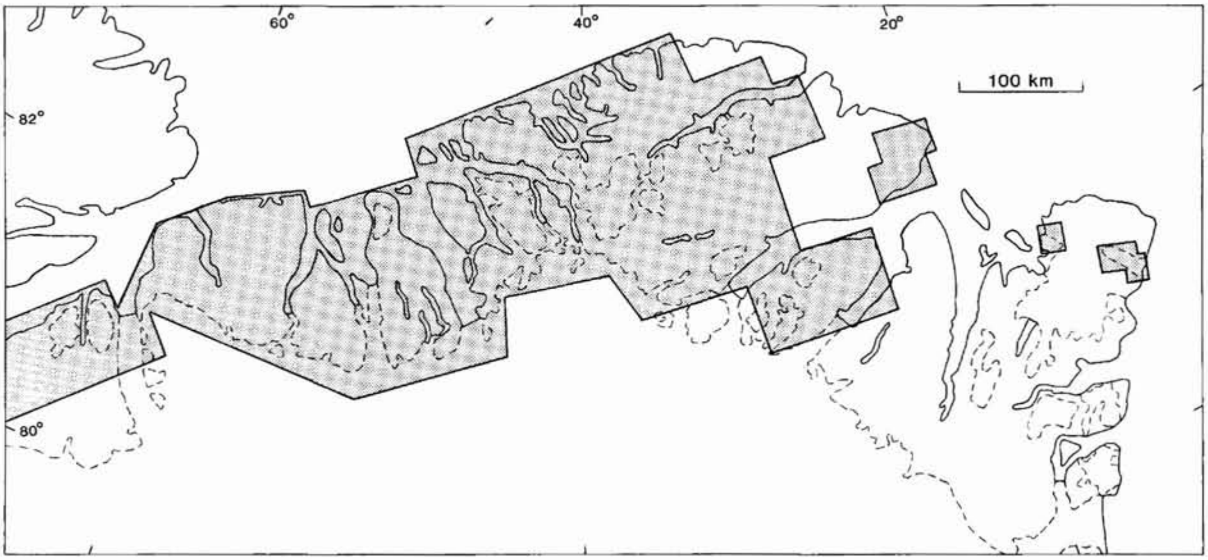

Fig. 7. North Greenland showing the areas (shaded) for which 1:100 000 topographical maps with a 100 m contour interval have been compiled by GGU using ground control data and aerial photographs supplied by the Geodetic Institute.

the new ground control points, new maps with 100 m contours were constructed, and publication by the Kort- og Matrikelstyrelsen is in the form of 1:100 000 orthophotographic maps which will eventually cover not only North Greenland, but also North-East Greenland with a southern boundary at Bessel Fjord (76°N; Fig. 6).

In the 1978 summer season geological observations were compiled mainly on individual 1:54 000 aerial photographs or 1:100 000 photomosaics, but from 1979 the new 1:150 000 photographs became available, as well as individual 1:100 000 orthophotographs. Subsequently new 1:100 000 topographic maps were used for compilation purposes, and these also provided the topographic base for published 1:100 000 and 1:500 000 geological map sheets.

In 1977 GGU purchased a Kern PG 2-D stereo-plotter and desk top calculator (Jepsen & Dueholm, 1978). Methods for calculating geological parameters developed by Dueholm were elaborated. In due course expanded computer facilities were added and a semi-automatic drawing table was attached to the system. Programs permit calculation of dip and strike, fault displacements and bed thicknesses from precise photogrammetric measurements. Calculated dip and strike measurements can also be combined to calculate local fold axes, and it is possible to extrapolate precisely the course of bedrock geological boundaries into poorly exposed and covered areas (cf. Pedersen, 1981; Bengaard, 1989; Hougaard *et al.*, 1991).

Photogeological studies using this instrumentation began with compilation of areas on both sides of Frederick E. Hyde Fjord (Pedersen, 1979, 1981, 1986), and later extended to other parts of Peary Land. A substantial part of the region was eventually interpreted photogeologically on a new 1:100 000 topographic base (Fig. 7). However, compilation of the 1978–80 geological field maps for the 1:500 000 Peary Land map (sheet 8) was carried out in a variety of ways, due to the overlap of field work, aerial photography, and photogeological interpretation. Some data were interpreted photogrammetrically, whereas other parts were transferred by hand from aerial photographs or photomosaics via orthophotographs to 1:100 000 outline maps.

Preparations for the second phase of field work (1984–85) included photogeological interpretation using the Kern stereo-plotter of the entire region. Data was compiled on a total of 20 1:100 000 topographic maps prepared in GGU on the basis of GI control points. Field observations from the 1984–85 summers were compiled on the same topographic base. Final compilation of the 1:500 000 Nyeboe Land map sheet was based on a combination of 1:100 000 photogeological and geological field maps.

Logistics

Access to North Greenland is only practical by air. There are only four landing strips in the region usable by large transport aircraft, and three of these are natural landing strips (Pileheden in Hall Land, Kap Harald

Fig. 8. Royal Danish Airforce C-130 transport aircraft on the natural landing strip at the Kap Moltke station, Kap Harald Moltke, Peary Land.

Fig. 9. Rubber bladder tanks for aviation fuel, each with a capacity of 3500 l, at Kap Moltke.

Moltke and Centrum Sø) without any facilities (Fig. 5). The fourth strip, at Station Nord, is operated by military personnel but offers few facilities. Any large expeditionary activity must be self-supporting, an obligation which necessitated careful planning at GGU's home offices in Copenhagen. All personnel, equipment and aircraft fuel were flown in at the beginning of the field season, and at the end of the season personnel, equipment and rock samples were flown out.

The willingness of the Royal Danish Air Force (RDAF) to assist the expedition with their C-130 Hercules transport aircraft (Fig. 8) was a major factor in the success of the North Greenland project. With a mixed cargo of personnel, equipment, provisions and small helicopters, the payload of these aircraft to North Greenland destinations was 10–12 tons. During the first three years of the project (1978–80) the expedition and its equipment were transported to and from Station Nord in one or two flights from Denmark. Bulk transport of aviation fuel was carried out with RDAF C-130 aircraft equipped with special tank equipment, in coordination with the annual resupply of Station Nord in May. A total of 100 000 l of jet fuel (JP-4) was purchased from U.S. military authorities at Thule Air Base each season and flown to Kap Harald Moltke (Fig. 9), where it was stored in large rubber bladder tanks, each with a capacity of 3500 l.

During the second phase of field work (1984–85) the Canadian Forces Station Alert in north-east Ellesmere Island was used as a transit and support base for the expedition. RDAF C-130 aircraft transported the expedition into and out of Alert, and were also used to air lift the expedition's fuel from Thule Air Base to Alert where it was stored in permanent fuel storage tanks until needed. The expedition's Twin Otter fixed-wing aircraft made regular flights from Alert to the field base camp in Greenland with a cargo of 1200–1500 l of fuel, mainly for helicopter use.

Transport of field parties within North Greenland was mainly by helicopter and, in each of the five seasons, two Bell 206 Jet Ranger helicopters were chartered by GGU. In 1979 and 1980, when the Geodetic Institute operated from their own base camp, an additional helicopter was chartered. The helicopters were operated with fixed flotation gear and, with a payload of 350–380 kg, could each transport a 2-person standard camp (Fig. 10). The two helicopters logged a total of 400–500 flying hours each season in North Greenland.

A Twin Otter aircraft with STOL (Short Take-off and Landing) capabilities and equipped with tundra tyres was chartered each season, and used mainly for transport of personnel, equipment, provisions and fuel from the C-130 airstrips to the base camp sites (Fig. 11). Its ability to operate from unprepared landing sites was widely exploited, notably for establishment of fuel de-

Fig. 10. Bell 206 Jet Ranger helicopter with equipment for a two-man geological field camp being loaded.

Fig. 11. De Havilland Twin Otter aircraft on the gravel terrace airstrip at the Fastelavnssø base camp. In the foreground all-terrain motor tricycles used for local transport, and several 55 gallon (200 l) reusable rubber drums of aviation fuel.

pots for use by the helicopters. More than 30 landing sites were established (cf. Fig. 5), few of which required more than a few hours of levelling with shovel and spade to be acceptable. The Twin Otter proved also to be ideal for low-level photographic flights, which were made along nearly all major fjords and valleys (Fig. 12). Black and white and colour photographs of the well exposed cliff sections have provided a considerable amount of geological information.

Nearly all geological field work was carried out by two-man teams. These usually comprised two geologists working together, often with different specialities, so that the various aspects of the geology could be more effectively studied. Field teams lived throughout the season in small tent camps. For the most part field camps were moved by helicopter 25–50 km at 5–7 day intervals; camp moves were often combined with helicopter reconnaissance so that geological mapping could be extended over larger areas. Each team had 8–12 camp positions each season (Fig. 13).

Base camps were established each year on locations known to be free of snow early in the season (Fig. 5). The base camp was the operational centre for the expedition, and comprised about 20 small living tents, three or four large (20 m^2) storage tents, an Atwell hut (30 m^2) for kitchen and canteen use and a small radio hut (Fig. 14). There was also a complete system for fuel storage and refuelling of aircraft. The base camp had a normal permanent staff of four; other residents usually included the expedition leader and aircraft pilots and mechanics, while members of field parties were occasional guests.

Communication between the base camp and aircraft and field camps was maintained using HF-SSB radios and frequencies in the 3000–5500 khz range. Despite the limited transmitter power of the field radios (5–10 watts) radio communication was generally very reliable, mainly because of the low radio noise level in the Arctic. During aircraft operations regular reports were made to base camp at 10–20 minute intervals, with positions indicated with reference to a 10 × 10 km UTM grid. The base camp radio, with a transmitter power of 100 watts, enabled regular connections to be made with other main stations in the region, as well as with the

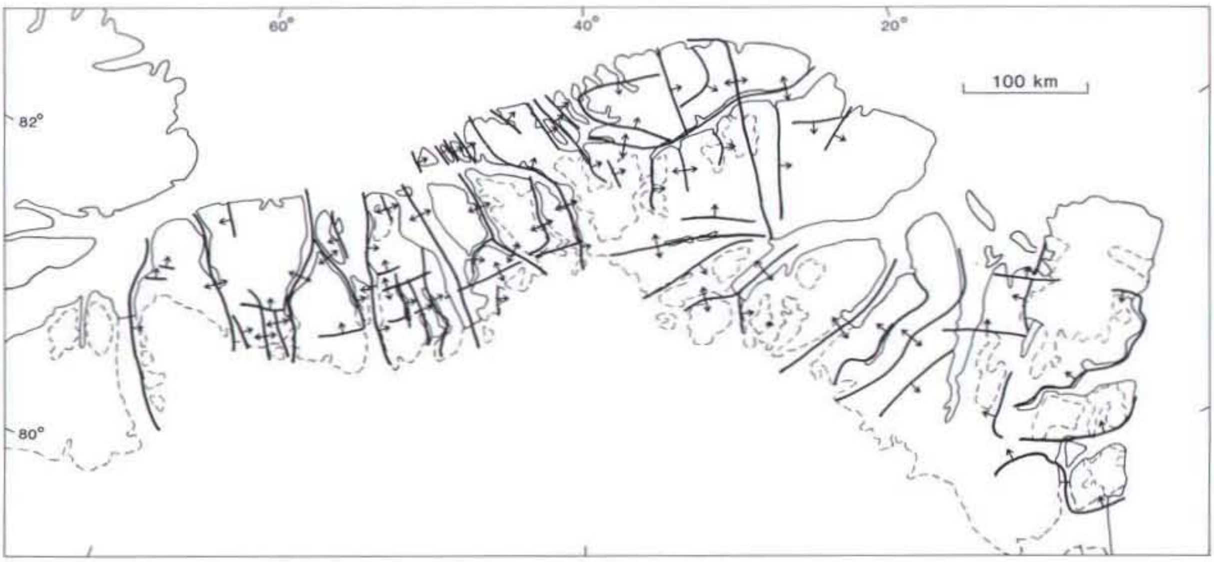

Fig. 12. Index map showing the routes of photographic flights made with the Twin Otter during the project. Black and white photographs and colour transparencies were taken of most steep-sided fjords and valleys.

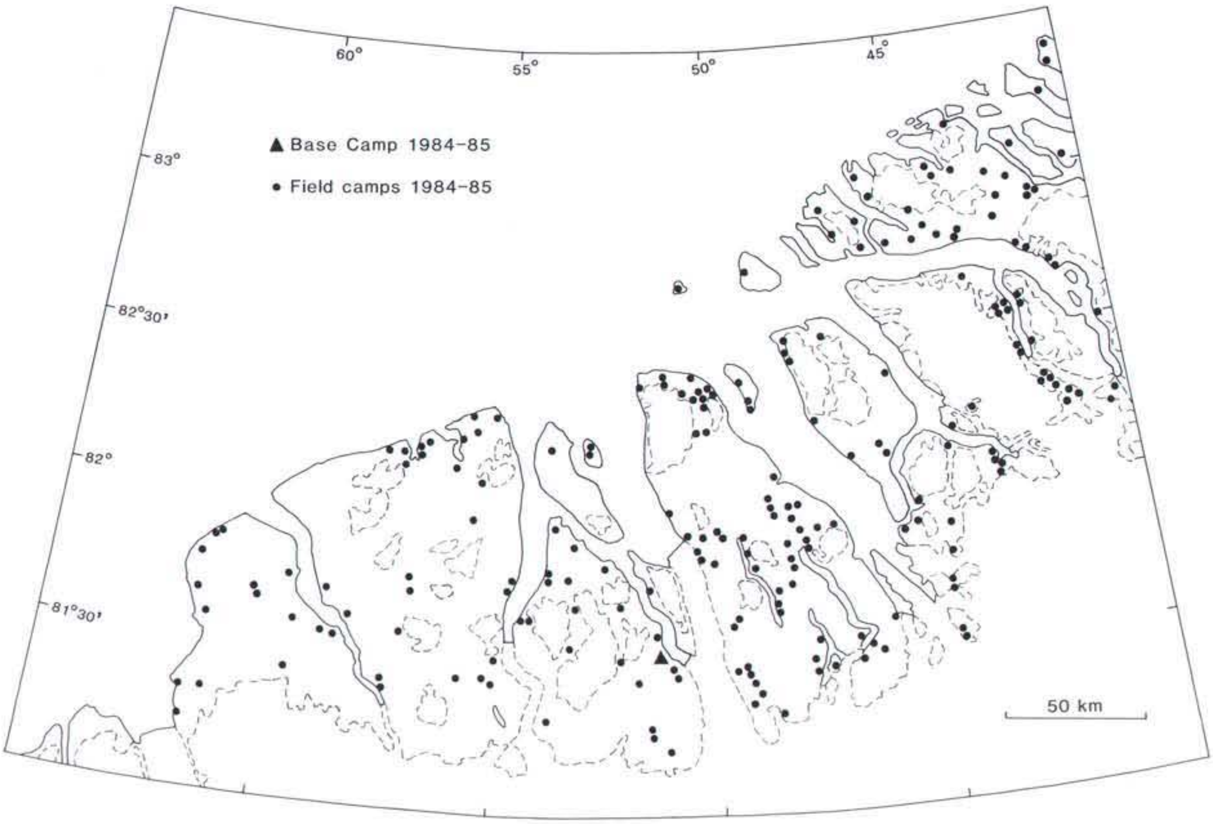

Fig. 13. Distribution of field party camp sites in the region of the 1:500 000 Nyeboe Land sheet (sheet 7) during the 1984–85 field seasons.

outside world via Danmarkshavn weather station and Thule Air Base.

The vulnerability of the Arctic environment and the inclusion of all of the working region within the North-East Greenland National Park placed a particular obligation on field parties and base camp personnel to cause

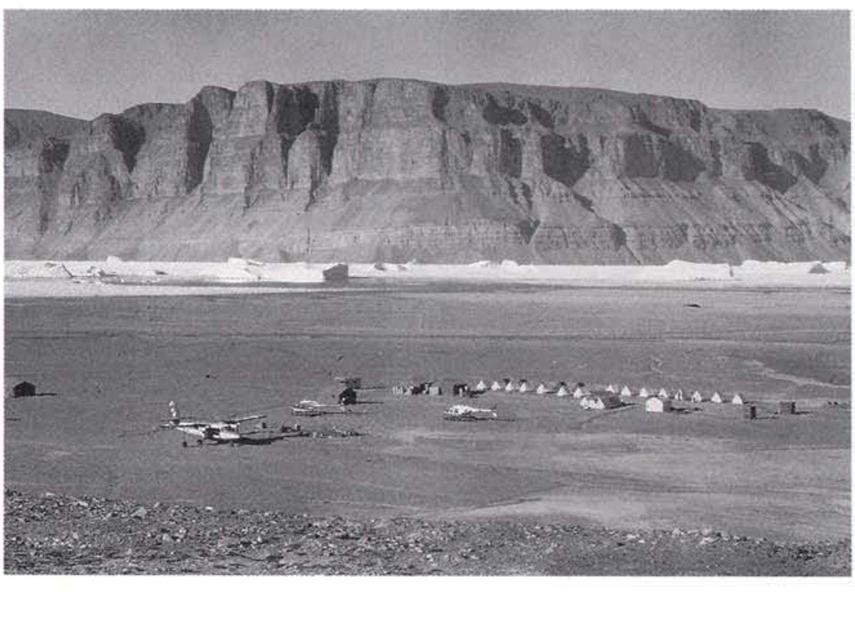

Fig. 14. Base camp on river terraces in south-eastern Warming Land, looking east towards Permin Land, with helicopters and the Twin Otter in the foreground. The camp comprises four large tents for equipment, radio and kitchen huts, and about 20 small tents for personnel.

as little disturbance as possible to the original conditions in their camp site vicinity. This applied particularly to the disposal of kitchen rubbish, which ideally was returned to base camp. The problem of disposal of metal fuel drums was avoided by use of rubber bladder tanks for main fuel storage, and 55 gallon (*c.* 200 l) reusable rubber drums (Fig. 11) for small fuel depots established by Twin Otter or helicopter. At the termination of the project, base camp sites were completely cleared, and no depots or huts remain.

Scientific cooperation

The close cooperation with the Geodetic Institute was, as noted above, a vital factor in resolving the problem of the poor quality of existing topographic maps. The formulation of the 1978–80 phase of field work as a joint GGU/GI project also added an important element of security, in that it became financially viable to operate with at least two helicopters each season. In the second phase of the project (1984–85) the same degree of security was achieved when the petroleum source rock programme 'Projekt Nordolie' financed by the Danish Ministry of Energy was fully integrated with the GGU work (Christiansen, 1989). Groups from the Greenland Technical Organisation and Greenland Fisheries and Environmental Research Institute also took part in the second phase of the project, carrying out a variety of technical, environmental and biological investigations (Grønlands Fiskeri- og Miljøundersøgelser, 1986).

Between 15 and 23 geologists participated in each of the 5 years of the project. Of these, 8 geologists took part for between 3 and 5 seasons each. The field geologists included 16 from GGU, 17 from Danish universities, and 20 from geological institutes outside Denmark. A particularly rewarding aspect of the geological work has been the number of Ph.D. or similar research studies which have been undertaken at Danish and foreign institutes. Pedersen (1982) and Bennike (1989) completed *lic. scient.* (= Ph.D.) studies at the University of Copenhagen. Three Ph.D. studies at the University of Nottingham, U.K., funded by the National Environmental Research Council (NERC) have pro-

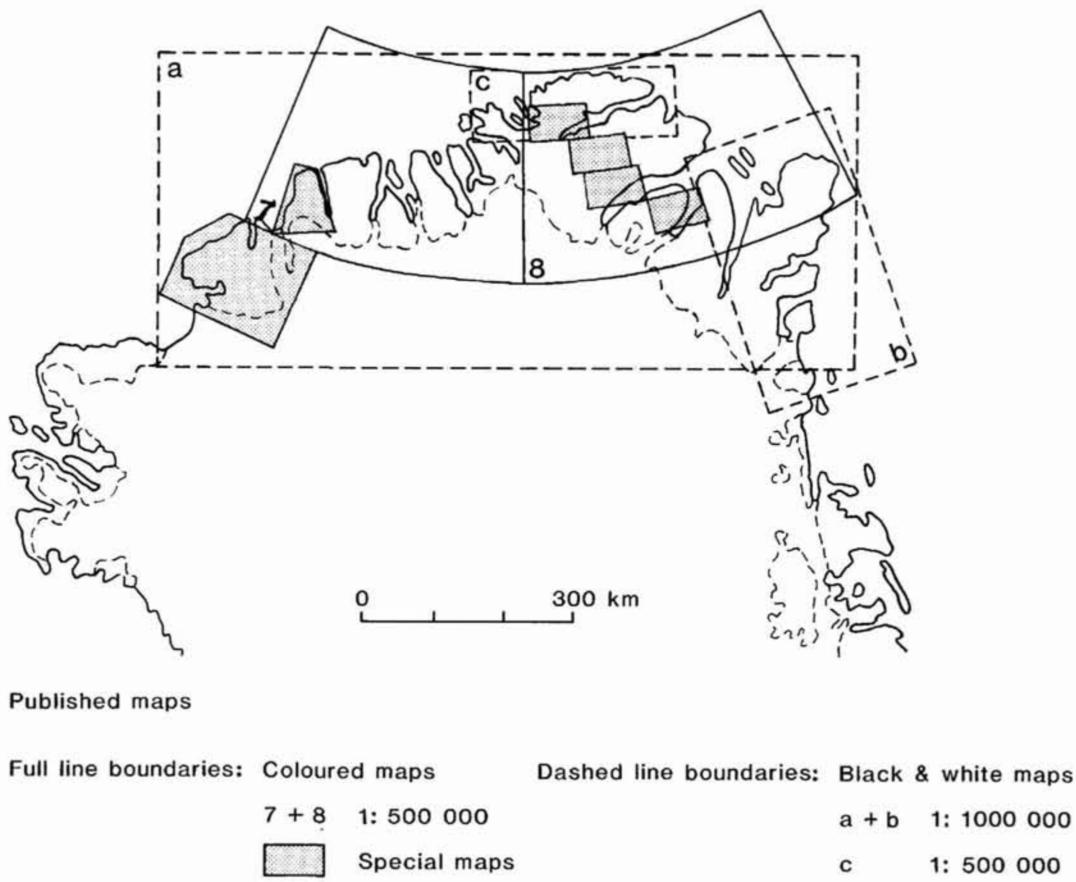

Fig. 15. Published geological maps resulting from the North Greenland Project and associated activities.

vided a biostratigraphic framework for much of the carbonate platform sequence (Armstrong, 1983, 1990; Smith, 1985, in press; Tull, 1988). Ph.D. projects at the Universities of Keele, U.K., and Kansas, U.S.A., studied aspects of Cambrian basin evolution and biostratigraphy (Ineson, 1985; Babcock, 1990; M. R. Blaker, in preparation at Keele University).

Scientific results

GGU has published two 1:500 000 geological map sheets (sheet 7, Nyeboe Land; sheet 8, Peary Land) and four 1:100 000 geological maps forming a NW–SE transect from J. C. Christensen Land to Peary Land (Fig. 15). Coloured geological maps of Washington Land (1:250 000, printed 1983) and Hall Land (1:66 500; Dawes, 1987) have also been published. A black and white geological map of North Greenland (1:1 000 000) published in 1987 (*Rapp. Grønlands geol. Unders.* **133**) is reproduced herein with minor modifications as Map 1. A compilation at a scale of 1:1 000 000 of the Kronprins Christian Land area accompanied *Rapp. Grønlands geol. Unders* **106**, together with a 1:500 000 geological map of Johannes V. Jensen Land. A preliminary map of the area from J. P. Koch Fjord to Danmark Fjord accompanied *Rapp. Grønlands geol. Unders* **88**. One of two maps of Quaternary geology at a scale of 1:1 000 000 planned to cover the same area as the Nyeboe Land and Peary Land map sheets has been printed (Bennike & Kelly, 1990).

Reference to many of the publications arising from the North Greenland Project is made in the respective papers which make up this bulletin. These are mainly in respect of the stratigraphical, sedimentological and palaeontological aspects of the sedimentary basin studies.

Other published studies include: Precambrian crystalline basement at the head of Victoria Fjord (Henriksen & Jepsen, 1985); structural studies in the North Greenland fold belt (Bengaard *et al.*, 1987; Friderichsen & Bengaard, 1985; Higgins *et al.*, 1985; Pedersen, 1986; Soper *et al.*, 1980; Soper & Higgins, 1990; structural studies in the northern part of the Caledonian fold belt (Hurst & McKerrow, 1985; Hurst *et al.*, 1985; Jepsen & Kalsbeek, 1985); geochronological studies (Hansen *et al.*, 1987; Kalsbeek & Jepsen, 1983; Larsen & Graff-Petersen, 1980; Springer, 1981); studies of Tertiary volcanics (Brown *et al.*, 1987); Quaternary geology (Funder & Hjort, 1980; Bennike & Kelly, 1990); geomagnetic and palaeomagnetic investigations (Abrahamsen & Marcussen, 1980; Abrahamsen & Van der Voo, 1987a, b; Marcussen & Abrahamsen, 1983); geochemical exploration reconnaissance (Ghisler & Stendal, 1980; Jakobsen & Stendal, 1987; Steenfelt, 1980, 1985, 1987).

Research on rock and fossil collections continues, both at GGU and in collaboration with outside institutes (e.g. Peel, 1988). In some cases supplementary field work has been carried out in North Greenland, funded by the Carlsberg Foundation, Copenhagen. Thus, additional field studies were made of the Plio-cene–Pleistocene Kap København Formation in 1984 (Bennike, 1989), in the Wandel Sea Basin sequence around Station Nord and at Kilen in 1985 (Håkansson & Stemmerik, 1989, in press; Håkansson *et al.*, in press), and new collections of a soft-bodied Burgess Shale type fauna were made from near J. P. Koch Fjord in 1989 (Conway Morris *et al.*, 1987, 1990; Peel, 1990). Field work mainly supported by external sources is scheduled to continue in 1991 in the Wandel Sea Basin sequence of eastern Peary Land and the J. P. Koch Fjord area.

Acknowledgements. It is not possible to acknowledge all the individuals, companies and institutions who have contributed to the successful conclusion of the North Greenland Project. However, mention must be made of the Royal Danish Air Force and the crews of the C-130 aircraft who carried the expedition to and from Greenland. The Swiss company Heliswiss A. G. of Berne, who have 20 years experience of charter operations for GGU in Greenland, and the Icelandic Company Flugfélag Norðurlands of Akureyri who carried out Twin Otter operations, also deserve special mention. Canadian and U.S. military authorities are acknowledged for their permission to use military facilities at Alert and Thule Air Base, respectively.

Eigil Knuth, leader of the Danish Peary Land expeditions provided a great deal of help in the planning stage of the project, and use was made of the natural airstrip established and maintained by Knuth at Kap Harald Moltke. Danish military personnel at Station Nord were most helpful during the first phase of the project (1978–80). Danish military authorities also gave permission for the use of huts established by the Sirius Sledge Patrol in North Greenland.

Ulla Johansen, Grethe Hougaard and Jakob Lautrup are thanked for technical assistance in the preparation of this manuscript which was reviewed by Peter R. Dawes and John S. Peel.

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Tectonostratigraphy of North Greenland

Finn Surlyk

A succession of at least eight tectonostratigraphic basins occurs in North Greenland, spanning over 1200 million years from Middle Proterozoic to Tertiary times. They represent major events of plate reorganisation associated with extension or compressional loading of the crust. The tectonostratigraphic basins consist of depositional sequences composed of linked depositional systems. Five major collisional events are recorded which influenced or closed and deformed former basins. The main basins, basin-forming and collisional events are: 1, Middle Proterozoic interior sag (Independence Fjord Basin), *c.* 1380 Ma; 2, Middle Proterozoic rifting and volcanism (Midsommersø – Zig-Zag Dal volcanic event), *c.* 1230 Ma; 3, Grenvillian Orogeny (no direct evidence preserved), 1100–1000 Ma; 4, Late Proterozoic rifting and opening of the Iapetus Ocean (Hagen Fjord – Rivieradal passive margin basin), *c.* 800(?)–590 Ma; 5, latest Proterozoic – earliest Cambrian rifting, and Early Palaeozoic passive margin (Franklinian Basin), *c.* 640?–380 Ma; 6, early Caledonian accretionary event causing formation of a westwards migrating peripheral bulge (terminated in the Early Ordovician), 480 Ma; 7, early onset of Caledonian orogenic uplift, *c.* 435 Ma; 8, latest Silurian – Early Devonian final Caledonian suturing, and westwards nappe transport and formation of a Caledonian foreland basin (not preserved), *c.* 410 Ma; 9, Late Devonian – Early Carboniferous closure of the Franklinian Basin (Ellesmerian Orogeny) and formation of a foreland basin (not preserved), *c.* 360 Ma; 10, Early Carboniferous – Middle Permian rifting of the northern extension of the East Greenland rift basin, 360–260 Ma; 11, Mesozoic (Triassic, Late Jurassic – Cretaceous) oblique-slip basin, 250–80 Ma; 12, Late Cretaceous rifting (Eurasia Basin), 80–65 Ma; 13, Eurekan thrusting and faulting, 65–55 Ma; 14, Early Tertiary initiation of transform margin basin, 55–0 Ma. Each basin fill constitutes a tectonostratigraphic basin and reflects a major plate tectonic event. The indicated ages are in most cases crude approximations only.

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A coherent tectonic and stratigraphic picture of the geological evolution of North Greenland has emerged after a decade of systematic mapping and topical studies by the Geological Survey of Greenland (GGU) in cooperation with groups from the University of Copenhagen and various non-Danish institutions (Figs 1, 2). These studies represent the culmination of a long exploration history, with field work often carried out under harsh conditions (see Henriksen & Higgins, 1991).

It is now possible to distinguish a succession of at least eight major separate tectonostratigraphic basins ranging in age from Middle Proterozoic to Tertiary and in most cases separated by episodes of deformation (Figs 2, 3). The basins correspond to plate tectonic events and periods of plate reorganisation and they are thus categorised as first order, tectonostratigraphic units in a hierarchy of basinal stages. Several of the tectonic episodes overlap temporally and have direct interrelations in terms of controlling sedimentation and subsidence or uplift histories. This is particularly the case with the interplay in eastern areas of North Greenland between the passive margin evolution of the Franklinian Basin and Caledonian closure of the Iapetus Ocean (Surlyk & Hurst, 1983, 1984; Hurst *et al.*, 1983; Surlyk, 1988).

Precambrian crystalline basement

In North Greenland and adjacent North-West Greenland crystalline basement is exposed in several areas (Map 1). In Inglefield Land Proterozoic crystalline rocks are overlain by Proterozoic and Cambrian sediments (e.g. Peel *et al.*, 1982). At the head of Victoria Fjord, along the margin of the Inland Ice, Archaean gneisses are overlain by flat lying sediments of the Up-

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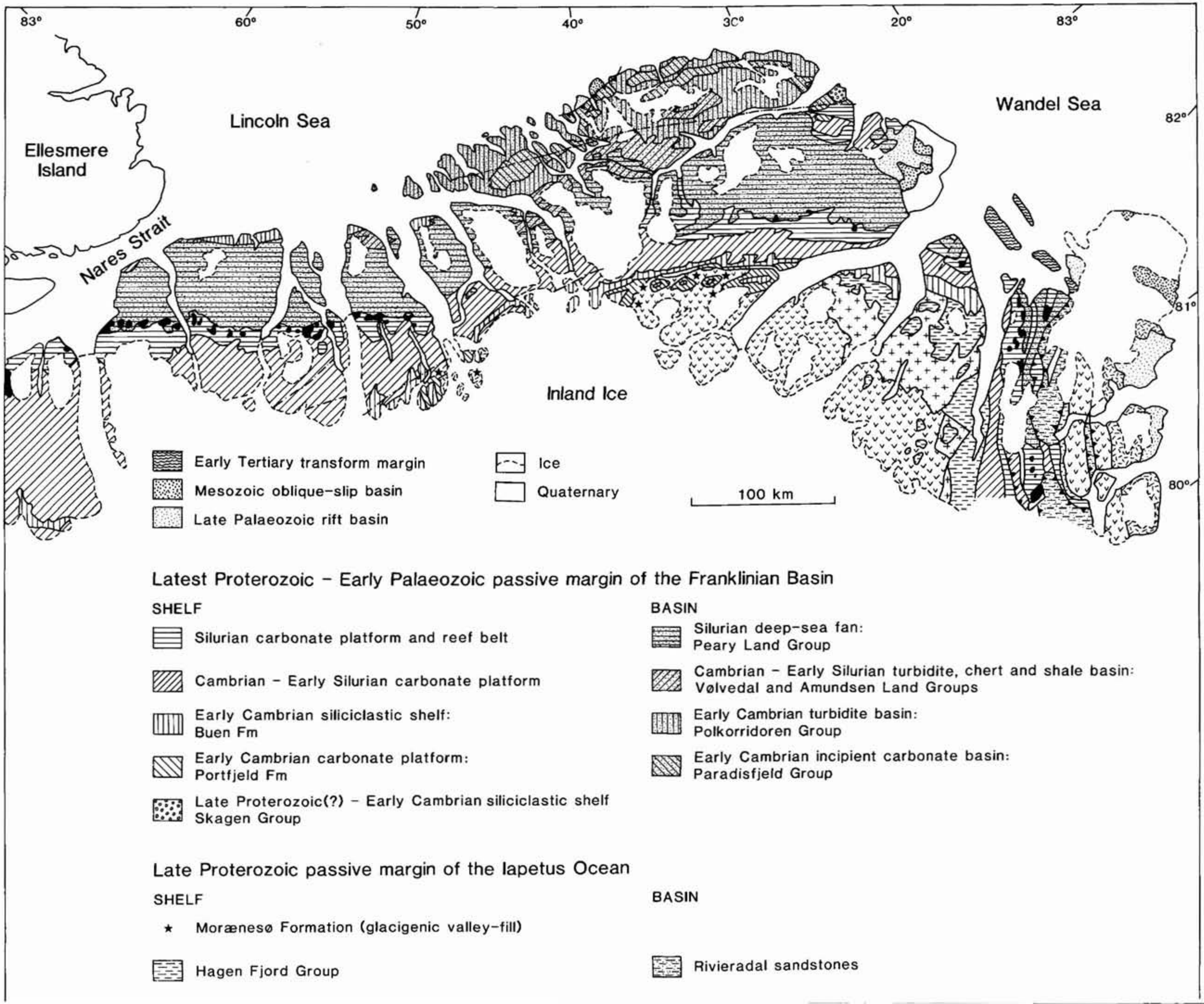
83°
60°
50°
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82°
81°
80°
Lincoln Sea
Wandel Sea
Ellesmere Island
Nares Strait
Inland Ice
100 km
Early Tertiary transform margin
Mesozoic oblique-slip basin
Late Palaeozoic rift basin
Ice
Quaternary
Latest Proterozoic - Early Palaeozoic passive margin of the Franklinian Basin
SHELF
Silurian carbonate platform and reef belt
Cambrian - Early Silurian carbonate platform
Early Cambrian siliciclastic shelf: Buen Fm
Early Cambrian carbonate platform: Portfjeld Fm
Late Proterozoic(?) - Early Cambrian siliciclastic shelf Skagen Group
BASIN
Silurian deep-sea fan: Peary Land Group
Cambrian - Early Silurian turbidite, chert and shale basin: Vølvedal and Amundsen Land Groups
Early Cambrian turbidite basin: Polkorridoren Group
Early Cambrian incipient carbonate basin: Paradisfjeld Group
Late Proterozoic passive margin of the Iapetus Ocean
SHELF
★ Moræneso Formation (glacigenic valley-fill)
Hagen Fjord Group
BASIN
Rivieradal sandstones

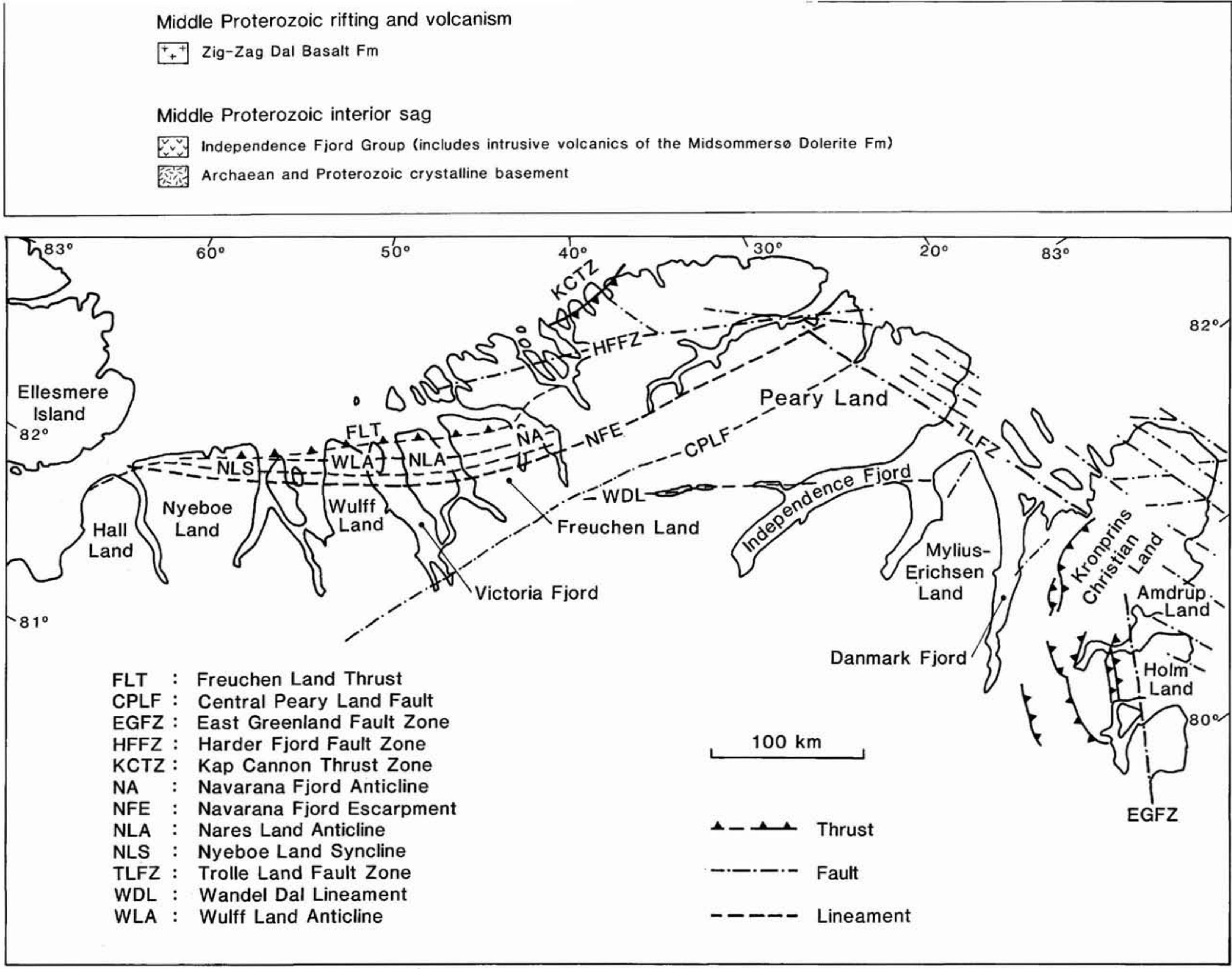


Fig. 1. Simplified geological map of North Greenland showing main structural features (below). Based on various GGU maps and other published sources. The term Freuchen Land Thrust is introduced to replace the slightly inappropriate Buen Thrust of Soper & Higgins (1990).

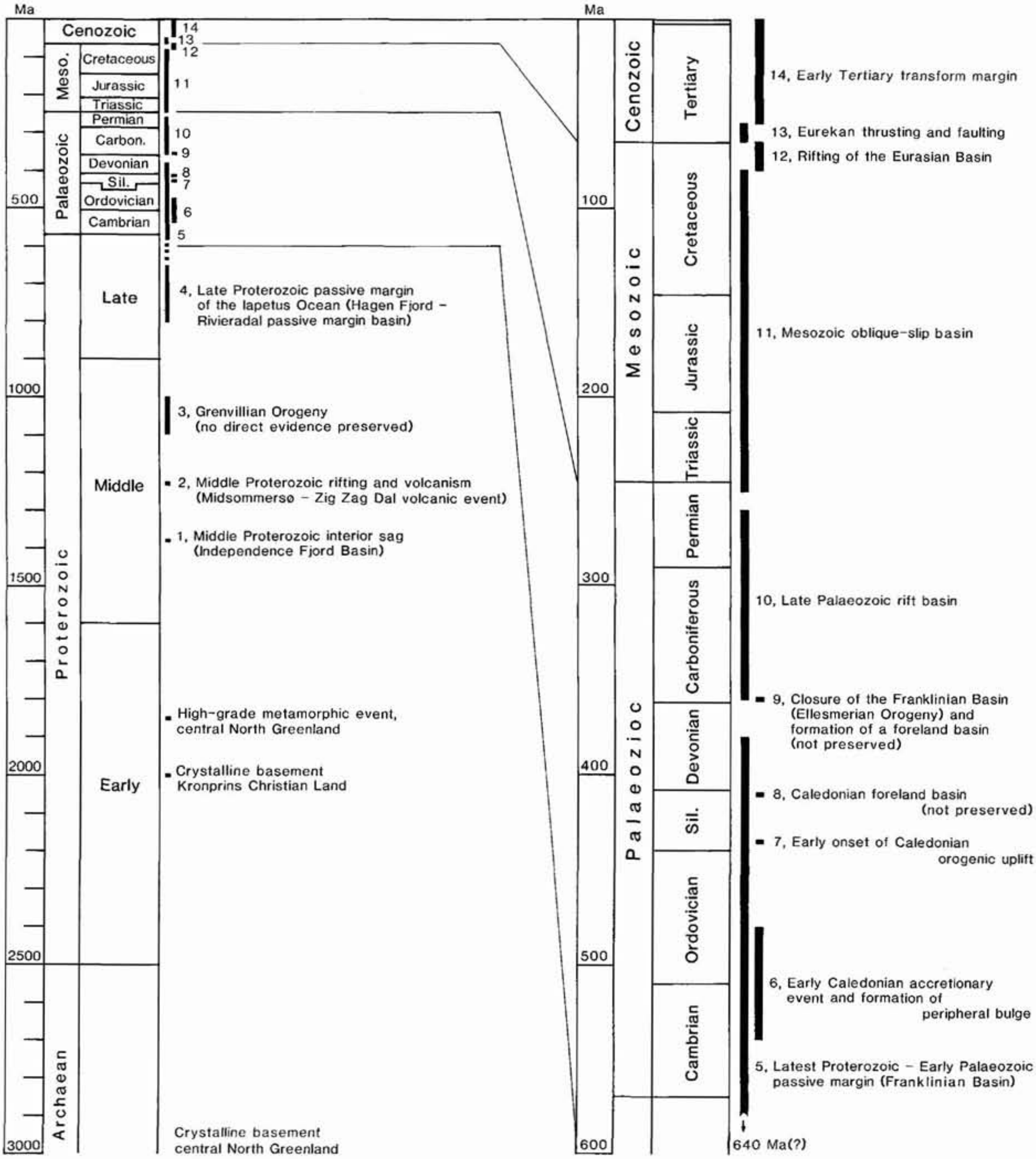


Fig. 2. Tectonostratigraphic basins and collisional events in North Greenland.

per Proterozoic Moraenesø and the Lower Cambrian Portfjeld Formations. Zircon, U/Pb and Rb/Sr whole-rock isotope data give Archaean ages (*c.* 3000 Ma) for the basement, but K/Ar analyses on hornblende show that the area underwent a phase of high-grade metamorphism during the Proterozoic, probably around 1850 Ma (Hansen *et al.*, 1987). Along the east coast of Kronprins Christian Land Proterozoic crystalline basement (*c.* 2000 Ma) is overlain by Middle Proterozoic sandstones of the Independence Fjord Group (*c.* 1380 Ma). It is uncertain whether the crystalline rocks of Victoria Fjord form the extension of the Archaean basement beneath the Rinkian and Caledonian fold belts, or whether they are separated from these by an area of Proterozoic crust (Hansen *et al.*, 1987).

1, Middle Proterozoic interior sag (Independence Fjord Basin), *c.* 1380 Ma

The earliest preserved sedimentary basin in North Greenland is represented by the Middle Proterozoic Independence Fjord Group (Figs 3A, 4) (Sønderholm & Jepsen, 1991). Clays within the middle part of the group have yielded Rb/Sr ages around 1380 Ma. The group is more than 2 km thick and is inferred to rest unconformably upon Archaean crystalline basement. It consists of the geographically-separated, sandstone-dominated Inuiteq Sø and Norsemandal Formations. The group is dominated by sandstones which were deposited in fluvial and aeolian environments on very low angle alluvial fans possibly forming bajadas. Relative rises in base level resulted in the formation of ephemeral saline lake and playa systems which are represented by several laterally extensive siltstone members. The exact nature of the basin is not known. The uniformity of the continental deposits, the great lateral extent of the facies and the apparent lack of syn-depositional faults suggest that it was an intracratonic sag basin which did not develop into a rift and spreading centre. Collinson (1983) tentatively suggested that minor phases of heating and cooling at depth led to the extensive lacustrine intervals and that a much larger but related thermal event led to the extensive intrusion of dolerite and extrusion of the basalts which directly overlie the Independence Fjord Group.

2, Middle Proterozoic rifting and volcanism (Midsommersø – Zig-Zag Dal volcanic event), *c.* 1230 Ma

A major volcanic event occurred in the Middle Proterozoic and intrusive and extrusive volcanic rocks are preserved in a more than 100 km wide belt curving along the present northern and eastern margin of the Canadian-Greenland Shield (Fig. 3B). Huge volumes of basic magma (the Midsommersø Dolerite Formation) intruded the crystalline basement and the Independence Fjord Group (Kalsbeek & Jepsen, 1983). Extrusive equivalents covering an area of more than 10 000 km^2 comprise at least 1350 m of quartz tholeiitic lava flows forming the Zig-Zag Dal Basalt Formation (Kalsbeek & Jepsen, 1984). Whole rock Rb/Sr data from the intrusives give ages of about 1230 Ma. The volcanic event probably represents the onset of rifting and formation of an oceanic spreading centre following the Independence Fjord sag basin. The ocean was apparently situated along the northern margin of the Canadian-Greenland Shield (Jackson & Ianelli, 1981). It is of pre-Grenvillian age but remains of true oceanic crust are not preserved in North Greenland.

3, Grenvillian Orogeny, 1100–1000 Ma

The Proterozoic volcanic event was followed by uplift, block-faulting and peneplanation. These processes took place in the long time interval between about 1230 Ma and the next basin-forming episode which was initiated during the Late Proterozoic (later than 800 Ma). This hiatus which represents over 400 Ma includes the time interval during which the Grenvillian Orogeny took place (1100–1000 Ma). There is no direct evidence of this collisional orogenic event in North Greenland, but it resulted in intense deformation, metamorphism and plutonic intrusion along the northern margin of the Canadian Shield (Trettin, 1987).

4, Late Proterozoic passive margin of the Iapetus Ocean (Hagen Fjord – Rivieradal basin), *c.* 800(?)–590 Ma

The next major basin formation event took place some time between 800 and 590 Ma and is interpreted as heralding the early phases of rifting of the Iapetus Ocean (Figs 2, 3C). The succession includes up to 1000 m of shelf deposits of the Hagen Fjord Group and more than 2500 m of partly age equivalent basinal turbidites and conglomerates included in the Rivieradal sandstones (Fig. 4; Clemmensen & Jepsen, in press; Sønderholm & Jepsen, 1991).

The Hagen Fjord Group unconformably overlies and onlaps the peneplained Independence Fjord sandstones and Zig-Zag Dal basalts from east to west (Fig. 5). It consists of a lower sandstone dominated part which passes upwards into limestones and dolomites and finally back to sandstones in the upper part (Clemmensen & Jepsen, in press). The lower onlapping sandstone unit (Jyske Ås Formation) was deposited on a shallow tidally influenced shelf. Palaeocurrent data suggest that the open sea was towards the north-east. The transgressive sandstone unit is followed by variegated mainly peritidal sandstones and siltstones, and shallow subtidal stromatolitic dolostones (Campanuladal and Catalinafjeld Formations).

This phase was followed by a change from siliciclastic to carbonate deposition in the younger part of the group. The change records the development of an incipient carbonate platform (Kap Bernhard Formation), which eventually evolved into a true carbonate platform

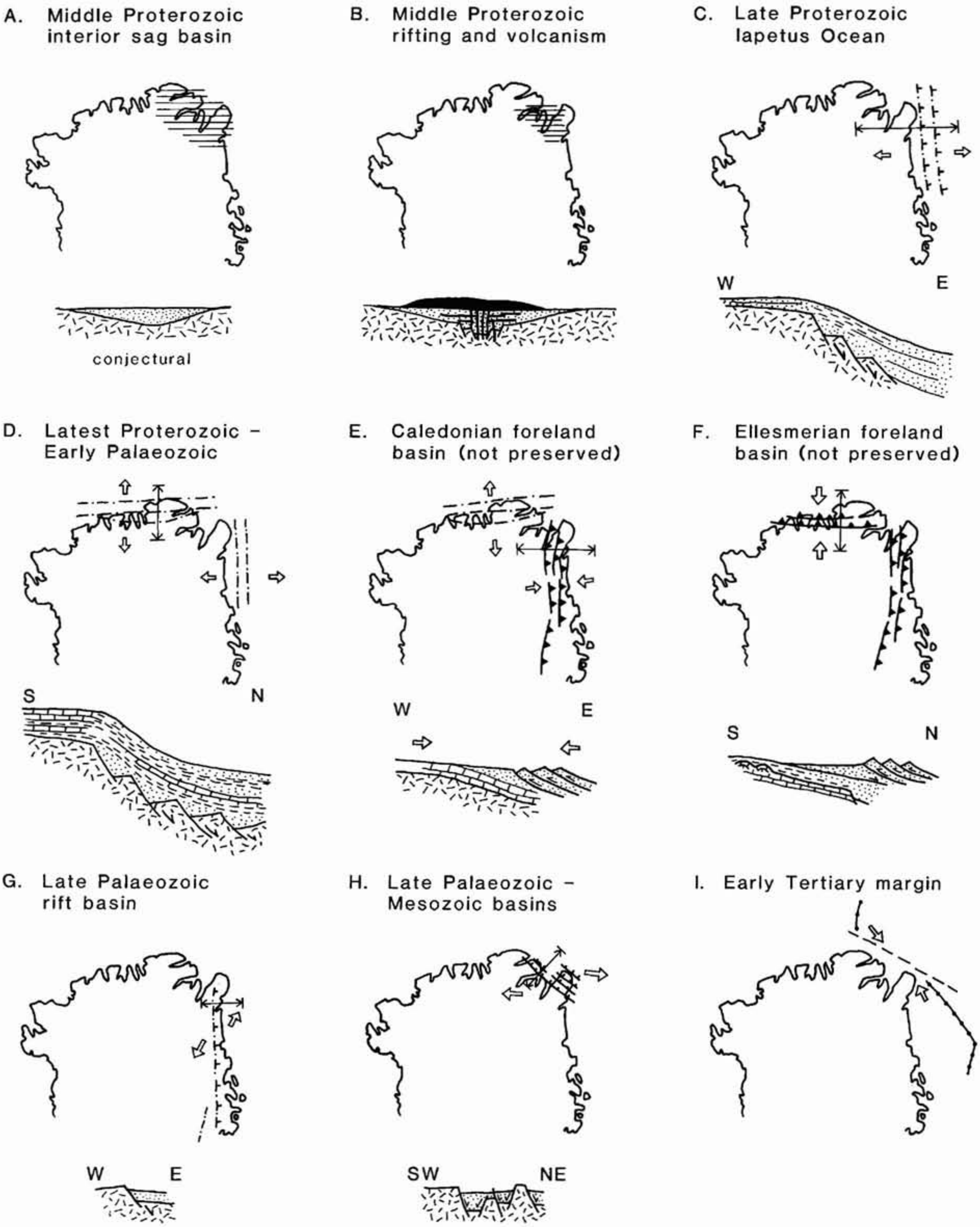


Fig. 3. Schematic maps showing the preserved distribution and plate tectonic reconstructions of the eight tectonostratigraphic basins and intervening volcanic and deformational episodes of North Greenland. A, Middle Proterozoic interior sag (Independence Fjord Basin), *c.* 1380 Ma; B, Middle Proterozoic rifting and volcanism (Midsommersø – Zig-Zag Dal volcanic event), *c.* 1230 Ma; C, Late Proterozoic passive margin of the Iapetus Ocean (Hagen Fjord – Rivieradal Basin), 800–590 Ma; D, Latest Proterozoic – Early Palaeozoic passive margin (Franklinian Basin), 640(?)–380 Ma; E, Caledonian foreland basin, *c.* 410 Ma; F, Closure of the Franklinian Basin (Ellesmerian Orogeny) and formation of a foreland basin, *c.* 360 Ma; G, Late Palaeozoic rift basin, 360–260 Ma; H, Mesozoic oblique-slip basin, 250–80 Ma; I, Early Tertiary initiation of transform margin, 50–0 Ma.

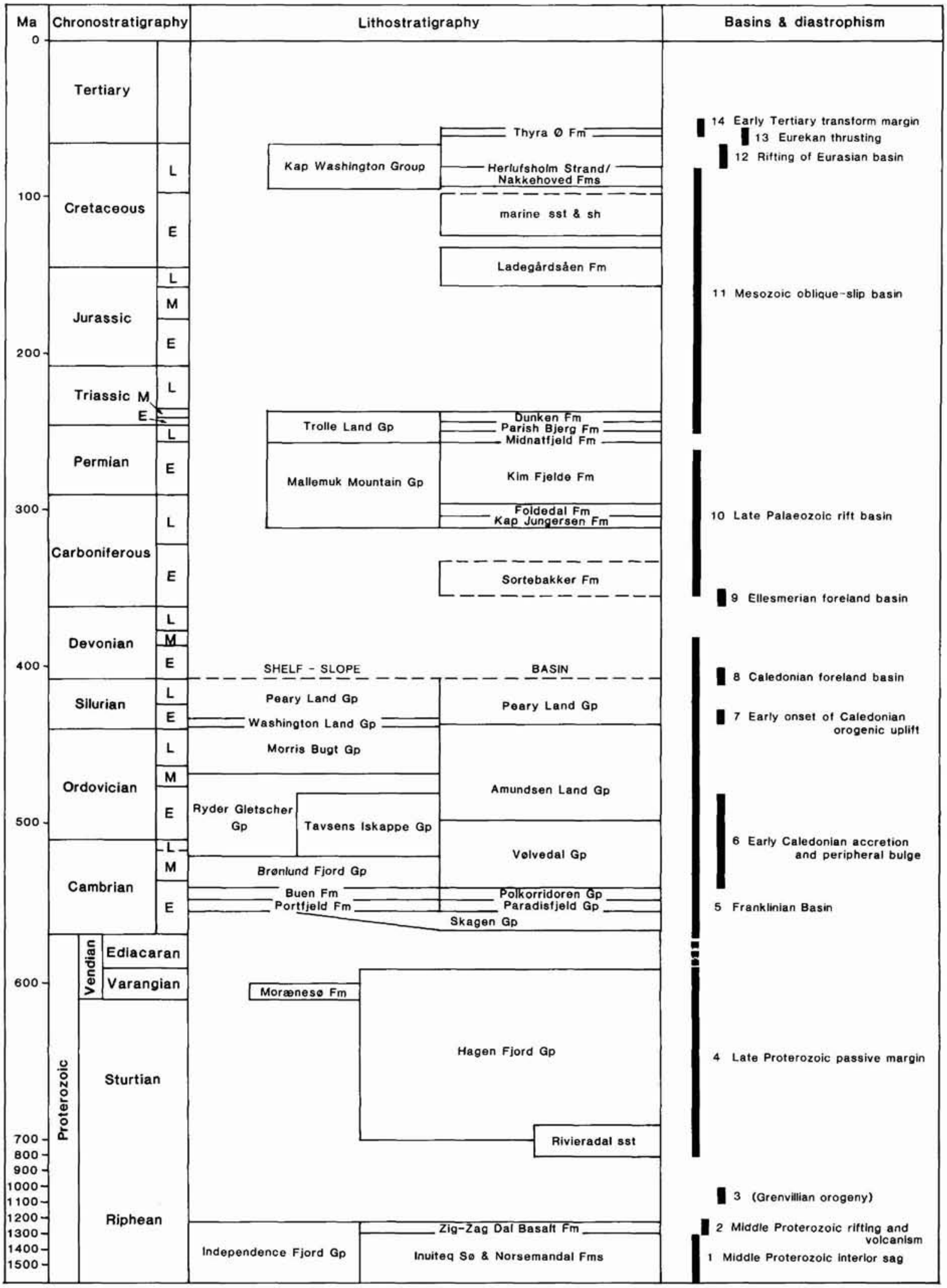


Fig. 4. Simplified stratigraphic scheme covering the Middle Proterozoic to Tertiary succession of North Greenland. Basins and periods of diastrophism as in Fig. 2.

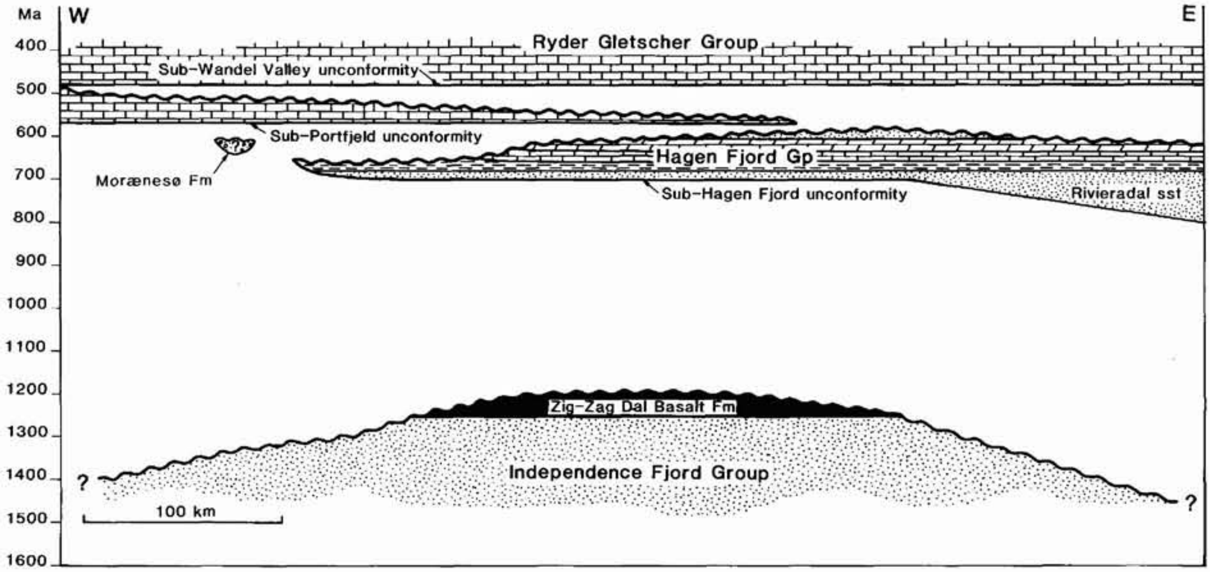


Fig. 5. Cross-section from Peary Land (west) to Kronprins Christian Land (east) showing sub-Hagen Fjord, sub-Portfjeld and sub-Wandel Valley unconformities (after Clemmensen & Jepsen, in press).

represented by stromatolitic dolostones (Fyns Sø Formation). The presence of an outer platform slope is recorded by slump breccias and subtidal stromatolitic *Conophyton* mounds.

The demise of the platform coincided with the reappearance of glauconitic, tidally influenced shelf sandstones with *Skolithos* (Kap Holbæk Formation).

An approximately 2500 m thick deep-water succession of basinal turbidites and conglomerates referred to the Rivieradal sandstones occurs to the east in large Caledonian nappes in Kronprins Christian Land. The nappes were probably derived from the east or southeast and were transported westwards for at least 100–150 km (Hurst & McKerrow, 1981; Hurst *et al.*, 1985).

Due to tectonic complexity, the sedimentary and stratigraphic relationships between the Hagen Fjord Group and the Rivieradal sandstones are not yet fully elucidated. However, a conformable shallowing upwards transition from the Rivieradal sandstones to the upper part of the Hagen Fjord Group (Campanuladal Formation and younger units) has been described from one of the nappes (Hurst & McKerrow, 1981). The Rivieradal sandstones may thus be a deep-water correlative of the onlapping Jyske Ås Formation of the lower part of the Hagen Fjord Group, and this important occurrence, if correct, may document the genetic association of the two depositional systems.

The deep-water turbiditic facies and the shallowing-upwards progradational nature of the combined Rivieradal – Hagen Fjord system suggests a syn-rift to early stage passive margin setting possibly related to the development of the Iapetus Ocean in areas currently east of present-day North Greenland.

Acritarchs from the upper part of the Rivieradal sandstones indicate a general Sturtian to Vendian age (*c.* 800–570 Ma). The top sandstones of the Hagen Fjord Group contain *Skolithos* suggesting an age not older than latest Proterozoic (late Vendian, Ediacaran).

A succession of glacially influenced deposits occur in southern Peary Land and southern Wulff Land. It is referred to the Morænesø Formation and is probably related to the Late Proterozoic (Varangian), glaciation known from Spitsbergen, East Greenland, Europe, Canada and U.S.A. The glacial event is poorly dated, however, and it may be of older Proterozoic age. The data do not allow any clear correlation between the Morænesø Formation and the Hagen Fjord Group (Sønderholm & Jepsen, 1991). Deposition took place in widely separated valleys and the unconformity at the base of the formation reflects a relief of at least 190 m (Collinson *et al.*, 1989). The main facies are diamictites representing resedimented tills, and fluvial, aeolian and lacustrine sandstones and shales. However, only a single true till has been found. The glacigenic succession is topped by a thin, but spectacular stromatolitic dolostone with laterally linked domal stromatolites up to 2 m high and 8 m in cross section. This transgressive development possibly reflects a glacio-eustatic rise in sea-level.

5, Latest Proterozoic – Early Palaeozoic passive margin (Franklinian Basin), *c.* 640(?)–380 Ma

The east-west trending Franklinian Basin was initiated by rifting probably in latest Proterozoic time (Figs 2, 3D, 4). This is reflected by uplift, block-faulting and erosion of Late Proterozoic and older strata. The timing of the onset of rifting is poorly known. Trettin (1989) suggested that the Franklinian diabase swarm (*c.* 750 Ma) and basic volcanics (635–640 Ma) in Arctic Canada represent the initial rifting. The oldest exposed Franklinian deposits are of Early Cambrian age, but may extend back into the latest Proterozoic.

The Franklinian sea transgressed the eroded surface from north to south, and more than 1 km of onlapping Lower Cambrian sediments were deposited. The hiatus between the oldest exposed Cambrian rocks and the Proterozoic Iapetus succession in eastern North Greenland is estimated to 10–30 Ma by Sønderholm & Jepsen (1991).

The Franklinian Basin extends today westwards from easternmost North Greenland into Ellesmere Island and probably as far as Melville Island in the Canadian Arctic Islands (Trettin, 1989). A well defined syn-rift succession is not known, but the oldest exposed deposits show features suggestive of a late syn-rift or early post-rift origin. Ocean floor volcanic rocks related to the opening of the Franklinian Basin have not been directly observed.

The Franklinian Basin is oriented roughly perpendicular to the western margin of the slightly older Iapetus Ocean, marked today by the front of the East Greenland Caledonides. It may thus represent an aulacogen which reached a narrow ocean stage (Surlyk, 1982; Surlyk & Hurst, 1983, 1984). The aulacogen interpretation is supported by the dominantly ensialic nature of the Franklinian Basin. The marked Early Palaeozoic differentiation into a wide shallow marine shelf bordered by a deep-water basin suggests that a spreading centre was formed and a narrow ocean stage was reached, possibly already in Early Cambrian times.

A series of small volcanic centres occurs in Peary Land spatially related to the Harder Fjord Fault Zone (Fig. 1). Blocks in the pipes are intensely brecciated and comprise local sediments, fresh basement metamorphic rocks and associated igneous rocks, and a suite of highly altered basic volcanics, gabbros and serpentinites (Parsons, 1981). The alteration occurred prior to their incorporation in the pipes. A single whole rock K/Ar age of 380 ± 5 Ma (Middle Devonian, Ellesmerian) has been obtained (Pedersen & Holm, 1983). Parsons (1981) speculated that the spilite-serpentinite assemblage is an otherwise unexposed, marginal, ocean-floor assemblage, and this is supported by the occurrence of abundant volcanic fragments in a nearby Cambrian Vølvedal Group conglomerate. This scenario is followed here, and it is suggested that the preserved mainly ensialic part of the Franklinian continental margin had reached a state of extension where submarine volcanicity accompanied turbidite deposition in the vicinity of an old deep-seated basin margin fault revived much later as the Harder Fjord Fault Zone.

The southern margin of the Franklinian Basin is well exposed across North Greenland, whereas the original northern margin is not preserved due to later compressive deformations, strike-slip faulting and plate separations.

The exposed succession shows a clear distinction between a southern shelf and a northern deep-water basin with an intervening slope. The boundary between the basin and shelf is strongly disturbed by Ellesmerian and later tectonism in most areas.

The shelf-slope-basin formed linked depositional systems during Cambrian-Ordovician times, whereas independent shelf and basin systems were developed in the Silurian (Surlyk *et al.*, 1980). Nine depositional stages were recognised in the evolution of the deep-water basin (Surlyk & Hurst, 1983, 1984). Soper & Higgins (1987) suggested that a re-grouping into three phases of the nine basinal stages was more meaningful in terms of geotectonic control. This represents a mixing of the depositional systems concept with the concept of syn-rift and thermal subsidence phases of the simple stretching model of McKenzie (1978). Their suggestion of the first three stages of Surlyk & Hurst (1983, 1984) as representing the syn-rift prism is not followed here. Franklinian syn-rift deposits have not been identified with certainty, and the bulk of the first three stages undoubtedly represents a fairly late stage in passive margin evolution where clear differentiation into a broad shelf, a slope and a deep-water basin had taken place.

The boundary between these three main sedimentary regimes progressed towards the craton in several steps (Surlyk *et al.*, 1980; Surlyk & Hurst, 1983, 1984). The deep-water basin thus expanded southwards by foundering of the outer shelf-upper slope along east-west lineaments which may represent deep-seated normal faults or flexures. This pattern of evolution has now also been recognised in the Canadian Arctic Islands (Trettin, 1987, 1989).

Despite earlier objections (Higgins *et al.*, 1981; Higgins, 1986; Soper & Higgins, 1987), the concept of a *structurally controlled* back-stepping shelf margin is now widely accepted (cf. Soper & Higgins, 1990). Basement faulting is considered to have controlled the rough posi-

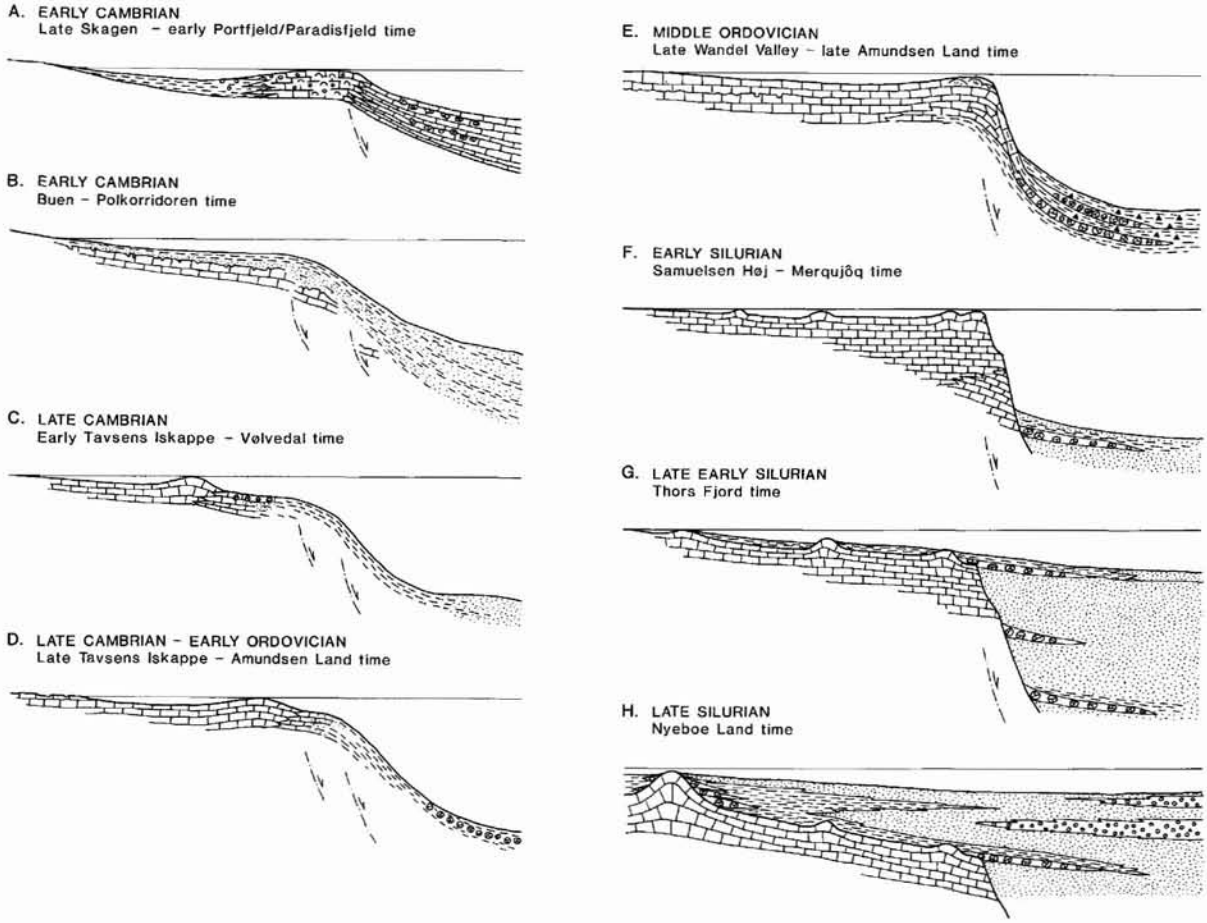


Fig. 6. Simplified south-north cross-sections of the Franklinian Basin (not to scale). A, Late Skagen – early Portfjeld/Paradisfjeld time (Early Cambrian); B, Buen – Polkorridoren time (Early Cambrian); C, Early Tavsens Iskappe – Vølvedal time (Late Cambrian); D, Late Tavsens Iskappe – Amundsen Land time (Late Cambrian – Early Ordovician); E, Late Wandel Valley – late Amundsen Land time (Middle Ordovician); F, Samuelsen Høj – Merqujôq time (Early Silurian); G, Thors Fjord time (late Early Silurian); H, Nyboe Land time (Late Silurian).

tion and configuration of the shelf-slope transition, but the boundary itself was not necessarily an actual fault or a faulted scarp.

The oldest known sediments of the Franklinian Basin belong to the Skagen Group of presumed Early Cambrian age (Figs 4, 6). The group was first recognised in the fold belt in Peary Land as a strongly deformed succession of sandstones and mudstones, at least 500 m thick. The depositional environment is not known. Stratigraphically equivalent, well preserved, strata occur in western North Greenland (Wulff Land) and have been studied in more detail (Surlyk & Ineson, 1987a). The unit is here at least 500–600 m thick but the base of the group is not seen. The thickness may be much greater as the correlative Kennedy Channel Formation in Ellesmere Island has a maximum exposed thickness of *c.* 1200 m (Long, 1989a).

Skagen Group sediments are of marine shelf origin and a number of siliciclastic, carbonate, and mixed facies occur. Deposition took place on a storm-dominated shelf and on shallow water carbonate shoals. The unit thus records the initial differentiation of the shelf into a carbonate platform and a mainly siliciclastic storm-influenced shelf (Fig. 6).

The Skagen Group as seen in Wulff Land wedges out to the south over a few tens of kilometres and is overstepped by the overlying Portfjeld Formation, which rests directly on crystalline basement or the Proterozoic Moræneso Formation in southern Wulff Land (Fig. 5). The basin configuration during Skagen – Kennedy

Channel times is not known. There is no direct evidence for rifting such as fault-scarps, tilted fault-blocks or syn-rift conglomerates. A late syn-rift or early post-rift origin is possible and is supported by the apparent lack of differentiation into shelf, slope and basin. The occurrence of coarse pebbly sandstones, and the cratonwards overstep and onlap by the overlying Portfjeld Formation also lend credence to this interpretation.

The predominantly siliciclastic deposits of the Skagen Group gradually gave way to platform carbonates of the Portfjeld Formation which pass northwards into slope-to-incipient basin carbonate mudstones and conglomerates of the Paradisfjeld Group.

The Portfjeld Formation thickens appreciably from a few hundred metres to as much as 700 m from south to north, suggesting the development of a northern, rapidly accreting high-energy platform rim. Carbonate deposition in this area was probably initiated when the inner shelf still received terrigenous sand and mud (Fig. 6).

The Paradisfjeld Group is at least 1 km thick and displays features characteristic of both shelf and slope or basinal environments. Hummocky cross-stratified units occur in eastern Peary Land while calcarenitic turbidites and carbonate debrites are common especially in the upper part of the unit.

The nature of the shelf-to-basin transition is not known due to strong deformation. A tectonic control of the shelf margin has been suggested, and may have coincided with a precursor to the present-day Harder Fjord Fault Zone in Peary Land (Surlyk & Hurst, 1984; Soper & Higgins, 1987; Fig. 1). Huge olistoliths derived from the Portfjeld Formation occur in the lower part of the turbiditic Polkorridoren Group which overlies the Paradisfjeld carbonates. This suggests that the Portfjeld platform margin was developed as a steep escarpment, parts of which persisted or were revived by later faulting in Polkorridoren times.

The Portfjeld-Paradisfjeld system was terminated by a major fall in sea-level. The top of the Portfjeld platform was eroded, stained red and brecciated in many areas. The top of the deeper water Paradisfjeld succession in contrast passes into the siliciclastic Polkorridoren Group without any recognised break in sedimentation (Figs 4, 6). The strongest effects of the sea-level fall are seen along the southern outcrop margin. A remarkable mega-breccia, 85–270 m thick, was formed by collapse, break-up and mass-transport of the entire Portfjeld Formation (Surlyk & Ineson, 1987a). The mega-breccia rests upon crystalline basement or thin remnants of the Proterozoic Moræneso Formation and consists of blocks and large slabs of Portfjeld carbonate, quartzite, gneiss, and red siltstone set in a matrix of carbonate and quartz sand. The mega-breccia was probably formed after a period of karstification during an interval of major sea-level drawdown. Subsequent collapse and basinwards mass movement was possibly triggered by earthquakes along the southern basin hinge line or along the platform margin scarp. The basinal equivalent is possibly represented by limestone conglomerate debrites which occur in the top part of the Paradisfjeld Group in a broad belt over a length of 250 km along the southern outcrop margin of this unit.

It may be speculated that the unconformity topping the Portfjeld Formation was caused by a late rift peripheral bulge migrating southwards and that it is analogous to the so-called breakup unconformity (cf. Falvey & Middleton, 1981; Long 1989b). The marked seawards thickening of the sedimentary prism and the beginning of differentiation into shelf, slope and basin environments may alternatively suggest that the Portfjeld-Paradisfjeld system represents an early passive margin succession formed after the onset of sea-floor spreading.

The sea-level fall resulting in the demise of the Portfjeld platform was followed by a major sea-level rise, and a siliciclastic mud-dominated shelf sea transgressed the karstified surface of the carbonate platform (Fig. 6). This shift in facies was accompanied by a marked seawards increase in subsidence, and by a cratonwards shift in the shelf-slope boundary, possibly caused by flexural downbending of the outer shelf (Surlyk & Hurst, 1984).

The shelf mudstones and tidally influenced inner shelf sandstones referred to the Buen Formation are 425–500 m thick over most of the shelf, but thin to 250 m along the shelf-slope break (Higgins *et al.*, 1991). This change is probably due to mass wasting and sediment bypassing in the slope region and does not reflect a local decrease in subsidence. The succession thickens rapidly in the mid and lower slope regions and correlative deposits reach thicknesses of 2–3 km in the basin.

The basinal deposits are referred to the Polkorridoren Group and consist of alternating packages of variegated mudstones and thick-bedded sandy turbidites, 100–500 m thick, showing transport directions towards west, north and, less commonly east. They were deposited on relatively small sand-rich submarine fans which were deflected mainly westwards along the basin axis. Carbonate conglomerates also occur and a particularly spectacular level is situated 600 m above the base of the group. It is traceable over 120 km along strike, and the clasts range in size from cobbles to 300 m long blocks, mainly derived from the Portfjeld Formation. This indicates that parts of the Portfjeld platform margin escarpment were exposed to erosion and spalling of joint blocks also in early Buen – Polkorridoren times. The Polkorridoren Group is topped by the widespread, up to 400 m thick variegated Frigg Fjord mudstone, reflecting progressive abandonment of the submarine fans, probably caused by a major sea-level rise.

6, Early Caledonian accretionary event and formation of peripheral bulge, *c.* 540–480 Ma

Starvation of the Polkorridoren fans reached a climax in the late Early Cambrian. From then on through Ordovician times the Franklinian passive margin was characterised by the development of a thick carbonate platform and a sediment starved black shale and chert basin (Figs 4, 6). This pattern was modified, however, by progressive shelf uplift in eastern North Greenland terminating in the Early Ordovician (Fig. 7). The western Franklinian shelf beyond the influence of the uplift is represented by a thick and varied succession of carbonates mainly of restricted platform aspect with subordinate siliciclastic sediments and evaporites, which together form the up to 1500 m thick Ryder Gletscher Group. In the earliest Ordovician carbonate deposition was interrupted by a siliciclastic interlude of the Permin Land Formation, reflecting maximum uplift and erosion in eastern North Greenland coupled with eustatic lowstand (Bryant & Smith, 1990).

The progressive late Early Cambrian – earliest Ordovician uplift of the eastern shelf is reflected by the complex facies relationship exhibited by the Brønlund Fjord and Tavsens Iskappe Groups (Fig. 4).

The basinal succession off the eastern uplifted shelf is thickly developed. It forms the 600–700 m thick Vølvedal Group, which in addition to the essentially condensed deposits of dark cherts and shales contains quartzose turbidite units and carbonate conglomerates (Figs 4, 6). The resedimented deposits were derived from the southern platform and formed one or more relatively small borderland fans. It is significant that the onset of fan deposition was contemporaneous with the siliciclastic Permin Land event on the shelf.

Subsequent to the Permin Land event uniform carbonate platform deposition was resumed all along the Franklinian shelf. The uplifted and eroded platform in eastern and central North Greenland was submerged and a major unconformity was formed below the late Early – Middle Ordovician Wandel Valley Formation (Fig. 7).

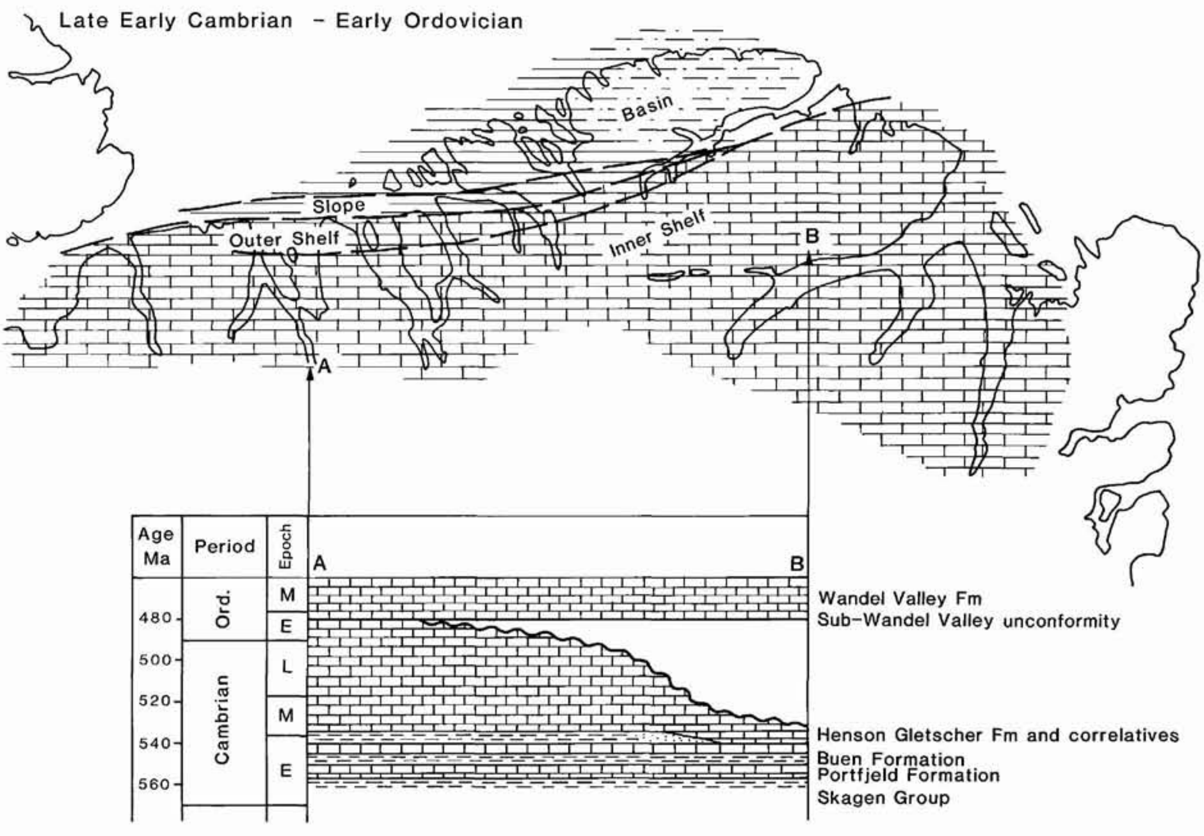


Fig. 7. Stratigraphic east-west cross-section of the Franklinian shelf showing the sub-Wandel Valley unconformity.

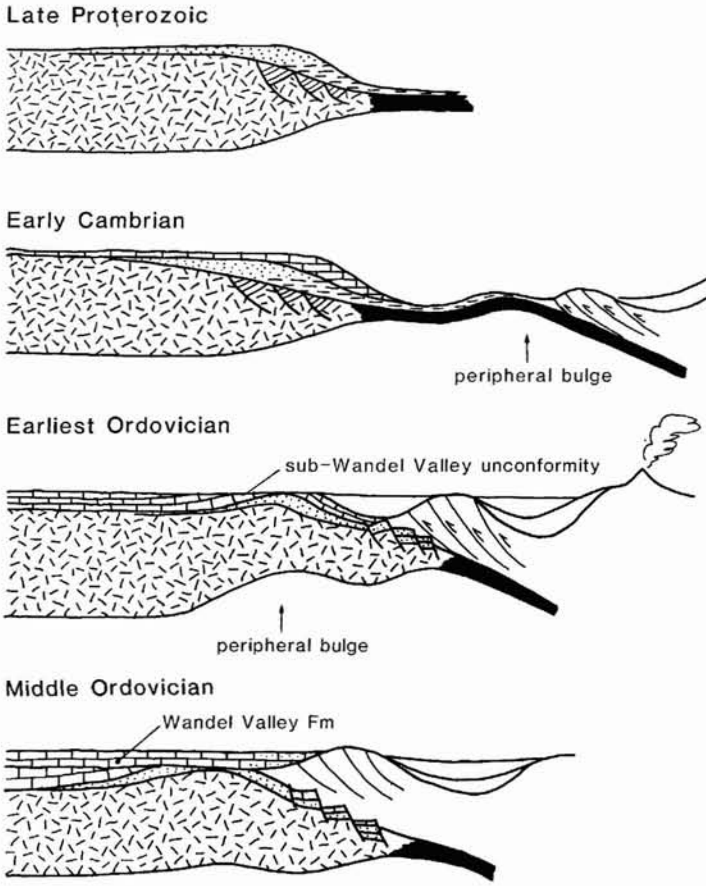


Fig. 8. Schematic diagram showing formation of a westwards migrating peripheral bulge during an early Caledonian collisional event along the western margin of the Iapetus Ocean. Bulge uplift and erosion were responsible for the formation of the sub-Wandel Valley unconformity (Fig. 7).

The underlying control of uplift and erosion is interpreted as a reflection of westwards migration of a peripheral bulge during an early collisional event along the western margin of the Iapetus Ocean in Middle Cambrian – earliest Ordovician times (Figs 7, 8; Surlyk & Hurst, 1984). This is the first in a series of Caledonian events influencing the evolution of the Franklinian passive margin.

It is significant that the Caledonian bulge uplift of the eastern Franklinian shelf (Surlyk & Hurst, 1984) coincided in time with the M'Clintock Orogeny of Ellesmere Island, the Taconic Orogeny of Newfoundland, ophiolite obduction and uplift in western Norway, and pre-Caradocian deformation in central western Spitsbergen (Thon, 1985; Trettin, 1987; Williams & Hatcher, 1983). The Early Ordovician unconformity of the eastern Franklinian shelf provides an important link in constraining the timing of amalgamation of the first in a series of successively accreting slices of Pearya – the composite terrane forming the northernmost part of Ellesmere Island (Trettin, 1987).

It is suggested here that collision of a microplate of Spitsbergen affinity with the eastern margin of the Franklinian Basin was initiated in Middle Cambrian times. The southern part of this plate was firmly welded to eastern North Greenland in the earliest Ordovician. After this event regular subsidence was resumed throughout the Franklinian passive margin.

A fault slice of the northern part of the microplate possibly slid westwards along a major E-W trending strike-slip fault situated in the northern part of the Franklinian deep-water basin. This slice was accreted to northern Ellesmere Island during the early Middle Ordovician M'Clintock Orogeny (cf. Trettin, 1987).

The stable, uniformly subsiding period that succeeded the long period of progressive shelf uplift to the east was characterised by platform margin backstepping, aggradation and development of a steep, precipitous slope, the Navarana Fjord Escarpment (Fig. 6). North of the escarpment a broad sediment-starved bypass slope formed, whereas the rate of deposition was higher in the basin floor environment. Stable platform aggradation commenced with the late Middle Ordovician sea-level rise and persisted into the Early to Middle Llandovery (Early Silurian).

A pronounced shallowing followed by marked deepening occurred, however, in latest Ordovician – earliest Silurian times. These fluctuations in relative sea-level may be of true eustatic nature related to the late Ordovician glaciations.

In the deep-water basin the small borderland fans of the Vølvedal Group were abandoned and a long period of sediment starvation and, at times, also stagnation was initiated in the basin floor and slope regions. The deposits of this phase are referred to the Amundsen Land Group and include chert, cherty shale, black limestone, and dolomitic mudstone.

The eastern part of the basin received in addition thick carbonate conglomerates of the up to 200 m thick Kap Mjølner Formation. These Early Ordovician debris sheet units can be traced over wide areas of Johannes V. Jensen Land but become less important westwards and northwards. They were derived from unroofing of the pre-Wandel Valley peripheral bulge of the eastern shelf.

Conglomerate deposition faded out in middle Ordovician times in conjunction with termination of uplift and the development of an aggrading, gradually subsiding shelf, and slow sedimentation of fine-grained deposits was resumed throughout the basin. Towards the end of this stage in the Late Ordovician – Early Llandovery, the incoming of thin-bedded silty turbidites heralded an important event in the evolution of the basin. Starved basin deposition of the Amundsen Land Group came to an end, and turbidite sedimentation of the very thick sand-rich Peary Land Group commenced abruptly in the Llandovery (Fig. 4).

7, Early onset of Caledonian orogenic uplift: *c.* 435 Ma

At the beginning of fan building of the Peary Land Group the platform margin was formed by the 1300 m high Navàrana Fjord Escarpment dipping up to 45°. The basin became rapidly filled with sandy turbidites which onlapped the scarp towards the south (Fig. 6). The outer shelf was gradually down-flexed due to loading by fan turbidites with their source in the rising Caledonian mountain belt to the east (Surlyk, 1982; Higgins *et al.*, 1991). The evolution of the carbonate platform during this time interval thus reflects normal passive margin processes upon which were superimposed the far reaching effects of Caledonian mountain building.

The early Late Llandovery flexural down-bending of the outer shelf can be traced all across North Greenland. The initial phases are recorded by deposition of relatively deep-water, low-energy carbonates. In the southern inner platform contemporaneous deposits include biostromal units formed in extensive high-energy shoals.

The progressive drowning of the outer platform was accompanied by retreat of the shelf margin to a more southerly position, and the developement of a reef belt 850 km long and up to 100 km wide (Fig. 6). The reefs, however, did not form a complete barrier across the region and a steep indented shelf margin developed. An essentially flat carbonate platform was maintained between and behind the mounds (Sønderholm & Harland, 1989). Continued subsidence and associated sea-level rise ultimately resulted in complete drowning of the platform and inundation by deep-water muds during latest Llandovery to earliest Wenlock time. Carbonate deposition was only maintained in some of the larger buildups, and a few of these appear to have continued at least to the end of the Silurian.

The huge deep-sea fan of the Peary Land Group possibly represents the world's largest ancient deep-sea fan (Hurst & Surlyk, 1982; Surlyk, 1982; Surlyk & Hurst, 1984). It developed extremely rapidly in the Late Llandovery after the start of fine-grained turbidite deposition in Peary Land close to the Ordovician-Silurian boundary. The Peary Land fan extended from the eastern end of the Franklinian Basin far into the Canadian Arctic Islands. The provenance area was the rising Caledonian mountain belt, and the main source of the huge thickness of quartzose turbidites was undoubtedly the thick successions of Proterozoic sandstones exposed in central and eastern North Greenland, and their correlatives.

The fan system was elongate, parallel to the Franklinian platform margin. The length was 1500–2000 km if its down-current extension in the Canadian Arctic Islands is included. The original width is not known, because the northern margin is not preserved, but it was more than 200 km. The maximum preserved thickness is about 5 km. The total fan volume is thus considerably more than 2 million km^3.

During the first stage of fan development the southern margin was formed by the Navarana Fjord Escarpment. The bulk of this first phase of fan deposits is referred to the Merqujôq Formation. Turbidite deposition was punctuated by several episodes of carbonate conglomerate deposition from the outer platform and marginal escarpment (Hurst & Surlyk, 1982; Surlyk & Ineson, 1987a, b).

The turbidites had filled the basin to the edge of the platform in the latest Llandovery, when the shelf foundered and was inundated by black mudstones and siltstone turbidites of the Thors Fjord Member (Figs 4, 6). This fine-grained unit covered the northern outer shelf in the Late Llandovery, and reached the southern inner part somewhat later, at the Llandovery-Wenlock boundary. It extends unchanged from the platform, across the escarpment and further basinwards over the turbidites of the Merqujôq Formation.

Hurst *et al.* (1983) suggested that loading of the eastern shelf by Caledonian nappes was a direct cause of the latest Llandovery foundering of the Franklinian carbonate platform. This interpretation is not followed here: the drowning of the platform was an integrated event which affected the entire Franklinian shelf not just the eastern part adjacent to the Caledonian nappes. The drowning event is represented by the mudstones of the Thors Fjord Member which drape both the platform carbonates and the sandy turbidite succession of the Merqujôq Formation. This means that platform drowning was associated with fan starvation and near abandonment, which is the opposite effect to that which would be expected according to the nappe loading hypothesis. Furthermore, the youngest turbidites preserved in the nappes in eastern North Greenland are of middle Wenlock age. This indicates that deep-water turbiditic environments still existed in the areas east of Kronprins Christian Land at a significantly later time than the Late Llandovery foundering of the platform. This excludes loading by nappes transported from the east as a cause for the foundering. The foundering of 30 000 – 40 000 km^2 of carbonate shelf in North Greenland is here ascribed to the combined effects of progressive flexural down-bending of the outer shelf due to loading of the Franklinian deep-water basin by the Peary Land turbidites, and a major eustatic sea-level rise, which has been demonstrated for other parts of the world by Johnson *et al.* (1985).

Following this phase of basin expansion the Peary Land fan rapidly built up again and now reached its greatest dimensions. A change in nature of the Caledonian provenance terrain is reflected by the influx of chert pebble turbidites in Middle Wenlock times. These were probably derived from Ordovician cherts correlative with the basinal Amundsen Land Group which were uplifted and eroded in the Caledonian mountains. The pebbly system is up to 600 m thick and reached the western parts of the basin in early Ludlow times.

The last phase of basin filling is only known from western North Greenland. It is of latest Silurian age, up to 1000 m thick and includes mainly fine-grained thin-bedded turbidites, contourites and mudstones (Fig. 6).

The Franklinian Basin thus records more than 150 million years of passive margin evolution. The syn-rift succession is not exposed, and the oldest rocks probably represent the latest syn-rift to early post-rift stage in basin evolution (Fig. 3).

8, Caledonian foreland basin, *c.* 410 Ma

Closure of the Iapetus Ocean during the Caledonian orogeny was accompanied in north-eastern Greenland by westerly migration of thrust sheets or nappes (Fig. 3E).

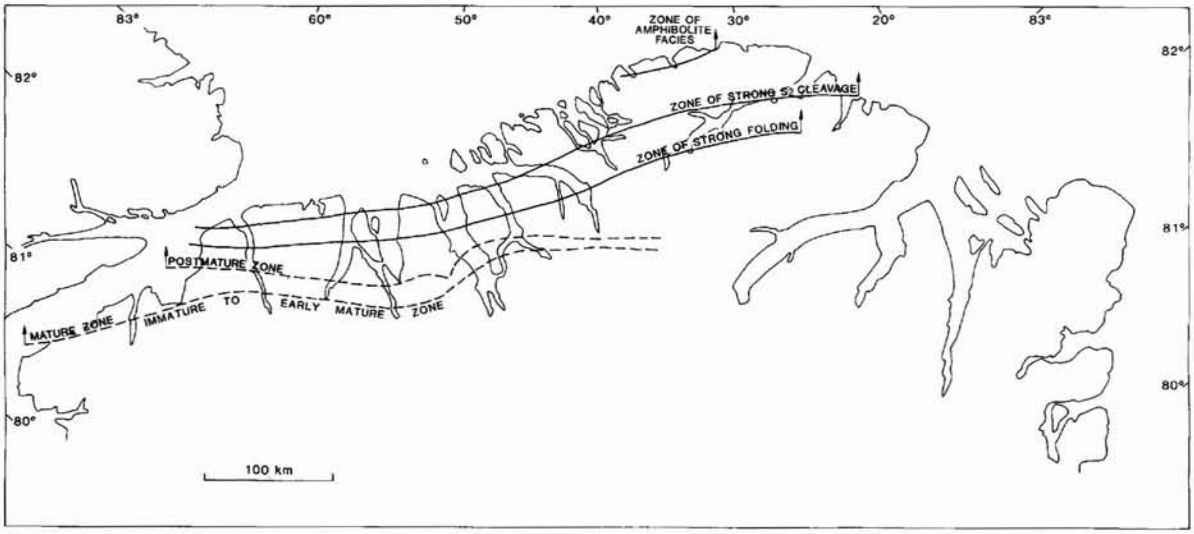
The nappes originated from east of the present-day coast-line of eastern North Greenland and North-East Greenland and travelled westwards for at least 100 km. The thickness of the total nappe pile can be estimated to be about 5 km (Hurst *et al.*, 1983). Loading by the nappes must have caused flexural down-bending of the eastern Franklinian shelf resulting in the formation of a roughly N-S trending foreland basin, parallel to the Caledonian front. The Caledonian nappe front was probably situated close to the east coast of Mylius-Erichsen Land in Danmark Fjord (Hurst *et al.*, 1983).

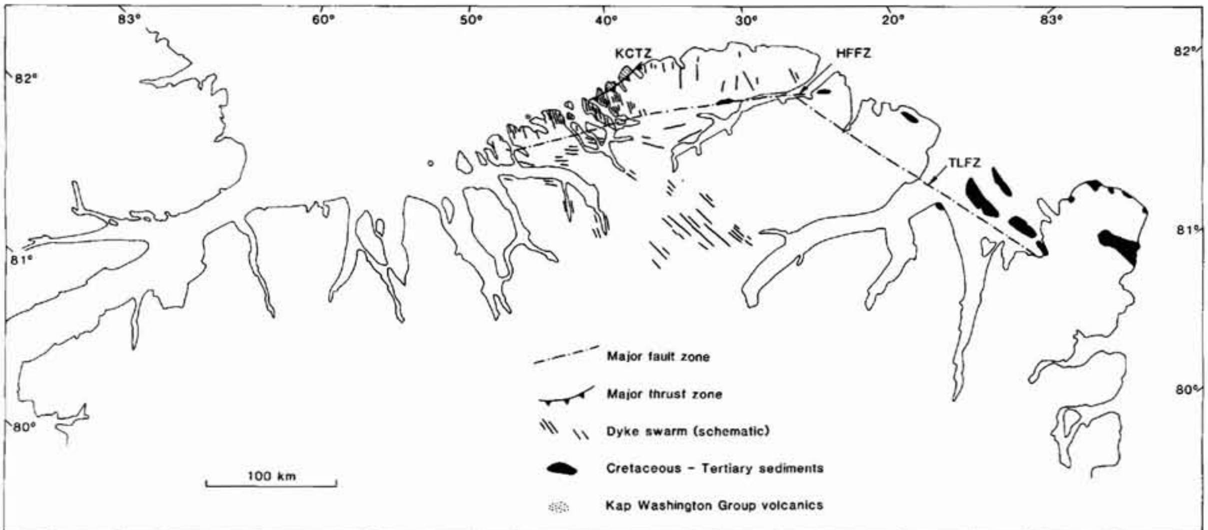
The axial part of the E-W trending Franklinian Basin probably received some of the material derived from erosion of the thrust-belt, whereas some material must have accumulated in the foreland basin. The latter is not preserved due to later uplift and erosion. Its former presence is revealed, however, by the pronounced southwards extension of the low metamorphic zone in central and eastern North Greenland (Fig. 9; fig. 48 of Christiansen, 1989). This probably indicates that a wide N-S oriented belt situated west of the Caledonian front was at one time covered by a thick succession of post-Franklinian sediments. The foreland basin was probably *c.* 200 km wide and the distal part of the basin was located roughly at the head of Independence Fjord (Figs 1, 3).

9, Closure of the Franklinian Basin (Ellesmerian Orogeny) and formation of a foreland basin, *c.* 360 Ma

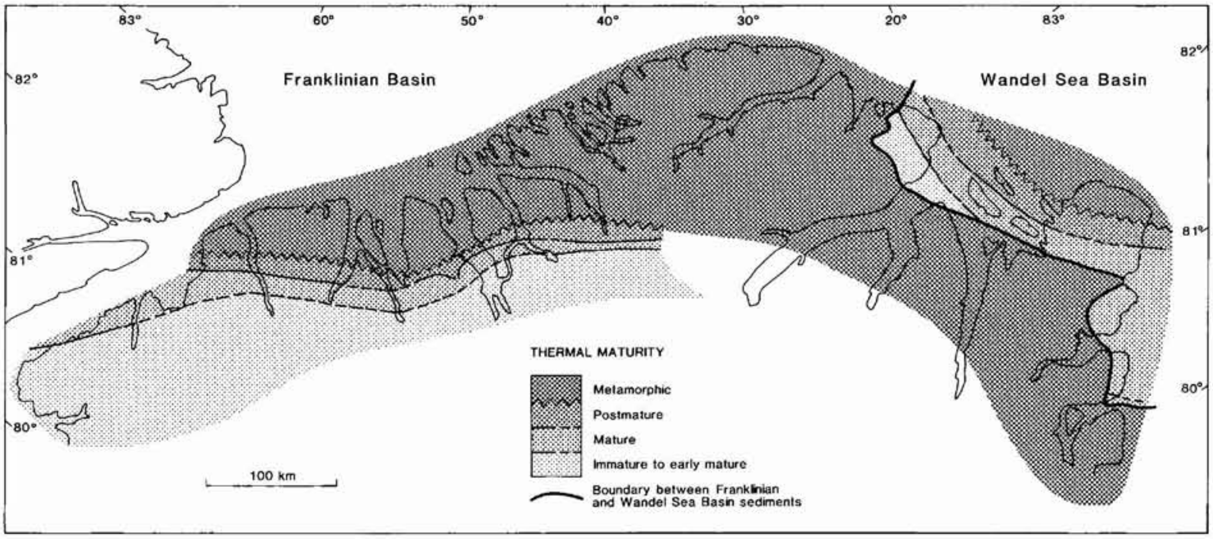
The youngest preserved Franklinian deposits are of latest Silurian – earliest Devonian age (Fig. 4). Closure of the Franklinian Basin took place in Middle or Late Devonian – Early Carboniferous times during the Ellesmerian Orogeny, when the North Greenland fold belt was formed (Fig. 3F). The orogeny is poorly dated and a clear separation between Caledonian, Ellesmerian and Tertiary (Eurekan) structures has not yet been made (Soper & Higgins, in press a).

There is no evidence in North Greenland for an opposing plate which caused the Ellesmerian Orogeny by relative N-S convergence with its Greenland couterpart. The orogeny corresponds to the closure of the Franklinian Basin by N-S compression. It affected the entire belt from eastern North Greenland to Prince Patrick Island in Arctic Canada and created a more than 375 km





wide fold belt assemblage (see Trettin, 1989). In Canada the age of the orogeny is Middle or Late Devonian – Early Carboniferous and it is assumed that this is also the case of the North Greenland fold belt. In the northern 'orthotectonic' part of the fold belt in North Greenland, polyphase north-vergent structures are developed in low amphibolite facies metasediments, and both the deformation and metamorphism decrease southwards. Along the southern margin of the fold belt approaching the foreland, structures verge south and take the form of a thin-skinned fold and thrust zone in which the basinal sediments were compressed against the Ordovician – Lower Silurian platform margin, the Navarana Fjord Escarpment. In western and central North Greenland the Navarana Fjord Escarpment is oriented almost east-west perpendicular to the stress direction, but it approaches a more north-easterly direction in Peary Land. Traced westwards across central North Greenland, the Ellesmerian margin changes character to become a major mountain front monocline which attains a maximum amplitude of about 7 km. Soper & Higgins (1990) suggested that the crystalline basement was involved in the formation of the monocline. They modelled the deep structure of the monocline as a Franklinian extensional basement ramp which was reactivated during the Ellesmerian Orogeny. After locking of the structure, shortening continued by development of thin-skinned thrusts on the upper limb of the monocline.



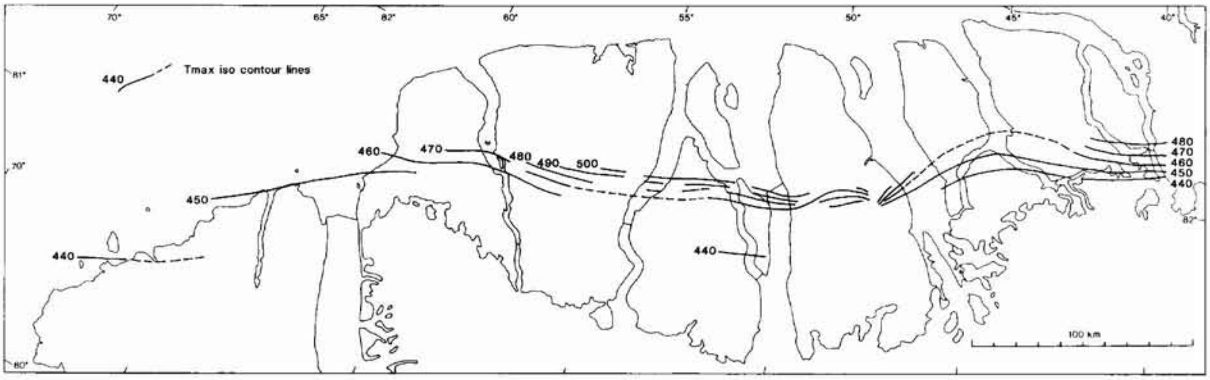


Fig. 9 A, Map of Ellesmerian tectono-metamorphic zones. From Christiansen (1989), modified after Dawes (1976) and Higgins *et al.* (1982, 1985); B, Map showing Cretaceous-Tertiary magmatic and tectonic features. After Christiansen (1989, fig. 61). For abbreviations, see Fig. 1; C, Map showing thermal maturity at the present-day surface. Modified from Christiansen (1989); D, Maturity map of central and western North Greenland showing T_{max} iso-contour lines. Modified from Christiansen (1989).

A remarkable thrust-fault zone occurs in Peary Land and was termed the Vølvedal Orogeny by Pedersen (1986). It is limited to the north from the main North Greenland fold belt by the E-W trending Harder Fjord Fault Zone (Fig. 1). According to Pedersen (1986) the main tectonic transport direction was to the west with refraction toward south-west along the buried Lower Silurian platform margin formed by the Navarana Fjord Escarpment. It was interpreted as a foreland deformation related to the Caledonian mobile belt, which involved gravity gliding from a former existing northward extension of the East Greenland Caledonides (Håkansson & Pedersen, 1982).

Surlyk & Hurst (1984) alternatively suggested that the thrust faulting was caused by sinistral up-to-north oblique-slip transpression on the Harder Fjord Fault Zone. This interpretation explains the absence of the thrust belt in the relatively uplifted areas north of the fault zone. Both hypotheses thus consider the Vølvedal Orogeny as part of the Caledonian succession of sinistral transport events along an E-W trending mega-shear situated at the northern margin of the Franklinian Basin.

It is possible that the Vølvedal Orogeny of Håkansson & Pedersen (1982) is nothing but a local variation in the Ellesmerian frontal thrust zone formed by bending of the south-verging thrusts along the buried Navarana Fjord Escarpment (Soper & Higgins, 1985; A. K. Higgins, personal communication, 1990). If this interpretation is correct the concept of a separate Vølvedal Orogeny is redundant.

The Ellesmerian Orogeny was in all probability accompanied by the formation of an E-W striking foreland basin caused by loading of the crust of southwards migrating thrust-sheets (Fig. 3). The moat-like basin was probably rather wide due to the mechanical strength of the old Archaean crust underlying the southern Franklinian shelf.

Later uplift in North Greenland has caused erosional removal of all direct evidence of the foreland basin deposits. In Arctic Canada the foreland basin is still preserved, however, and consists of an enormous clastic wedge initiated by early Middle Devonian time (Embry, in press). However, the Ellesmerian tectono-metamorphic zones show a striking parallelism to the thermal maturity pattern of Lower Cambrian and Lower Silurian source rock intervals (Fig. 9). The maturity increases markedly from immature-early mature in the south to post-mature in the north over only 10–30 km as the fold belt is approached (Christiansen, 1989). This strong gradient is interpreted as corresponding to the position of the Ellesmerian thrust front, and the proximal foreland basin. The maturity pattern thus reflects the combined effects of Silurian basin subsidence, Ellesmerian thrust sheet loading, and loading by the Ellesmerian foreland basin. South of the high maturity gradient the foreland basin decreased in thickness and it was probably only about 1 km thick at the T_{max} 400 iso-contour line (Fig. 9D).

10, Late Palaeozoic rift basin, 360–260 Ma

The later Palaeozoic history of North Greenland following the mid-Palaeozoic Ellesmerian Orogeny and foreland basin formation is poorly known. The main outcrop area of younger rocks is in eastern Peary Land and in northern Kronprins Christian Land, Amdrup Land and Holm Land (Fig. 1). In the remaining part of North Greenland younger rocks are only preserved in a few narrow fault blocks in the Harder Fjord Fault Zone and in the Kap Cannon Thrust Zone on the north coast of Peary Land (Fig. 1).

These rocks range in age from Early Carboniferous to Tertiary and have previously been described under one term, the Wandel Sea Basin (Dawes & Soper, 1973). It is clear from recent work that this single concept is inappropriate, and it is now recognised that a long series of basin-forming events occurred under different stress regimes (Håkansson & Stemmerik, 1989; Stemmerik & Håkansson, 1991). During the Late Palaeozoic, deposition took place in two largely independent basins, described as the North Greenland – Svalbard rift basin and the East Greenland – West Norway rift basin, respectively (Håkansson & Stemmerik, 1989; Fig. 3). In the present context the Wandel Sea Basin is considered roughly synonymous with the former basin, and it should be understood that it only exposes the marginal facies of an extensive basin between eastern North Greenland and Svalbard.

Continental sedimentation was initiated in North Greenland during the Early Carboniferous with deposition of 600 m of fine-grained sediments of flood-plain origin in southern Holm Land at the northern end of the East Greenland rift basin (Figs 1, 3G, 4). This phase was followed by faulting, uplift and erosion. In the Late Carboniferous (early Moscovian) marine sedimentation commenced in small fault blocks in Holm Land and Amdrup Land delimited to the west by a major N-S trending fault zone and by NW-SE cross-faults. The Late Carboniferous (early Moscovian) transgression resulted in submergence of southern Amdrup Land and the whole region east and north of the East Greenland, Trolle Land and Harder Fjord Fault Zones in late Moscovian – Gzelian time (Fig. 3G).

During Late Carboniferous times shelf deposition was dominated by interbedded sandstone, shale and carbonate. In the latest Carboniferous a general sea-level rise led to the development of an extensive carbonate platform which persisted through the Early Permian.

This regime was brought to an end in mid-Permian times, and the carbonate platform was drowned by an influx of siliciclastic sediments. This change may be related to a major change in oceanographic circulation following the important mid-Permian phase of extensional block faulting and rotation known from the East Greenland basin (Surlyk *et al.*, 1986). Contemporaneous coarse-clastic alluvial deposits formed in small fault-bound basins in the Harder Fjord Fault Zone.

The Upper Permian succession of the Trolle Land Group consists of shale and chert forming thickly developed (1000–1200 m) shallowing-upwards cycles reflecting basin subsidence along the Trolle Land and Harder Fjord Faults associated with a general Late Permian sea-level fall. The marked mid-Permian facies changes reflect large-scale plate reorganisation concurrent with the final stages of Uralian fusion (Stemmerik & Worsley, 1989). At this time the important seaway between the Boreal Ocean and the European Zechstein Basin was established along the system of submerged intracratonic rifts in the area between Greenland and Norway.

Both the continental and marine Late Palaeozoic successions show a pronounced cyclity on several scales (Stemmerik & Worsley, 1989). Contemporaneous cyclic deposits are well known from many parts of the world and most probably reflect eustatic sea-level fluctuations induced by repeated glaciation (see review in Miall, 1990). Major regressive events may thus correspond to times of exceptionally widespread Gondwanan glaciations. The smaller cycles may be within the Milankovitch frequency band and thus due to astronomical forcing. Major cycle boundaries are recorded in the mid-Moscovian, latest Gzelian, at the Kungurian-Ufimian boundary, near the Kazanian-Tatarian boundary, and at the Permian-Triassic boundary.

11, Mesozoic oblique-slip basin, 250–80 Ma

The Mesozoic history of central and eastern North Greenland reflects basin development in a different stress field from the Late Palaeozoic (Fig. 3H). Small fault-block sub-basins were formed in a NW-SE trending oblique-slip belt extending from Kronprins Christian Land to eastern Peary Land. These faults may extend south-eastwards across the present shelf and relate directly to the developing Spitzbergen Fracture Zone (Håkansson *et al.*, 1991).

During much of the Mesozoic the area between Greenland and Norway was characterised by phases of roughly E-W extension. At the northern end of this major rift basin the extension was relieved by oblique slip along the nascent Spitzbergen Fracture Zone. Phases of transpression alternated with basin forming phases of transtension along this mainly dextral oblique-slip zone.

Triassic rocks are only known from a small area in eastern Peary Land where they unconformably overlie Upper Permian deposits. This marine succession is up to 1000 m thick, and comprises two upwards-coarsening progradational cycles (Parish Bjerg and Dunken Formations). The age is not well known, but seems to fall within the early part of the Triassic (Scythian-Anisian). This is roughly contemporaneous with the only marine Triassic deposits in East Greenland, the Wordie Creek Formation. It is thus possible that the absence of younger Triassic deposits in North Greenland is primary, reflecting the same overall low sea-level stand.

Deposition was only resumed with the onset of the Late Jurassic transgression. In eastern Peary Land the onlapping Middle Oxfordian – Valanginian Ladegårdsåen Formation (more than 250 m thick) mainly consists of marine fine-grained sediments, except for an Early Valanginian progradational pulse of non-marine sandstone. A more southern sub-basin in Kronprins Christian Land started to receive about 900 m of mainly restricted marine fine-grained sediments in the Early Kimmeridgian, and fully marine conditions were only reached in the Early Valanginian.

Facies development in the individual pull-apart basins is remarkably different, reflecting differences in tectonic events and subsidence patterns over short distances.

Early Cretaceous (Aptian-Albian) marine deposits, up to 650 m thick, are only known from a few occurrences in Kronprins Christian Land, with an outlier as far west as Valdemar Glückstadt Land.

In Late Cretaceous times a major pull-apart basin developed, and six local blocks or sub-basins have been recognised along the oblique-slip belt (Håkansson *et al.*, 1991). With few exceptions they show different stratigraphic developments and were initiated at different times, although a tendency to progressive younging towards the north-west was noted by Birkelund & Håkansson (1983). The two westernmost sub-basins contain the only evidence of magmatic activity, and one sub-basin is almost entirely volcanic.

The facies of the individual sub-basins are markedly different. Thus, more than 1500 m of marine shallowing-upwards deposits of Middle Turonian – Early Coniacian or younger age accumulated in northern Kronprins Christian Land. Deposition was followed by strong transpressional deformation and development of domal folds and thrusts.

In a neighbouring basin the development was quite different and more than 600 m of Late Cretaceous fine-grained marine sandstones were deposited and later subjected to a short-lived pulse of increase in heat flow leading to low greenschist metamorphism. A highly sheared and deformed Late Santonian succession, some 400 m thick, occurs in the Harder Fjord Fault Zone. Strongly deformed fluviatile sandstones and shales of probable Late Cretaceous age also occur in close association with the Harder Fjord and Trolle Land Fault Zones.

12, Rifting of the Eurasia basin, 80–65 Ma

A succession of at least 5 km of volcanic extrusive rocks and interbedded sediments constituting the Kap Washington Group is exposed in south-easterly inclined thrust wedges on the north coast of Greenland (Figs 1, 4). The suite is of peralkaline provenance and includes rhyolitic lavas and pyroclastic flows, trachytic and basaltic lavas, as well as tuffs, agglomerates and breccias (Brown & Parsons, 1981). The age is somewhat uncertain, but palaeobotanic evidence indicates a Late Cretaceous age for the volcanic activity, probably mainly in the interval from Campanian to the Maastrichtian-Danian boundary (Batten *et al.*, 1981; Håkansson *et al.*, 1991).

A dense swarm of N-S trending late Cretaceous dolerite dykes occurs in the area south of the Kap Washington volcanics. South of the Harder Fjord Fault Zone the N-S swarm is replaced by a less dense suite of WNW trending dykes, and further south, in Peary Land, by a NW trending set. The main, N-S swarm was formed during a period of E-W extension of mainly continental crust, preceding the opening of the Eurasia basin (e.g. Soper & Higgins, in press b). The NW trending swarm shows a remarkable parallelism with the Trolle Land Fault Zone and may reflect extensional events during basin formation to the east.

13, Eurekan thrusting and faulting, 65–55 Ma

The volcanic episoede was followed by the development in Palaeocene-Eocene time of the SE-dipping Kap Cannon Thrust Zone. This has been interpreted as a Eurekan compressional, within-plate, response to the anticlockwise rotation of Greenland due to spreading in the Labrador Sea (Soper & Higgins, in press b), or may have formed in conjunction with transpression during dextral NW-SE strike-slip movements (Håkansson & Pedersen, 1982).

On a larger plate tectonic scale it is possible that these two interpretations can be united when more precise datings become available.

14, Early Tertiary initiation of transform margin, 55–0 Ma

Tertiary sediments of the Thyra Ø Formation only occur in northernmost Kronprins Christian Land and on the islands south-east of Peary Land (Figs 1–4). The formation is up to 50 m thick in outcrop and consists of gravel, sand, silt and abundant coal seams deposited in a broad flood-plain. The sediments have not undergone any deformation and thus post-date the transpressional events characterising the Mesozoic basin. Their age is probably Late Palaeocene. They represent the earliest ocean margin sediments formed when the stress in the Wandel Sea area was relieved by onset of spreading of the Norwegian-Greenland Sea (see review by Larsen, 1990; Fig. 31).

The Thyra Ø Formation contains the youngest pre-Quaternary deposits of North Greenland and marks the end of a long succession of independent tectonostratigraphic basins formed during alternating extensional and compressional episodes.

Summary

Tectonostratigraphy describes sedimentary basins formed during major events of plate reorganisation. In North Greenland tectonostratigraphic basins include an interior sag basin (Middle Proterozoic), two rift-to-passive margin basins (Late Proterozoic and Early Palaeozoic), two foreland basins (mid-Palaeozoic, both removed by later uplift and erosion), an intracontinental rift basin (Late Palaeozoic), an oblique-slip pull-apart basin complex (Mesozoic), and a poorly preserved proximal transform margin basin (Early Tertiary).

The tectonostratigraphic basins cover a span of time of more than 1200 million years from the Middle Proterozoic to the Early Tertiary. The exact nature of the earliest recognised tectonostratigraphic unit, the Middle Proterozoic Independence Fjord basin (*c.* 1380 Ma), is poorly known. It overlies Archaean crystalline basement, and the great uniformity and lateral extent of the continental sandstones and thin siltstones constituting the basin fill suggest that it is an interior sag basin. Rifting and early spreading occurred around 1230 Ma and is represented by the Midsommersø – Zig-Zag Dal volcanic event.

A phase of trough subsidence, faulting and peneplanation followed which may be interpreted as reflecting closure of an ocean during the Grenvillian Orogeny (1100–1000 Ma) well known from Arctic Canada.

Rifting and spreading of the Iapetus Ocean was initiated in Late Proterozoic times between 800 and 570 Ma. The Late Proterozoic Hagen Fjord – Rivieradal Basin which was deposited within this time-interval may thus represent a shelf-slope-proximal basin of the Iapetus passive margin. Remnants of a Varangian glacial succession belong to this tectonostratigraphic unit.

Rifting of the Franklinian Basin took place close to the Proterozoic-Cambrian boundary (between 640 and 570 Ma). Onset of spreading and formation of a remarkably well preserved E-W trending passive margin succession continued through Cambrian, Ordovician and Silurian times.

The eastern passive margin was influenced by the westwards migration of a peripheral bulge reflecting an early closing event in the Iapetus Ocean and accretion of a micro-continent. This event terminated in the Early Ordovician (*c.* 500 Ma) and the regular evolution of the Franklinian Basin continued.

Final closure of the Iapetus Ocean took place during the Silurian, and the onset of Caledonian orogenic uplift in the Early Silurian is reflected by rapid westwards outbuilding in the Franklinian deep-water basin of the huge Peary Land deep-sea fan sourced from the rising Caledonian mountain belt. The Franklinian shelf rap-

idly foundered by flexural bending caused by basinal loading of the enormous volumes of deep-sea fan deposits. The foundering of the platform was aided by a major eustatic rise in the Late Llandovery.

Final suturing of the Iapetus Ocean took place close to the Silurian-Devonian boundary (*c.* 410 Ma) and was marked by westwards transport of nappes. Loading by a pile of nappes at least 5 km thick caused flexural down-bending of the eastern part of the Franklinian shelf and the formation of a roughly N-S trending foreland basin. The latter is not preserved due to later uplift and erosion. Its former presence is revealed by a pronounced change in the trend in maturity iso-lines from E-W, parallel to the Franklinian margin, to N-S, parallel to the Caledonian front in eastern areas of North Greenland.

Iapetus suturing was followed by closure of the Franklinian Basin in Late Devonian – Early Carboniferous time (*c.* 360 Ma). Loading of the Franklinian slope and shelf region by Ellesmerian thrust sheets caused flexural down-bending and formation of an E-W trending Ellesmerian foreland basin. This tectonostratigraphic basin is not preserved but its former presence is revealed by maturity parameters. The position of the thrust front and the proximal foreland basin is indicated by a marked increase in the S-N maturity gradient over a short distance.

A continental rift basin was formed in the Early Carboniferous. It represents the northernmost extension of the Late Palaeozoic rift basin of East Greenland and intersects the eastern part of the Franklinian Basin in eastern North Greenland. It was followed by faulting, uplift and erosion, succeeded by marine onlap in Late Carboniferous, Moscovian time (*c.* 300 Ma). Rifting culminated in the mid-Permian, as in central East Greenland, and the Late Palaeozoic carbonate platform was drowned during the event.

During the Mesozoic a new type of tectonostratigraphic basin developed mainly caused by extensional oblique slip in the weakness zone in the Barents Shelf between eastern North Greenland and Svalbard. A NW-SE trending pull-apart basin complex was initiated in the Triassic. Early and Middle Jurassic rocks are not preserved or were never deposited, and marine onlap started in the Late Jurassic, concomitant with a major eustatic rise in sea-level. Transtensional and transpressional events alternated during the Cretaceous.

Opening of the Eurasia Basin is reflected by N-S, WNW-ESE and NW-SE dyke swarms and interbedded volcanic extrusives and sediments of the Late Cretaceous Kap Washington Group. This unit was overthrust by Late Palaeozoic rocks during the Kap Cannon thrusting event which possibly represents a Eurekan within-plate response to the anticlockwise rotation of Greenland due to spreading in the Labrador Sea.

The stress between eastern North Greenland and Svalbard was relieved by the onset of spreading of the Norwegian-Greenland Sea in the Palaeocene and the youngest pre-Quaternary tectonostratigraphic basin in North Greenland is represented by thin undeformed Palaeocene proximal transform margin deposits. They mark the end of a long succession of tectonostratigraphic basins formed as a consequence of major plate tectonic events and changes in plate configuration.

Acknowledgements. I am grateful to F. G. Christiansen, A. K. Higgins, E. Håkansson, H. F. Jepsen, L. Stemmerik and M. Sønderholm for placing unpublished information and manuscripts at my disposal and for critically reading parts or all of the manuscript. M. Sønderholm, in particular, gave a thorough review of the first draft. D. Pugliese, T. Damholt, B. Sikker Hansen and Bente Thomas are thanked for assistance in preparation of the manuscript.

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The North Greenland Project: transportation of the expedition and daily logistics.

Proterozoic basins of North Greenland

Martin Sønderholm and Hans F. Jepsen

Three major phases of sedimentary basin evolution can be recognised in the Proterozoic geological record of North Greenland. The earliest sedimentary basin phase is witnessed by the Middle Proterozoic Independence Fjord Group, a more than 2000 m thick sandstone-dominated succession consisting of intracratonic, mainly ephemeral stream and probable aeolian deposits with thin, but widespread intervals of lacustrine sedimentation. These deposits were intruded around 1230 Ma by doleritic sills and dykes and overlain by associated basalts forming the second evolutionary phase. The basalts are at least 1350 m thick with a minimum extent of 10 000 km^2. This major volcanic phase can be traced from Arctic Canada to North-East Greenland and probably represents a period of rifting and continental break-up related to the opening of a pre-Grenvillian ocean.

After a period of at least 400 Ma with no preserved geological record, a Late Proterozoic sedimentary phase occurred. This is represented by the Moræmesø Formation and the Hagen Fjord Group which occur in geographically separated areas with no proven correlation between them. The Moræmesø Formation mainly consists of diamictites and sandstones forming valley-fill deposits in up to 200 m thick successions, recording Varangian deglaciation processes. The Hagen Fjord Group comprises up to 1000 m of siliciclastic and carbonate deposits of mainly shallow water shelf origin. Partly correlative deep water deposits referred to the approximately 2500 m thick Rivieradal sandstones are found in Caledonian nappe structures in Kronprins Christian Land.

The Proterozoic basins in central and eastern North Greenland are separated from the deposits of the Franklinian Basin (Cambrian-Silurian) by an extremely flat unconformity marking a hiatus of 10–30 Ma.

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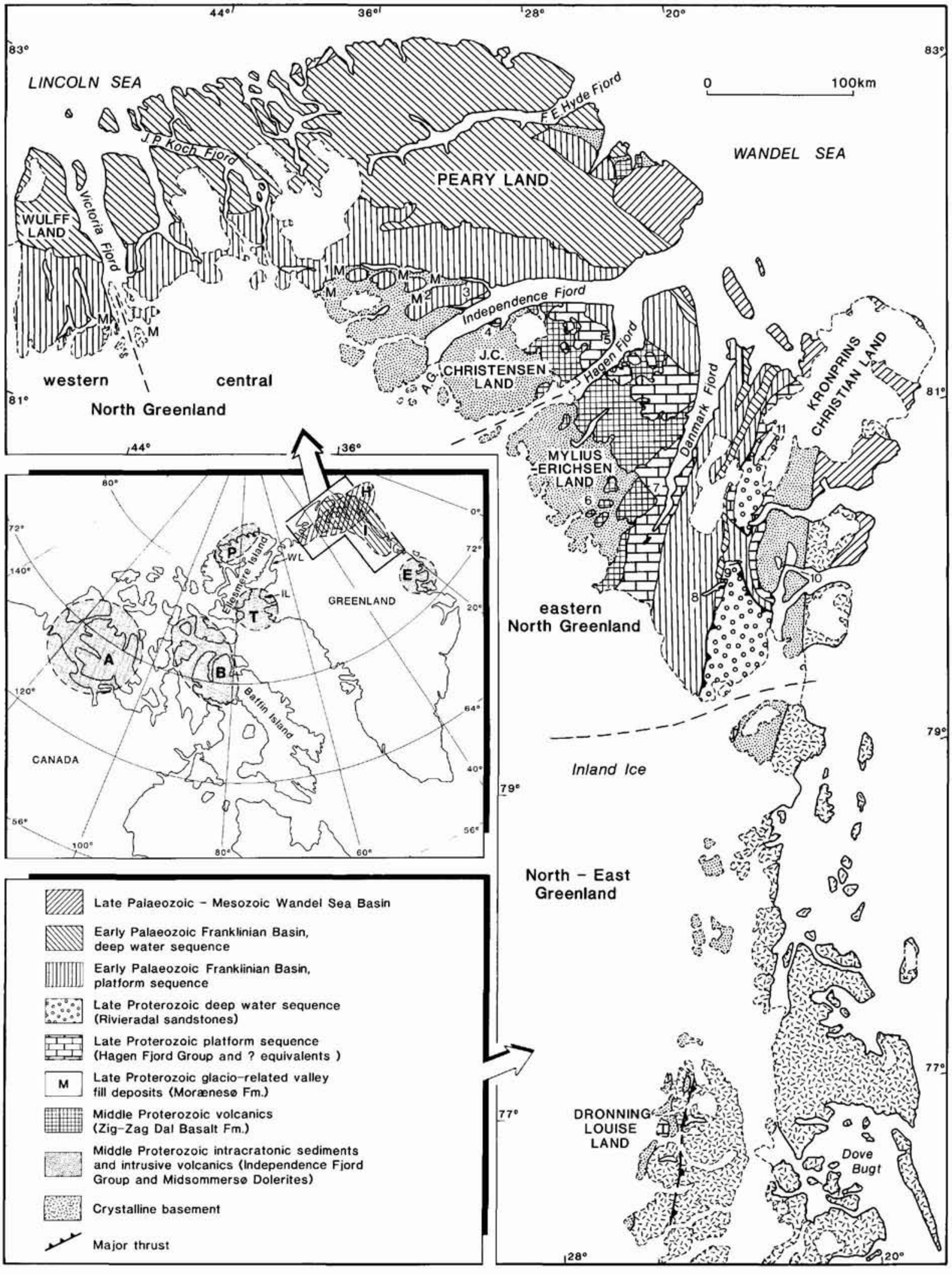
Proterozoic sedimentary and associated igneous rocks along the margin of the Precambrian crystalline shield in North Greenland (Fig. 1) have been studied by several geological field-teams since 1912 when they were first investigated during the First Thule Expedition. Pioneering work was carried out by Lauge Koch, first as a member of the Second Thule Expedition (1916–1918) and later as leader of the Danish Jubilee Expedition (1920–1923), resulting in a description of the geology of the area between the Thule district and Peary Land (Koch, 1920, 1925, 1929, 1933). Later, during the Danish Thule and Ellesmere Land Expedition 1939–41, information on the Proterozoic and Lower Palaeozoic sedimentary successions of the regions around Kane Basin and Kennedy Channel was collected by Troelsen (1950). Proterozoic and Lower Palaeozoic successions in Peary Land were studied by members of the Danish Peary Land Expeditions 1948–50 and 1963–68 (Troelsen, 1949, 1956; Ellitsgaard-Rasmussen, 1950; Jepsen, 1971). During the Danish Expeditions to East Greenland 1947–58, Adams & Cowie (1953) and Fränkl (1954, 1955) examined Proterozoic and Lower Palaeozoic sedimentary successions in the Kronprins Christian Land area; systematic aerial reconnaissance was carried out by Haller (e.g. 1971, 1983) in eastern North Greenland. This earlier work has been reviewed by Dawes (1971, 1976), Dawes & Christie (1982) and Christie & Dawes (in press).

More recently, the Proterozoic strata of North Greenland have been studied in greater detail by the Geological Survey of Greenland (GGU) during the North Greenland Project of 1978–80 and 1983–85 (e.g. Peel *et al.*, 1982; Collinson, 1983; Kalsbeek & Jepsen, 1983, 1984; Hurst *et al.*, 1985; Collinson *et al.*, 1989; Clemmensen & Jepsen, in press). The present paper reviews these studies in an attempt to elucidate the development of the sedimentary basins in North Greenland during the Proterozoic.


LINCOLN SEA
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0
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PEARY LAND
WULFF LAND
Victoria Fjord
J.P. Koch Fjord
F.E. Hyde Fjord
Independence Fjord
J.C. CHRISTENSEN LAND
A.G.
Hagen Fjord
Danmark Fjord
KRONPRINS CHRISTIAN LAND
MYLIUS ERICHSEN LAND
western
central
North Greenland
eastern North Greenland
Inland Ice
North - East Greenland
DRONNING LOUISE LAND
Dove Bugt
44°
36°
28°
20°
83°
81°
79°
77°
CANADA
GREENLAND
Ellesmere Island
Baffin Island
WL
IL
Late Palaeozoic - Mesozoic Wandel Sea Basin
Early Palaeozoic Franklinian Basin, deep water sequence
Early Palaeozoic Frankiinian Basin, platform sequence
Late Proterozoic deep water sequence (Rivieradal sandstones)
Late Proterozoic platform sequence (Hagen Fjord Group and ? equivalents)
Late Proterozoic glacio-related valley fill deposits (Moræneso Fm.)
Middle Proterozoic volcanics (Zig-Zag Dal Basalt Fm.)
Middle Proterozoic intracratonic sediments and intrusive volcanics (Independence Fjord Group and Midsommersø Dolerites)
Crystalline basement
Major thrust

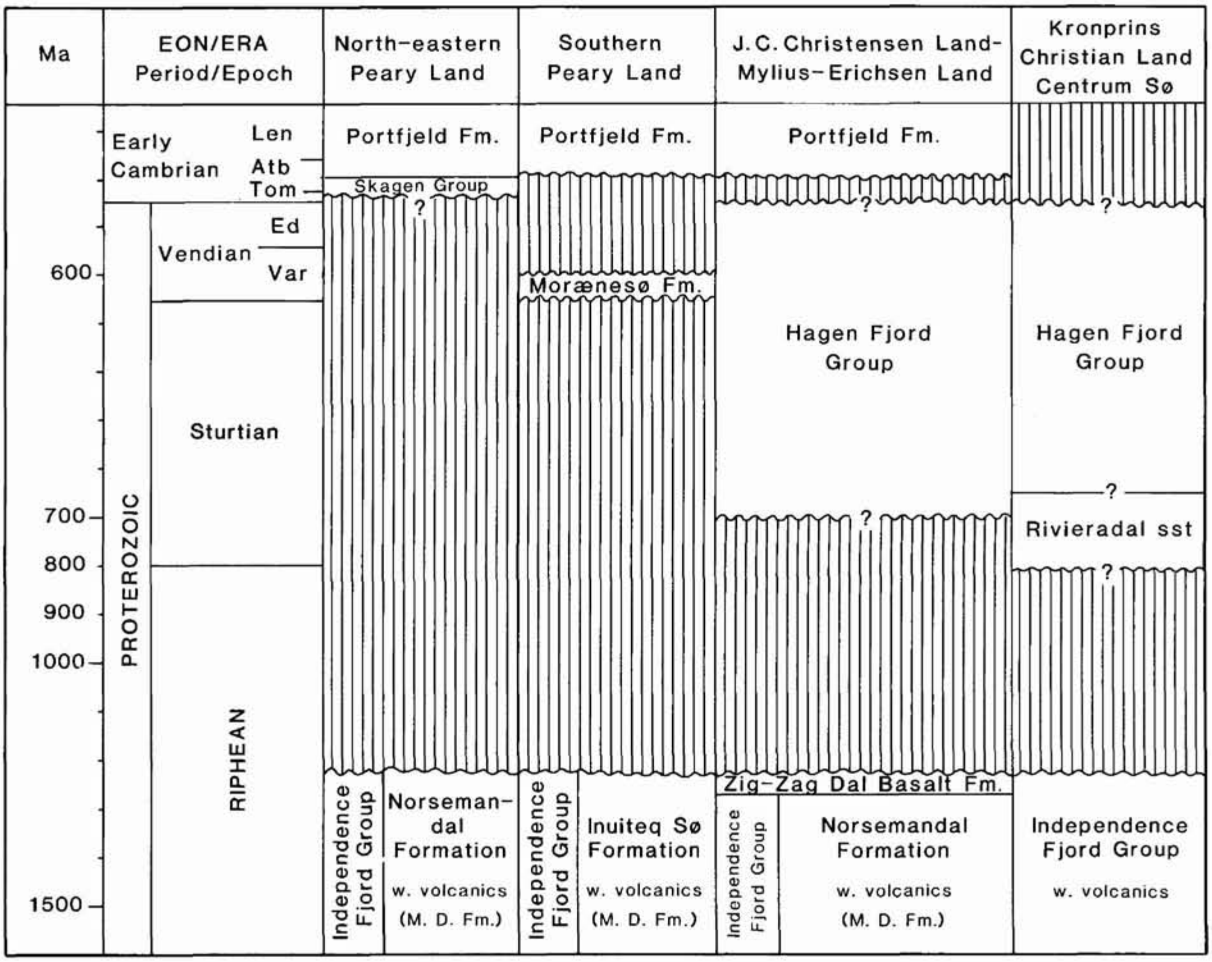
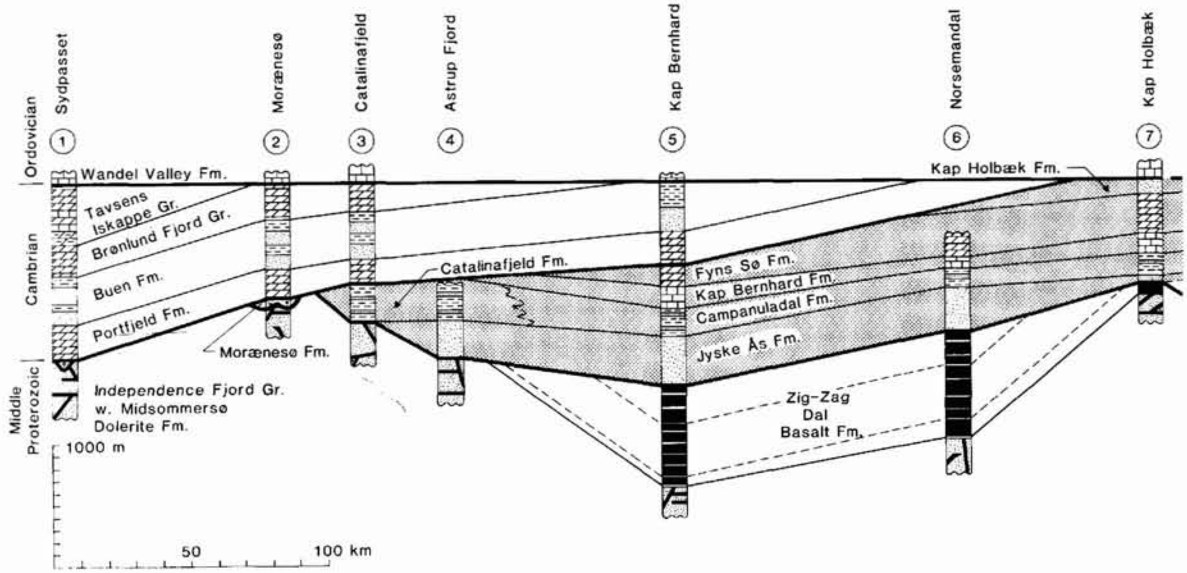


Fig. 2. Stratigraphy of the Proterozoic basins in North Greenland. M. D. Fm., Midsommersø Dolerite Formation. Atb, Atdabanian; Ed, Ediacaran; Len, Lenian; Tom, Tommotian; Var, Varangian. Time scale adapted from Harland *et al.* (1989).

Geological framework

Crystalline basement rocks of the Greenland Shield are exposed beneath Proterozoic and younger sedimentary strata in several areas in the northern part of Greenland (Fig. 1). In Inglefield Land, North-West Greenland, crystalline rocks of Proterozoic age are overlain by a succession of Proterozoic and Cambrian sediments (Peel *et al.*, 1982; Dawes, 1988; Dawes *et al.*, 1988). In southern Wulff Land, and on the nunataks at the head of Victoria Fjord (Fig. 1), Archaean gneisses are overlain by Upper Proterozoic sediments (Hansen *et al.*, 1987). In eastern North Greenland, crystalline basement rocks are exposed in the fjord region along the

Fig. 1. Simplified geological map of North and North-East Greenland showing the outcrops of Proterozoic basins and main structural elements in Kronprins Christian Land. 1, Sydpasset; 2, Moræneso; 3, Heilprin Land/Catalinafjeld; 4, Astrup Fjord; 5, Kap Bernhard; 6, Norsemandal; 7, Kap Holbæk; 8, Centrum Sø; 9, Sæfaxi Elv; 10, Hekla Sund; 11, Romer Sø. Insert map shows the occurrence of other Proterozoic basins in adjoining areas. A: Amundsen Embayment (Late Proterozoic; Young, 1981); B: Borden Basin (Middle to ?Late Proterozoic; Jackson & Ianelli, 1981; Fahrig *et al.*, 1981; Stewart, 1987); E: Eleonore Bay Group and Tillite Group basins (Late Proterozoic; Haller, 1971; Hambrey & Spencer, 1987; Caby & Bertrand-Sarfati, 1988; Sønderholm *et al.*, 1989; Sønderholm & Tirsgaard, 1990); H: Hagen Fjord Basin and Moræneso Formation (Late Proterozoic); I: Independence Fjord Basin (Middle Proterozoic); P: Pearya basin (?Late Proterozic possibly exotic terrane; Trettin, 1987); T: Thule Basin (Middle to Late Proterozoic; Dawes *et al.*, 1982; Dawes & Vidal, 1985; Dawes & Rex, 1986); IL: Inglefield Land; WL: Washington Land. Maps adapted from Clemmensen & Jepsen (in press).



east coast of Kronprins Christian Land, as well as further south in North-East Greenland.

In central and eastern North Greenland and in North-East Greenland the crystalline basement is unconformably overlain by Middle Proterozoic, non-marine siliciclastic sediments (Fig. 2). These sediments are referred to the Independence Fjord Group (Collinson, 1980), and to the Trekant 'series' (Peacock, 1956; Friderichsen *et al.*, 1990). Coeval sediments are found in the Thule Basin of northern Baffin Bay (Fig. 1; Dawes *et al.*, 1982; Dawes & Vidal, 1985; Dawes & Rex, 1986; P. R. Dawes, personal communication, 1990). Intrusive igneous rocks are conspicuous in both successions. In Inglefield Land on the northern margin of the Thule Basin (Fig. 1) they give K/Ar isotopic ages of 1190–1070 Ma (Dawes *et al.*, 1973) and in eastern North Greenland Rb/Sr isotope analyses of the Midsommersø Dolerite Formation yield ages of about 1230 Ma (Kalsbeek & Jepsen, 1983, 1984). This volcanism probably represents a period of rifting connected with the initial opening of an ocean along the northern margin of the Canadian-Greenland Shield (Jackson & Ianelli, 1981).

The upper boundary of these Middle Proterozoic intracratonic sediments and volcanics in central and eastern North Greenland is an erosional unconformity of regional extent upon which Late Proterozoic sediments rest. In the western part of the region the glacio-related Morænesø Formation was deposited while to the east the shallow-marine Hagen Fjord Group, with the partly equivalent deep-water Rivieradal sandstones, was deposited as a westwards transgressive sequence at the margin of the Iapetus Ocean (Hurst & McKerrow, 1985; Clemmensen & Jepsen, in press). In the intervening time interval of at least 400 Ma no geologic record is preserved in North Greenland (Fig. 2, see also Fig. 18). However, information from northern Ellesmere Island, Canada, suggests that plate collision took place during Grenvillian time (1100–1000 Ma) along the northern margin of the Canadian-Greenland Shield, resulting in intense deformation, amphibolite-grade metamorphism and intrusion of granitic plutons (Trettin, 1987). Although no obvious traces of this Grenvillian orogenesis are known from North Greenland (Jepsen & Kalsbeek, 1985), it may have been responsible in part for the period of uplift and erosion prior to the deposition of the Hagen Fjord Group.

Towards the end of the Proterozoic a period of significant uplift, block-faulting and erosion affected the area between southern Peary Land and J. C. Christensen Land (Fig. 2, see also Fig. 18). This uplift and erosion may be related to the initial phases of rifting during the opening of the Franklinian Basin. However, no signs of volcanic activity related to this opening have been observed in North Greenland.

During the Early Cambrian, the Franklinian sea transgressed the peneplained top of the Proterozoic shelf sequence of central and eastern North Greenland (Figs 2, 3, see also Fig. 18), resulting in north to south onlap by the mainly siliciclastic Lower Cambrian Skagen Group and the overlying platform carbonates of the Portfjeld Formation (Higgins *et al.*, 1991).

Regional uplift of the platform area in eastern North Greenland during the Cambrian and Early Ordovician, which was probably caused by early Caledonian tectonic

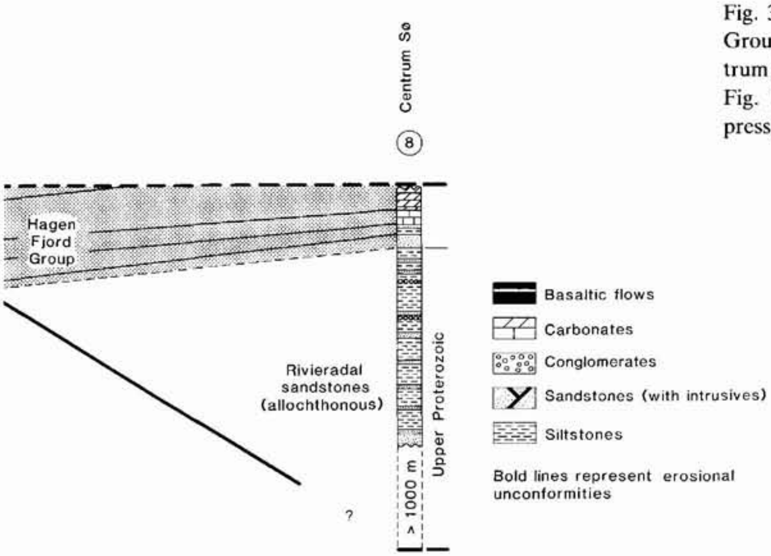


Fig. 3. Schematic cross-section of the Hagen Fjord Group from Sydpasset in the north-west to Centrum Sø in the south-east. Locality numbers refer to Fig. 1. Adapted from Clemmensen & Jepsen (in press).

activity, resulted in an overstepping of the Early-Middle Ordovician Wandel Valley Formation from Cambrian strata onto the Hagen Fjord Group in Kronprins Christian Land (Fig. 3, see also Fig. 18) (Higgins *et al.*, 1991).

Along the eastern coast of North Greenland, late Silurian Caledonian deformation resulted in westward transport of large nappe structures. The nappes are partly composed of strata belonging to the Rivieradal sandstones and to the Hagen Fjord Group. These allochthonous sediments may have been deposited east of the present-day coastline (Hurst & McKerrow, 1985).

Lithostratigraphy and basin evolution

Three major phases of basin evolution are recognised within the Proterozoic of North Greenland.

1. Middle Proterozoic intracratonic sag sedimentation (Independence Fjord Group).
2. Middle Proterozoic continental rifting and volcanic activity (Midsommersø Dolerite and Zig-Zag Dal Basalt Formation), followed by a more than 400 Ma long period without any preserved geological record.
3. Late Proterozoic sedimentation, represented by the glacially influenced Moræneso Formation and the shelf and trough sediments of the Hagen Fjord Group and Rivieradal sandstones.

These three phases are described in ascending order below. Stratigraphic relationships between the Morænesø Formation and the Hagen Fjord Group are uncertain since the two units occur in separate areas. Hence, the units are described separately below, while problems associated with their correlation are discussed at the end of the paper.

Middle Proterozoic intracratonic sag sedimentation

The oldest sedimentary basin phase in North Greenland is represented by the more than 2 km thick succession of mainly clastic alluvial deposits referred to the Independence Fjord Group (Collinson, 1980). Outcrops of the group and the correlative 'Trekant series' of Dronning Louise Land in North-East Greenland (Peacock, 1956) occur in a 400 km long belt stretching from the south side of Frederick E. Hyde Fjord in north-eastern Peary Land to the northern part of Dronning Louise Land (Fig. 1; Christie & Ineson, 1979; Collinson, 1980; Hurst *et al.*, 1985; Friderichsen *et al.*, 1990).

Radiometric data (Rb/Sr) have yielded ages around 1380 Ma for clays within the middle part of the group (Larsen & Graff-Petersen, 1980), and 1230 ± 25 Ma for dolerite and granophyre intrusions (Jepsen & Kalsbeek, 1979), indicating a Middle Proterozoic age.

The base of the Independence Fjord Group is hidden beneath the Inland Ice, but the group is inferred to lie unconformably upon crystalline basement. Strata assigned to the group are conformably overlain by an up to 1350 m thick succession of extrusive basalts (the Zig-Zag Dal Basalt Formation of Jepsen & Kalsbeek, 1979) in the area between Independence Fjord and Danmark Fjord, but to the north-west of Independence Fjord the group is unconformably overlain by Upper

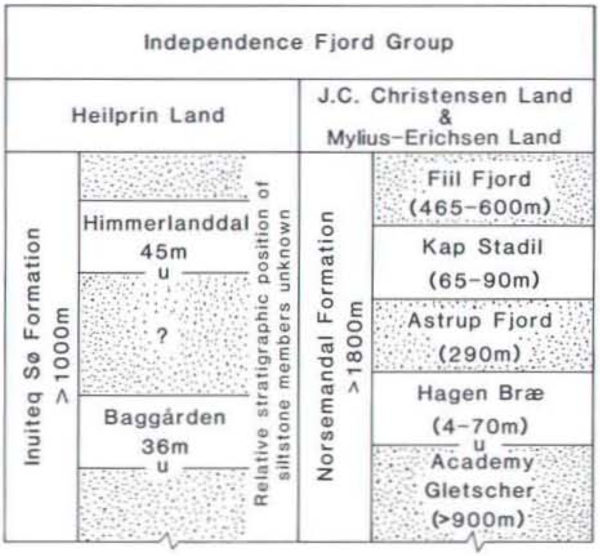


Fig. 4. Stratigraphy of the Independence Fjord Group in the type area between J. P. Koch Fjord and Danmark Fjord (Collinson, 1980, 1983). U, unconformities at base of siltstone members. Sandstone members are stippled.

Proterozoic and Lower Cambrian strata (Collinson, 1980).

The sediments of the Independence Fjord Group are only well known in the region between southern J. P. Koch Fjord and Danmark Fjord where the group has been formally subdivided into the sandstone-dominated Inuiteq Sø and Norsemandal Formations (Adams & Cowie, 1953; Jepsen, 1971; Collinson, 1980). These occur in geographically separated areas, between which correlation is uncertain (Fig. 4). Each formation consists of several sandstone members separated by laterally extensive siltstone members (Figs 4, 5). In the Norsemandal Formation these siltstone members can be traced for more than 100 km (Collinson, 1980).

The sandstones, which make up the bulk of the group, are mainly medium-grained to coarse-grained and generally quartz-rich. They chiefly show trough and tabular cross-bedding, but are interbedded with parallel-bedded units up to several metres thick in which the sandstone beds are separated by silty interbeds up to 10 cm thick. Bedding surfaces commonly show current or wave ripples, often in interference patterns, dessication polygons and synaeresis cracks. Scattered throughout the sandstones are thin conglomerate beds comprising both exotic pebbles and mudstone intraclasts. The vertical interbedding of the different sedimentary facies within the sandstones seems to be random (Collinson, 1980, 1983).

The red siltstone members mainly comprise thinly and irregularly interbedded sequences of homogeneous

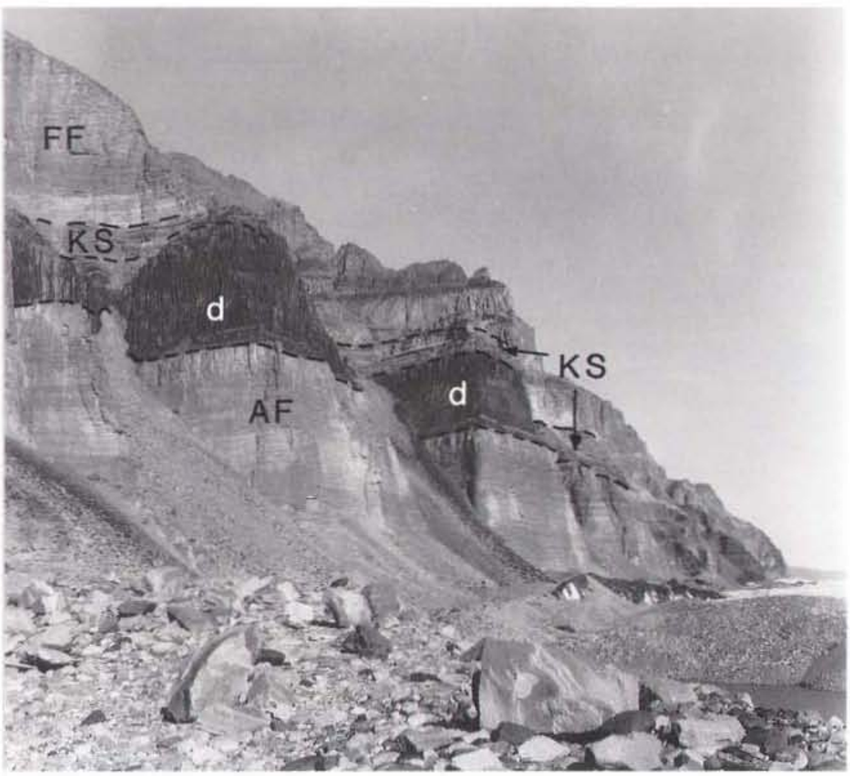


Fig. 5. Outcrops of the upper part of the Independence Fjord Group (Norsemandal Formation) in cliffs along the southern margin of J. C. Christensen Land. AF, Astrup Fjord Member (290 m); KS, Kap Stadil Member; FF, Fiil Fjord Member. A thick dolerite sill (d) of the Midsommersø Dolerite Formation occurs between the Astrup Fjord and Kap Stadil Members.

Fig. 6. Interbedded sandstones and siltstones in the top of the Hagen Bræ Member along the southern margin of J. C. Christensen Land. Height of section c. 40 m.

or rather poorly laminated coarse siltstones (sometimes with irregular dolomite concretions) and sandstones (Fig. 6). These sequences may show both upwards fining or coarsening. The sandstone beds are mostly less than 20 cm thick, but may reach 3.5 m. Top surfaces of the thicker beds commonly show wave or current ripples, often with interference patterns. Lower surfaces often show casts of dessication polygons and halite pseudomorphs. Rare intercalations of dolomite in beds generally less than 50 cm thick show fine horizontal lamination and small laterally linked stromatolitic domes. The lower boundaries of the siltstone members are always sharp while the upper boundaries generally are gradational (Collinson, 1980, 1983).

The sedimentary features and the very widespread nature of the siltstone members suggest that they represent ephemeral saline lakes which often dried out to form extensive playas. The sandstone members record fluvial and aeolian sedimentation on very low angle alluvial fans which gradually filled in the lakes (Collinson, 1983; L. B. Clemmensen, unpublished data).

The sharp lower boundaries of the siltstone members show features suggesting significant breaks in deposition, such as developments of local palaeotopography up to 70 m high (Fig. 7), vertical, sharp-sided conglomerate filled fissures in the underlying sandstones, and basal conglomerates associated with silica-cemented concretion horizons (Collinson, 1983). Sediments associated with the palaeotopographies include flanking conglomerates, steeply dipping (up to 30°) thinly bedded sandstone beds with wave-rippled upper surfaces, and cryptalgally laminated dolomites containing evaporite nodules replaced by chalcedony. The latter deposits, which indicate slight emergence for sustained periods, drape palaeotopographies of up to 10 m and suggest that considerable fluctuation in lake level during this relatively submerged phase occurred. Thicker successions of evaporite may have developed in the deeper parts of the lake under such conditions and, at one locality, an angular discordance observed within the Hagen Bræ Member of the Norsemandal Formation could have been caused by later dissolution of the evaporites (Collinson, 1983).

The large extent of the siltstone members in the Norsemandal Formation suggests that lacustrine conditions were very extensive. This, together with the fact that each siltstone member is preceeded by an erosional phase, led Collinson (1983) to suggest that the pattern of overall subsidence was punctuated by intervals of uplift, followed by initially rapid subsidence of probably basin-wide extent. Very tentatively it was suggested that minor phases of heating and cooling at depth resulted in the widespread lacustrine intervals and that a much larger, but related, thermal event led to the extensive

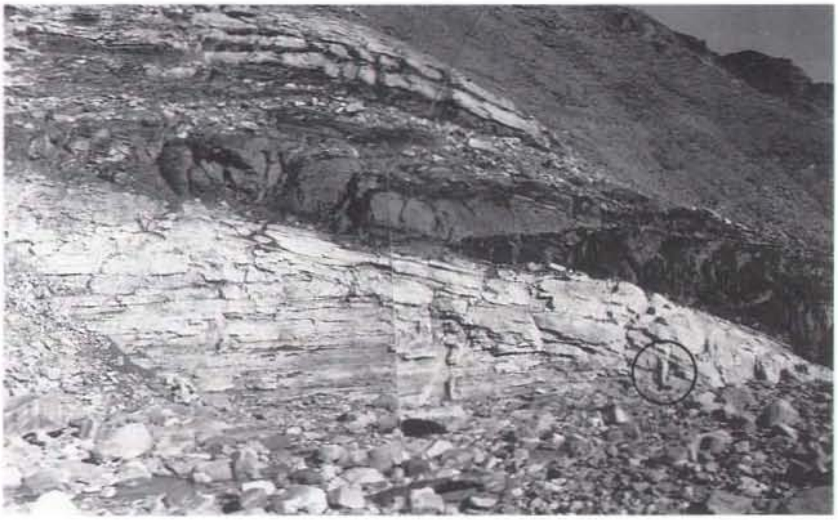


Fig. 7. Erosional relief on top of the Academy Gletscher Member with an overlying wedge of flanking sandstones in turn overlain by red siltstones of the Hagen Bræ Member. Person (encircled) for scale. Southern margin of J. C. Christensen Land.

extrusion of the basalts which directly overlie the Independence Fjord Group.

Middle Proterozoic continental rifting and volcanic activity

Following the deposition of the Independence Fjord Group a major Middle Proterozoic event of extensive basic volcanic activity occurred in a more than 100 km wide belt curving along the present northern and eastern margin of the Canadian-Greenland Shield. Rb/Sr and K/Ar isotope analyses of the basic rocks have yielded ages between 1260–1100 Ma (cf. Jackson & Ianelli, 1981). This important event probably represents rifting and continental break-up related to the opening of a pre-Grenvillian ocean (Jackson & Ianelli, 1981).

In central and eastern North Greenland the crystalline basement and the Independence Fjord Group were intruded by huge volumes of basic magma (the Midsommersø Dolerite Formation; Jepsen, 1971; Kalsbeek & Jepsen, 1983). Where the magma reached the surface, the Independence Fjord Group was overlain by at least 1350 m of lava flows with a minimum extent of 10 000 km^2 (the Zig-Zag Dal Basalt Formation; Jepsen, 1971; Kalsbeek & Jepsen, 1984).

In Dronning Louise Land in North-East Greenland

Fig. 8. Midsommersø Dolerite Formation intruded in sandstones of the Inuiteq Sø Formation (Independence Fjord Group). The intrusives consist of mobilised sandstone (rheopsammite) with a dark doleritic border zone. The bottom part of the section is occupied by a thick dolerite sheet. East-facing cliffs at the head of Independence Fjord; cliff height is approximately 600 m.

Fig. 9. Parallel bedded basaltic flows of the Zig-Zag Dal Basalt Formation (ZD) overlain by the Hagen Fjord Group (Jyske Ås Formation, JÅ). Zig-Zag Dal. Section height of the basalts in the mountain in the foreground is *c.* 500 m.

(Fig. 1) sediments correlated with the Independence Fjord Group (the 'Trekant series' of Peacock, 1956) are penetrated by numerous dolerite intrusions comparable to the Midsommersø Dolerite Formation (Friderichsen *et al.*, 1990). In North-West Greenland and on Ellesmere Island the Thule Supergroup of partly Middle Proterozoic age contains lava flows and is intruded by several generations of basic rocks of which the oldest have yielded K/Ar isotope ages of 1190 Ma (Dawes & Rex, 1986; P. R. Dawes, personal communication, 1990). In northern Canada Middle Proterozoic rocks are found in the lower part of the Borden Basin (Fig. 1). Middle Proterozoic basic volcanic activity has also been reported farther to the west in Canada, in the Coppermine area and the Great Slave area (cf. Jackson & Ianelli, 1981).

The Midsommersø Dolerite Formation is very widespread in the area between southern Peary Land and Kronprins Christian Land (Fig. 1). The intrusives occur as sheets, sills and dykes of dolerite and associated rocks. The intrusion types commonly pass into each other, often resulting in irregular and unpredictable outcrop patterns (Fig. 8). Flat-lying sheets of dolerite are most common; they range in thickness from a few metres up to several hundred metres and some of them can be followed for tens of kilometres. The aggregate thickness of the intrusions in many areas is probably at least 1000 m.

The intrusive rocks can be subdivided into three main groups: 1, normal dark grey to black dolerites; 2, red-brown to brick red or greenish mottled rocks which may be very fine grained; 3, very silicic rocks representing mobilised sandstones (rheopsammites). The different rock types are more or less contemporaneous. Intersections are common but show no systematic age differences (Fig. 8).

The normal dolerites and their red-brown derivatives are chemically classified as quartz tholeiites and only in the basal cumulative parts of the intrusions are normative olivine and nepheline present. Whole-rock Rb/Sr isotope data from the intrusive rocks give ages of about 1230 Ma. Previous K/Ar isotope age dates (Henriksen & Jepsen, 1970), which indicated ages ranging from *c.* 800 to 1000 Ma, are now regarded as unreliable due to Ar mobility (Kalsbeek & Jepsen, 1983).

The Zig-Zag Dal Basalt Formation (Figs 9, 10) which overlies the Independence Fjord Group in eastern North Greenland represents the effusive equivalent of the Midsommersø Dolerite Formation. Attempts to date the basalts by Rb/Sr whole-rock analysis have failed but similarity in chemistry and palaeomagnetism (Marcussen & Abrahamsen, 1983) supports the evidence for the two formations being contemporaneous.

The Zig-Zag Dal Basalt Formation mainly outcrops in the region between Danmark Fjord and Independence Fjord (Fig. 1). In this area the basaltic succession occupies a trough-shaped basin (Fig. 3) which apparently underwent subsidence after, and probably also during, the volcanic activity.

Prior to the deposition of the Late Proterozoic Hagen Fjord Group, the underlying sequences, including the volcanics, were block-faulted and peneplained. Thus, the thickness of the basalts varies from *c.* 100 m at the northern and southern extremities of the main outcrop area to *c.* 1350 m in the central part. It is probable that the basalts originally occupied a much larger area since the associated intrusions are very numerous in the area west and south-west of the present basalt outcrop.

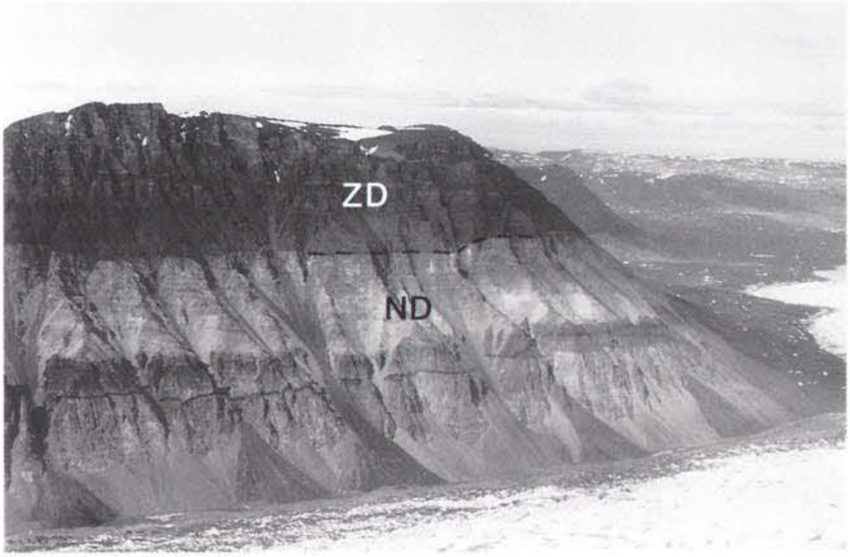


Fig. 10. Base of the Zig-Zag Dal Basalt Formation (ZD) overlying sandstones of the Independence Fjord Group (Norsemandal Formation, ND) along the southern coast of J. C. Christensen Land. Cliff height is *c.* 800 m.

Moreover, some 200 m of the Zig-Zag Dal Basalt Formation are found 100 km north-east of Independence Fjord in an uplifted fault block in eastern Peary Land; minor occurrences have also been found in the Hekla Sund area in eastern Kronprins Christian Land (Fig. 1). In both cases the basalts are associated with dolerite intrusives and sandstones of the Independence Fjord Group.

The Zig-Zag Dal Basalt Formation can be subdivided into three units in ascending order: the basal unit, the aphyric unit and the porphyritic unit (Jepsen *et al.*, 1980). The basal unit is 100–120 m thick and is composed of thin, macroscopically aphyric basalt flows, varying in thickness from less than 1 m to 10 m. Pillow lavas locally occur in the lower part, suggesting subaqueous effusion of at least the lower part of the unit. A thin

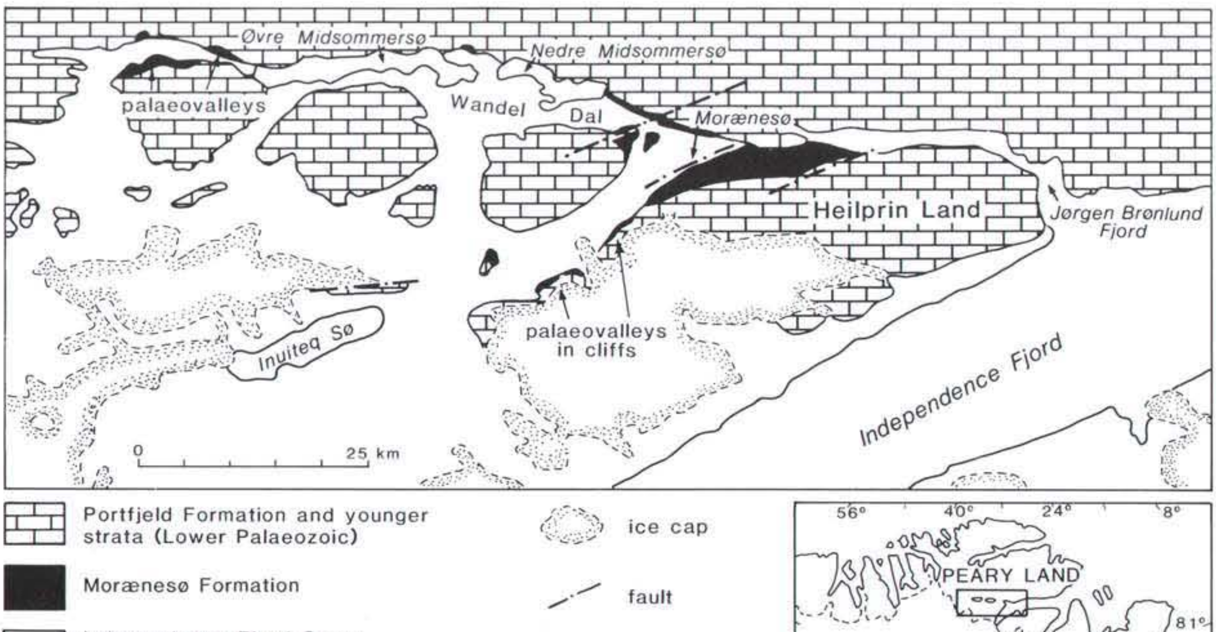


Fig. 11. Map showing the distribution of outcrops of the Morænesø Formation in the type area in southern Peary Land.

sediment horizon consisting of sandstone and dolomite locally overlies the basal unit and apparently marks a break in the volcanic activity.

The aphyric unit (390–440 m) and porphyritic unit (up to 750 m) are together composed of about 30 flows, varying in thickness from 10 to 120 m. Most flows have non-erosional tops indicating that the basalts were extruded within a short period of time. Some of the thicker flows can be traced laterally for more than 100 km and a volume of at least 600 km^3 has been estimated for one single flow (Kalsbeek & Jepsen, 1984). In one section a 100 m thick succession of rhyolitic flows is located near the top of the aphyric unit but the strongly altered red-coloured flows have not been investigated in detail. The lower part of the porphyritic unit changes character laterally. The flows in this interval are relatively thin and cannot be traced from section to section; sediments and pillow lava horizons are present and local erosional relief of up to 50 m has been observed. Volcanic activity was apparently less intense in the period following the deposition of the aphyric unit, and temporary breaks in the volcanic activity occurred before the main part of the porphyritic unit was formed.

Following the formation of the basaltic successions a long hiatus of at least 400 Ma occurred before any sedimentary record is preserved in North Greenland (Figs 1, 2). Grenvillian plate collision took place around 1100–1000 Ma along the northern margin of the Canadian Shield resulting in intense deformation (Trettin, 1987). No direct information of this orogenic event is known from North Greenland, although it may have influenced the degree of uplift and erosion prior to the deposition of the Morænesø Formation and the Hagen Fjord Group (Jepsen & Kalsbeek, 1985).

Late Proterozoic sedimentation

The youngest of the Proterozoic sedimentary basin phases in North Greenland occurred along the northwestern margin of the Iapetus Ocean. Two different major depositional settings can be recognised during this phase; a mainly continental setting dominated by post-glacial reworking, and a marine setting dominated by sedimentation of a subsiding shelf and trough.

Late Proterozoic glaciation

The Morænesø Formation (Jepsen, 1971) records a Late Proterozoic glacial event in North Greenland. These deposits were first described by Troelsen (1956) who interpreted them as tillitic due to the presence of diamictites together with facetted and striated clasts. Later, Clemmensen (1979, 1981) and Collinson *et al.* (1989) stated that most of the deposits are fluvial, lacustrine or aeolian facies formed during post-glacial reworking, and that only a minor part of the formation is of possible glacial origin.

The Morænesø Formation is only well known in the type area around Wandel Dal where it occurs as a series of palaeovalley fills, but it also occurs as scattered outcrops around the head of Victoria Fjord (Figs 1, 11; Collinson *et al.*, 1989; Henriksen, 1989). In the type area the Morænesø Formation is dominated by sandstones, diamictites, conglomerates and breccias with a minor although important interval of stromatolitic dolomite near the top of the exposed succession. Unconformities bound the formation both above and below; the lower of these shows considerable relief while the upper is extremely flat and truncates pre-Morænesø strata and syn-Morænesø Formation palaeotopography (Fig. 12). Underlying rocks consist of the sandstones and associated intrusive dolerites of the Inuiteq Sø Formation (Independence Fjord Group). Above the upper unconformity the Lower Cambrian Portfjeld Formation consists of a basal 1–2 m glauconitic sandstone unit which passes up into a thick mainly carbonate succession (Jepsen, 1971; Higgins *et al.*, 1991).

Acritarchs obtained from the Morænesø Formation are not age diagnostic (G. Vidal, GGU internal report, 1982) but stratigraphic considerations suggest that the Morænesø Formation at least in part is related to the Late Proterozoic (Varangian) glaciation also known from North America, Canada, East Greenland, Spitsbergen and Europe (Hambrey & Harland, 1981; Hambrey, 1988; Collinson *et al.*, 1989). Like the Morænesø Formation the tillite-bearing succession of Varangian age of central East Greenland and Spitsbergen is separated by a hiatus from the overlying Lower Cambrian sequence (Hambrey & Spencer, 1987; Hambrey, 1988). Furthermore, diamictites found in a palaeovalley setting similar to the Morænesø Formation are also known from the lower of the Varangian tillites in Finnmark (Føyn & Siedlecki, 1980).

The unconformity at the base of the Morænesø Formation reflects a palaeorelief of at least 190 m. Given the shapes of the preserved palaeovalleys and the great distances between some of them, however, a total relief of several hundreds of metres could have been present immediately prior to the deposition of the Morænesø Formation (Collinson *et al.*, 1989).

Direct evidence of the erosive process has only been observed at one locality where a diamictite containing striated clasts of glacial origin directly rests upon heavily disintegrated sandstones of the Inuiteq Sø Formation. This diamictite may represent the only preserved *in situ* till in the whole area. At all other localities diamictites

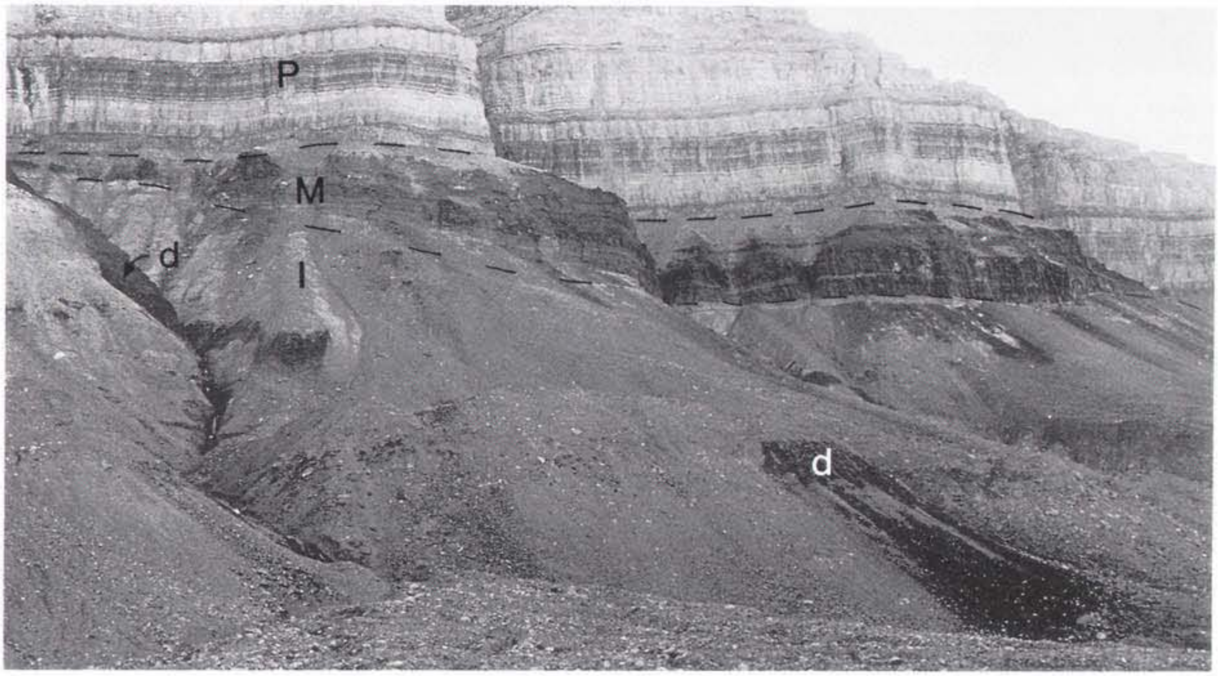


Fig. 12. Cliff-exposure of a palaeovalley cut into the sandstones of the Independence Fjord Group (Inuiteq Sø Formation, I) into which dolerites (d) of the Midsommersø Dolerite Fomation have been intruded. The dark sediments of the Moræneso Formation (M) thin away to either side and are overlain by the Cambrian Portfjeld Formation (P). Cliff section east of Inuiteq Sø, Fig. 11. Maximum thickness of Morænesø Formation is approximately 100 m.

are always separated from the unconformity by water-lain and aeolian sediments (Collinson *et al.*, 1989, p. 20). The broadly concave upwards, rounded forms of the palaeovalleys in cross-section (Fig. 12) could be taken as an argument for glacial erosion.

Directly overlying the basal unconformity, the deeper, more axial parts of the palaeovalleys contain sandstones and conglomerates of mainly fluvial origin, locally with some lacustrine and aeolian intervals. These deposits record initial valley floor aggradation prior to the deposition of the diamictites. Fluvial activity was ephemeral, as suggested by the presence of sands re-worked into aeolian dunes, but capable of transporting clasts up to 1 m in diameter and of forming large gravel bedforms. Considering that glaciers probably were involved in the erosion of the palaeolandscape, nearly all the deposits on the valley floor must have been eroded and reworked by this later fluvial activity. Evidence that the climate was at least seasonally cold during this phase is provided by dropstones in local lake deposits and by the presence of locally derived breccias. The latter were the products of a suite of gravity-driven mass movement processes, some of which are enhanced by freeze-thaw processes in cold climates (Collinson *et al.*, 1989).

The early valley floor sediments are overlain by diamictites (Fig. 13) which were deposited from mobile debris flows, possibly in a series of closely spaced events. The diamictites contain both local and exotic clasts, some of the latter being flat-iron shaped and striated. The textures and clasts of the diamictites suggest an earlier phase of glacial transport. Parts of these units show evidence of movement towards the valley axis, suggesting they were most likely derived from earlier lateral moraines deposited higher on the valley side, or as tills within hanging valleys, at a time when a glacier occupied the main valley. The remobilisation of these deposits occurred under a more humid period of climatic amelioration some time, perhaps thousands of years, after deglaciation of the region. This inference is supported by the presence of valley floor sediments which were deformed due to intense water saturation by mass flows. Similarly, deep spheroidal weathered dolerites close to the basal unconformity are unlikely to have survived a phase of glacial erosion; their deep weathering is more likely to have occurred after the initial erosion of the valley (Collinson *et al.*, 1989).

The uppermost beds of the Morænesø Formation sharply overlie the highest diamictite sheet and comprise a lower dolomite unit up to a few metres thick showing domal stromatolites (Fig. 14), and an upper

Fig. 13. Typical texture of diamictite with subhorizontal partings and well dispersed fabric. Hammer is 35 cm long.

thin unit of sandstone, infilling and draping the stromatolite domes. These beds record the establishment on the valley floor of shallow-water environments in which algal stromatolites flourished. This occurred with minimal reworking of the diamictites, suggesting low energy conditions during transgression. The stromatolite domes are laterally linked, up to 2 m high and 8 m in diameter; they are generally circular in plan view (Fig.

Fig. 14. Extensive bedding surface showing stromatolite domes within the upper part of the Moræneso Formation, western end of Jørgen Brønlund Fjord. Person (encircled) for scale.

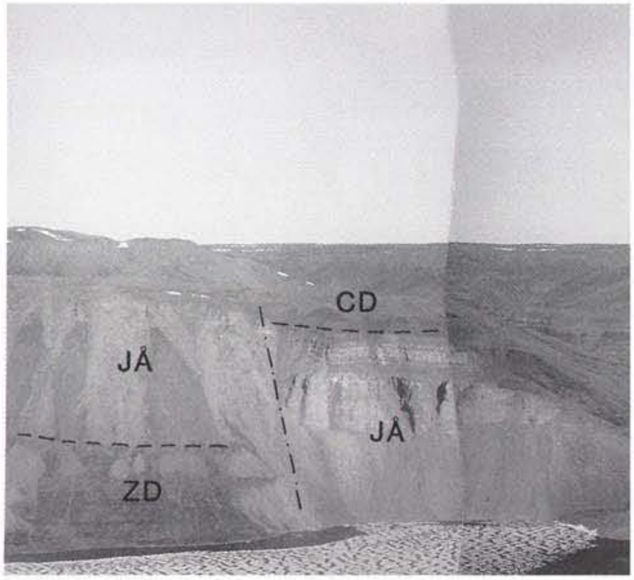


Fig. 15. Cliff section of the Hagen Fjord Group just south of Kap Bernhard, J. C. Christensen Land. CD, Campanuladal Formation; FS, Fyns Sø Formation; JÅ, Jyske Ås Formation; KB, Kap Bernhard Formation; ZD: Zig-Zag Dal Formation. The Hagen Fjord Group is overlain by the Lower Cambrian Portfjeld Formation (P). The thickness of the Campanuladal Formation is 175 m.

14). The domal stromatolites are capped by a thin coarsening-upwards siltstone and sandstone unit reflecting the re-establishment of clastic supply to a wave-aggitated setting, possibly a beach or a shoreface. There is no clear evidence within the algal stromatolites as to whether the widespread development of shallow water environments was related to intervals when lakes formed on the valley floors or to a marine ?glacio-eustatic transgression (Collinson *et al.*, 1989).

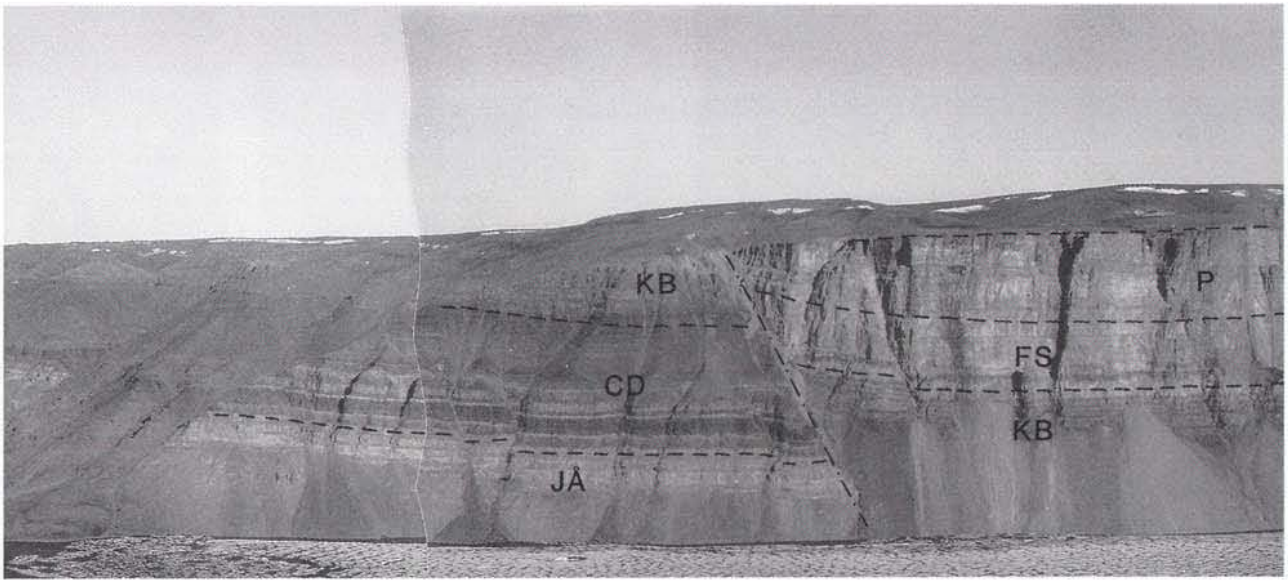
Late Proterozoic shelf and trough sedimentation

Late Proterozoic shelf and trough sediments in North Greenland are represented by the mainly shallow marine Hagen Fjord Group (up to 1000 m thick; Clemmensen & Jepsen, in press) and partly equivalent deep-water deposits referred to the more than 2500 m thick Rivieradal sandstones (*sensu* Hurst & McKerrow, 1981a) (Figs 2, 3). Outcrops of the Hagen Fjord Group are seen in the type region between the north-western side of Independence Fjord and Danmark Fjord, where sediments assigned to the group onlap the Independence Fjord Group and Zig-Zag Dal Basalt Formation with a very low angle unconformity (Fig. 1). In the area around Centrum Sø in Kronprins Christian Land, Hagen Fjord Group sediments conformably overlie the Rivieradal sandstones within large nappe structures (Figs 1–3; Hurst & McKerrow, 1981a). Between Kronprins Christian Land and Dronning Louise Land, possible correlatives of the Hagen Fjord Group overlie strata assigned to the Independence Fjord Group and associated basalts with a marked unconformity (Friderichsen *et al.*, 1990; Clemmensen & Jepsen, in press). The upper boundary of the group in the type area is a remarkably flat unconformity overlain by the Lower Cambrian Portfjeld Formation. At Kap Holbæk, furthest to the south-east in Mylius-Erichsen Land, and in Kronprins Christian Land this unconformity is truncated by the sub-Wandel Valley Formation unconformity, however, and the Hagen Fjord Group is thus overlain by the Ordovician Wandel Valley Formation (Fig. 3; see below).

In central and eastern North Greenland, the Hagen Fjord Group is divided into six formations (Figs 3, 15). The lowest is the Jyske Ås Formation (up to *c.* 500 m), which is overlain by the Campanuladal Formation (up to 175 m) in most of the area, and the Catalinafjeld Formation (up to *c.* 350 m) furthest to the north-west (Fig. 3). These formations, all consisting of siliciclastic sediments, are followed by the Kap Bernhard Formation (up to 215 m) which is dominated by limestones. This is overlain by a conspicuous yellow weathering dolomite unit, referred to the Fyns Sø Formation (up to 325 m). The top of the Hagen Fjord Group is formed by sandstones of the Kap Holbæk Formation (up to 150 m).

The Rivieradal sandstones *sensu* Hurst & McKerrow (1981a) are only found within large nappe structures in Kronprins Christian Land (Fig. 16). Hurst & McKerrow (1981b, 1985) suggested that the nappes were derived from the east or south-east and were displaced for distances in the order of 100 to 150 km. The Rivieradal sandstones form a *c.* 2500 m thick deep-water turbidite succession which, in the lower part, is dominated by mudstones (now shales and phyllites). These pass upwards into interbedded sandstones and mudstones and massive thick-bedded sandstones. Conglomerates occur at two distinct horizons. The conglomerates consist of rounded to spherical clasts of which 95–98% are quartzite and 2–5% are dolerite, indicating derivation from the sandstones of the Independence Fjord Group and their associated volcanics.

The Hagen Fjord Group conformably overlies the Rivieradal sandstones, indicating evolution from deep



water sedimentation into shallow shelf sedimentation (Fig. 3; Hurst *et al.*, 1985). The sedimentary and stratigraphic relationships between the Rivieradal sandstones and the Hagen Fjord Group are not yet fully elucidated, however, due to tectonic complexities associated with the Caledonian orogenesis in this little-studied area.

The Jyske Ås Formation records the marine transgressive event following the long hiatus represented by the sub-Hagen Fjord Group unconformity; it mainly consists of medium-grained sandstones internally dominated by cross-bedding. Foresets are sometimes covered by thin muddy drapes or may contain mudflake conglomerates at the base. Herringbone cross-bedding is present indicating a bimodal NE-SW palaeocurrent pattern with a dominant sediment transport towards NE. Current and wave-ripple cross-lamination and horizontal lamination occur locally in the sandstones, together with dessication cracks. Generally the formation lacks sequential patterns; thick coarsening-upwards sequences are locally present, however, and mudstone units up to several metres thick intercalated with sandstones only occur in the upper half of the formation. Although the basal part of the formation may include some fluvial deposits, the main part is interpreted to be of beach to shallow tidal shelf origin (Clemmensen & Jepsen, in press).

Fig. 16. Rivieradal sandstones (RS) as exposed in a thrust sheet on the western side of Romer Sø, Kronprins Cristian Land (Fig. 1, loc. 11). At this locality, the Rivieradal sandstones overlie Ordovician and Silurian carbonates of the Franklinian Basin (BR, Børglum River Formation; TU, Turesø Formation) with a thrusted contact (t). Cliff-face is approximately 700 m high.

The Campanuladal Formation, which overlies the Jyske Ås Formation in most of the area, consists mainly of a variegated sandstone and siltstone succession arranged in a characteristic sequence recognisable at most localities. The lower part of the formation consists of a variegated red and green or predominantly green unit of fine sandstone and siltstone. The upper part of the formation, which forms an excellent marker horizon throughout most of the outcrop area, consists of a stromatolitic dolostone unit overlain by green sandstones and siltstones with characteristic intercalations of yellow quartzitic sandstone beds. The green sandstones and siltstones display a coarse rhythmic interbedding. Internally, they are dominated by horizontal lamination and lenticular bedding, and dessication cracks are rare. Conspicuous gutter casts showing a preferred NE-SW orientation occur frequently along the sole of the green sandstone beds at most localities. The red sandstones and siltstones are similar; current and wave formed cross-lamination is much more abundant, however, and dessication cracks occur frequently. The features of the red sandstones and siltstones suggest deposition within the intertidal to supratidal zone, while the green sandstones and siltstones probably reflect deposition in intertidal to subtidal environments. The persistent orientation of the gutter casts, which is in accordance with the dominant flow direction in the underlying Jyske Ås Formation, suggests that the open sea was to the northeast. The stromatolitic dolostones in the upper part of the formation probably developed in shallow subtidal environments as a response to reduced clastic influx (Clemmensen & Jepsen, in press).

Furthest to the north-west within the outcrop of the Hagen Fjord Group, along the coasts of Independence Fjord, the Catalinafjeld Formation forms a possible lateral equivalent of the Campanuladal Formation (Figs 1, 3; Clemmensen & Jepsen, in press). On the northwestern side of Independence Fjord the Catalinafjeld Formation mainly consists of grey laminated mudstones with minor amounts of thin turbiditic sandstone beds. The mudstones show a distinct horizontal lamination consisting of alternating silty or fine-grained sandy and clayey laminae. Cross-lamination in the turbidites indicates palaeotransport directions towards the east. South of Independence Fjord the same lithologies are arranged in one, maybe two coarsening and thickening-upwards sequences. These sediments are considered to represent flooding and the establishment of deeper marine environments into the area (Clemmensen & Jepsen, in press).

The Kap Bernhard Formation rather abruptly overlies the Campanuladal Formation and marks the change from siliciclastic to carbonate deposition within the Hagen Fjord Basin. The formation consists of reddish-brown limestones with minor amounts of terrigenous silt associated with thin siliciclastic siltstone beds. In the lower part of the formation, soft sediment deformation structures are abundant, and intraformational breccias are locally conspicuous. Upwards the degree of soft sediment deformation decreases and intervals with horizontal lamination, wave ripples and small pockets with intraformational edge-wise breccias appear. Stromatolitic units up to 20 m thick occur locally in the upper part of the formation. These sediments were probably deposited in a subtidal lagoon and the rather sudden shift from siliciclastic shelf deposition to incipient carbonate platform deposition may relate to a climatic change towards more arid conditions (Clemmensen & Jepsen, in press).

Following the incipient platform deposits of the Kap Bernhard Formation, the Fyns Sø Formation records the establishment of a true carbonate platform (*sensu* Read, 1982). The formation consists of generally massive, yellow weathering dolostone which, in the upper part of the formation, is commonly interbedded with thin red or green terrigenous siltstones. Locally, however, sedimentary structures are preserved within the dolostones; these include slump structures, intraformational breccias and rare ripple marks. Stromatolitic horizons occur throughout the formation; they are especially common in the uppermost part where they locally form spectacular composite linked mounds with a relief of up to 2 m (Fig. 17; Clemmensen & Jepsen, in press). Conical columnar stromatolites ('conophyton') have also been reported from the formation (Adams & Cowie, 1953). These stromatolites were probably restricted to subtidal environments and often form the exclusive stromatolitic component in basinal and slope deposits; such stromatolite facies have been recognised as a transitional facies in incipient and terminally drowned platforms (Donaldson, 1976; Hoffman, 1976; Grotzinger, 1989). The co-occurrence of 'conophyton' and slumped horizons in the Fyns Sø Formation suggests subtidal deposition on the slope of a carbonate platform.

The last preserved phase in the evolution of the Hagen Fjord Basin is recorded by the Kap Holbæk Formation which marks the return to siliciclastic deposition and the resultant destruction of the earlier carbonate platform. The boundary between the Kap Holbæk Formation and the Fyns Sø Formation is well defined although not exposed in detail. The lowermost part of the Kap Holbæk Formation consists of a thin unit of variegated mudstones including thin sandstone beds while the remaining part comprises fine-grained to occasionally coarse-grained sandstones and associated mud-

Fig. 17. Composite linked stromatolite mounds of the Fyns Sø Formation in western Kronprins Christian Land.

stones. Glauconite is common in the upper part of the formation. The sandstones are internally massive or show trough cross-bedding, herringbone cross-bedding and rare wave-ripples. Locally the formation contains planar cross-bedded sets up to 8 m thick. *Skolithos*-like burrows occur at a few horizons. In the lower part of the formation, the lithologies apparently show random interbedding but one well developed coarsening-upwards sequence is present near the top of the formation. Apparently, the sediments of the Kap Holbæk Formation were deposited in shallow shelf to beach environments (Clemmensen & Jepsen, in press).

The Hagen Fjord Group, although still rather poorly known in detail, thus seems to record the establishment of a siliciclastic shelf that evolves into a carbonate platform; the demise of the carbonate platform coincides with the reappearance of siliciclastic sediments. The deep water deposits of the Rivieradal sandstone are probably in part equivalent to the lower part of the Hagen Fjord Group, although the precise relationship between these two successions remains to be fully established.

The planar unconformity between the Hagen Fjord Group and the overlying Lower Cambrian Portfjeld Formation marks a long hiatus around the Proterozoic-Cambrian boundary. During this period North Greenland was uplifted and peneplained before marine environments of the Franklinian Basin eventually transgressed the southern part of the shelf. The length of this hiatus is poorly constrained. Faunal evidence from the Portfjeld Formation suggests that the formation is of Early Cambrian (early Atdabanian?) age (J. S. Peel, personal communication, 1990) corresponding to an absolute age of *c.* 560 Ma (Harland *et al.*, 1989). The top of the Moræneso Formation/Hagen Fjord Group succession probably lies within the Ediacaran (570–550 Ma) which gives a hiatus of 10–30 Ma. However, in the northern part of the Franklinian shelf sedimentation started slightly earlier, since the Portfjeld Formation here is underlain by the Skagen Group of unknown, but probably earliest Cambrian age (Higgins *et al.*, 1991).

Late Proterozoic correlations in North Greenland

The stratigraphic relationship between the geographically separated outcrops of the glacially influenced sediments of the Moræneso Formation and the mainly shallow marine deposits of the Hagen Fjord Group is still uncertain, principally on account of the poor constraints on the age of the Hagen Fjord Group and its constituent formations.

The age of the Hagen Fjord Group can in part be assessed from acritarch assemblages from the upper part of the underlying Rivieradal sandstones at Centrum Sø; these suggest a general Sturtian to Vendian age (*c.* 800–570 Ma; G. Vidal *in* Hurst *et al.*, 1985). However, the youngest strata of the group (Kap Holbæk Formation) contain Proterozoic acritarchs (Peel & Vidal, 1988) and *Skolithos*-like burrows which together indicate an age not older than latest Proterozoic (late Vendian, Ediacaran; Crimes, 1987; Narbonne & Myrow, 1988). Thus, the Moræneso Formation diamictites,

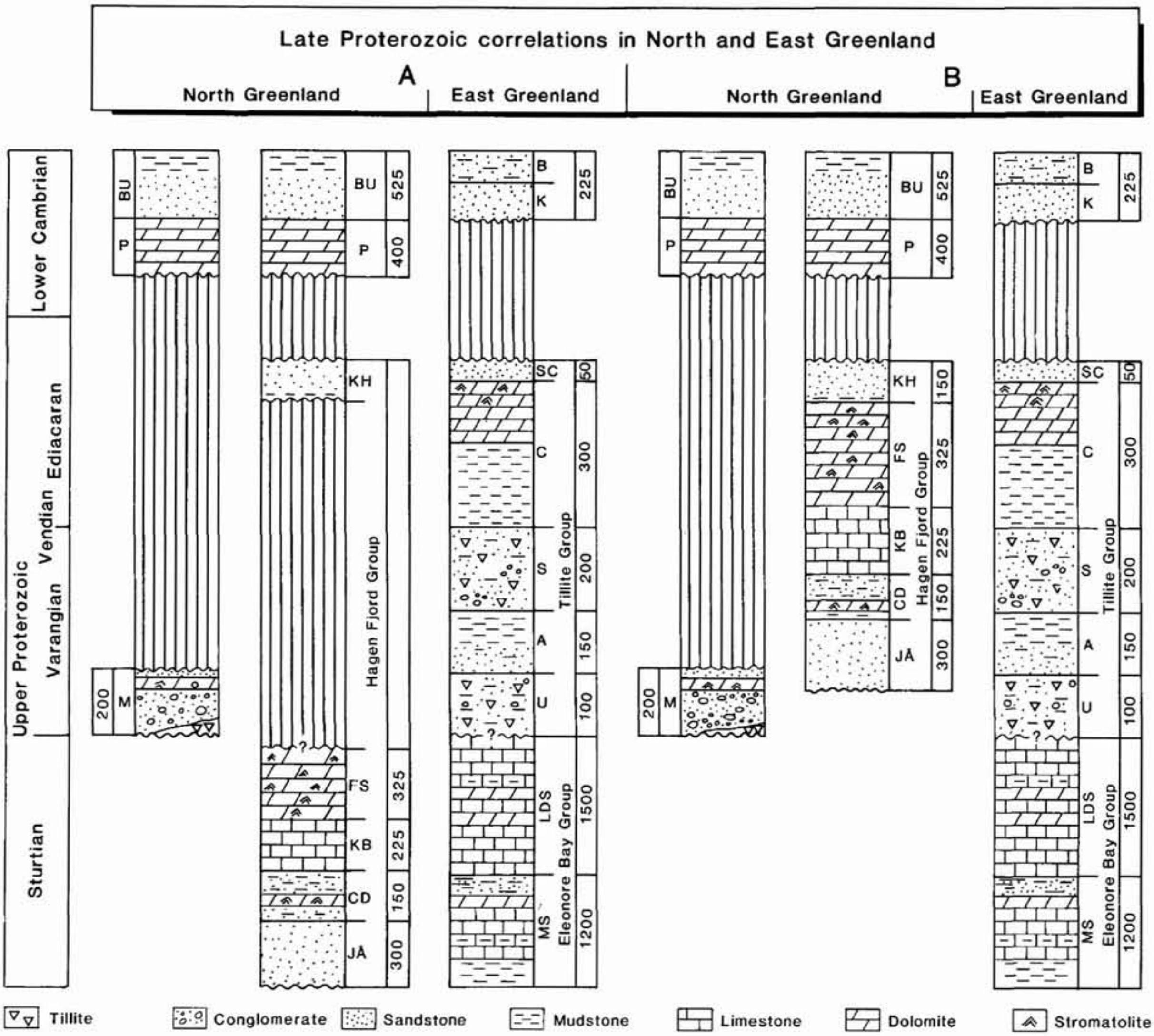


Fig. 18. Possible Late Proterozoic correlations in North and East Greenland. Abbreviations denote formations unless otherwise mentioned. A, Arena; B, Bastion; BU, Buen; C, Canyon; CD, Campanuladal; FS, Fyns Sø; JÅ, Jyske Ås; K, Kløftelv; KB, Kap Bernhard; KH, Kap Holbæk; LDS, Limestone-Dolomite 'series'; M, Moræneso; MS, Multicoloured 'series'; P, Portfjeld; S, Storeelv; SC, Spiral Creek; U, Ulvesø. Generalised thicknesses of individual units are indicated in metres.

if associated with the early Vendian (Varangian) glaciation, must be older than at least the Kap Holbæk Formation. As no signs of glacially related deposits have been found within the Hagen Fjord Group, the glacial diamictites of the Morænesø Formation therefore are likely to be either older than the entire Hagen Fjord Group or to be associated with an as yet unrecognised hiatus within the group, resulting in two possible stratigraphic schemes for the Late Proterozic of North Greenland (Fig. 18).

Correlation A outlined in Fig. 18 suggests a hiatus between the Fyns Sø and Kap Holbæk Formations. This hiatus is mainly based upon an occurrence in the Morænesø Formation of a stromatolitic dolomite clast very like the Fyns Sø Formation (J. D. Collinson, personal communication, 1990). Furthermore, similarities in the lithological evolution of the Eleonore Bay Group of East Greenland (cf. Henriksen & Higgins, 1976) and the Hagen Fjord Group (apart from the Kap Holbæk Formation), which both show a change from siliciclastic to carbonate deposition, may suggest that these two groups of Late Proterozoic strata are partly coeval. The Eleonore Bay Group is overlain by the Vendian Tillite Group (Hambrey & Spencer, 1987), and Hambrey &

Harland (1981) have suggested that the tillitic formations of Varangian age in the lower part of the Tillite Group correlate with the Moræneso Formation in North Greenland. This correlation suggests that the main part of the Hagen Fjord Group is older than Varangian, and the acceptance of an Ediacaran age for the Kap Holbæk Formation thus necessitates an interpreted hiatus between the Fyns Sø and the Kap Holbæk Formations covering at least the Varangian Epoch (approximately 20 Ma; Harland *et al.*, 1989).

The boundary between the Fyns Sø and Kap Holbæk Formations has only been described from the type locality of the Fyns Sø Formation where it is a 1.5 m thick covered interval (Clemmensen & Jepsen, in press). A hiatus at this level had been suggested earlier by Cowie (1961, p. 29 ff.), mainly based on observations by Fränkl (1955, p. 18 ff.) and from aerial reconnaissance by John Haller. Haller, however, apparently misidentified the carbonate-sandstone sequence now assigned to the Portfjeld and Buen Formations of Cambrian age, as the Proterozoic Fyns Sø and Kap Holbæk Formations.

The sub-Kap Holbæk Formation hiatus described by Fränkl (1955) was observed at a single locality within one of the nappe structures at Sæfaxi Elv in southern Kronprins Christian Land. At this locality a 1–5 m thick sandstone unit, which contains rafts of dolomite up to 1.5 m thick with 'karst-like' upper relief and a slightly erosive base, was correlated with the Kap Holbæk Formation (Fränkl, 1955, p. 18). The general stratigraphy at the locality at Sæfaxi Elv is very uncertain, however (see discussion in Peel & Smith, 1988, p. 20), and the correlation was dismissed by Hurst *et al.* (1985). Fränkl (1955, p. 20) himself noted the similarity of this sandstone to a quartzitic fissure-fill found at a similar stratigraphic level west of Sæfaxi Elv, and quartzitic cave and fissure-fills of Pliocene to Pleistocene age are known from many other localities in eastern North Greenland including Kap Holbæk (Loubière, 1987; J. S. Peel, personal communication, 1990).

Thus, an equally valid interpretation is that the Hagen Fjord Group as a whole postdates the tillites of the Moræneso Formation (B in Fig. 18). The Hagen Fjord Group succession may therefore be correlated in terms of lithostratigraphy with the upper (i.e. post-diamictite) part of the Tillite Group of East Greenland. The change from predominantly siliciclastic to carbonate deposition seen in the Hagen Fjord Group is also observed within the Canyon Formation in the upper part of the Tillite Group (Fairchild & Herrington, 1989; Fairchild, 1989). The basal part of the overlying Spiral Creek Formation (Fairchild & Herrington, 1989) consists of tidal sand flat deposits comparable to the Kap Holbæk Formation (Fig. 18). If this correlation is correct, the incursion of possible marine environments in the upper part of the Moræneso Formation and the onlap of the Hagen Fjord Group may both be related to a glacio-eustatic transgression following the Varangian glaciation.

In a similar manner to the need for a better understanding of the tectono-stratigraphic relationship between the shelf sequence of the Hagen Fjord Group and the deep-water Rivieradal sandstones, the solution of this problem of correlation between the Moræneso Formation and the Hagen Fjord Group must await further field work in eastern North Greenland.

Acknowledgements. Lars B. Clemmensen, John D. Collinson, Peter R. Dawes, Jon R. Ineson, Feiko Kalsbeek, John S. Peel and Finn Surlyk are thanked for critically reading the manuscript and for giving many valuable comments and suggestions for its improvement. Jette Halskov, Jakob Lautrup and Bente Thomas are thanked for technical assistance.

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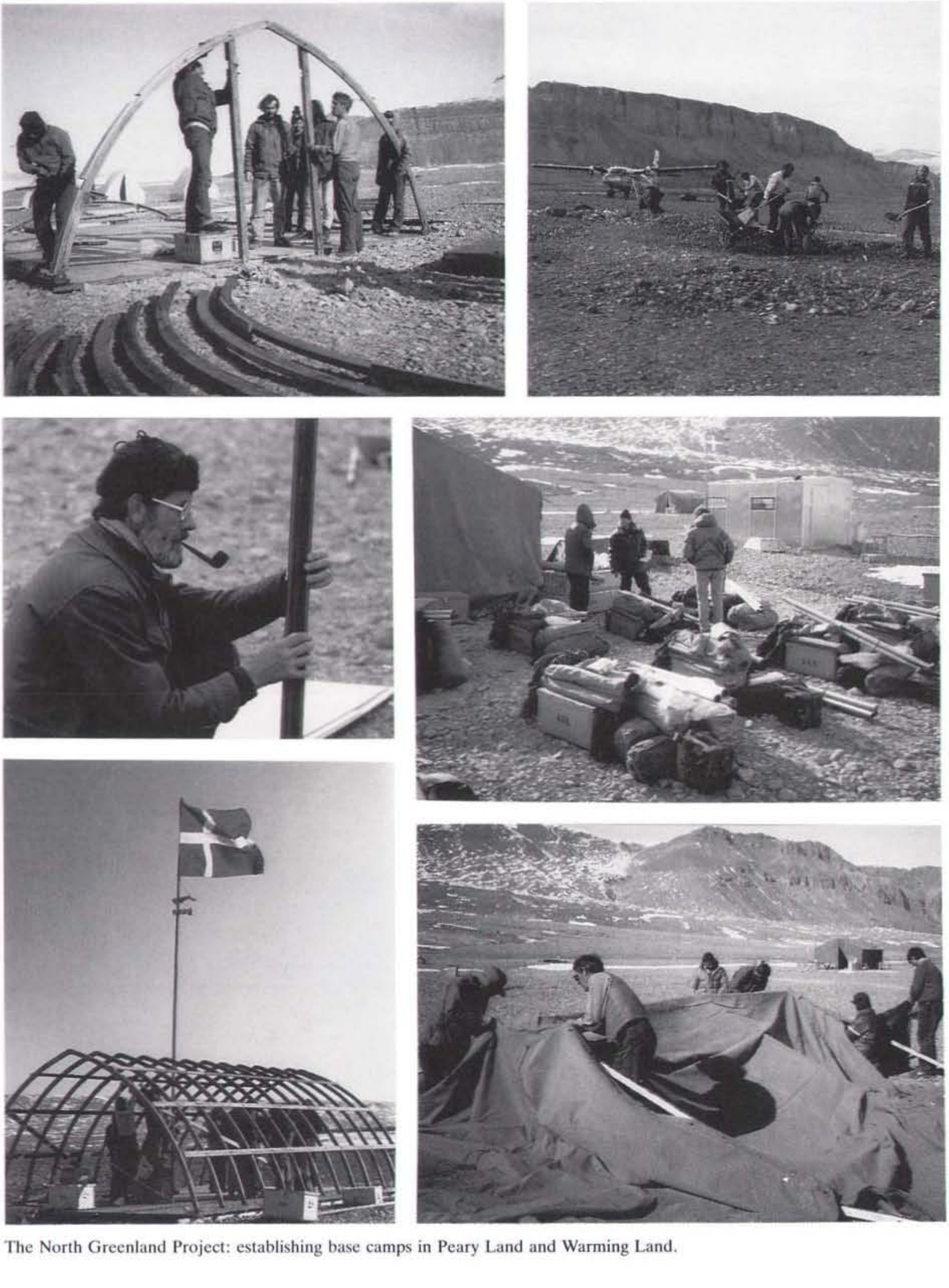

The North Greenland Project: establishing base camps in Peary Land and Warming Land.

Lower Palaeozoic Franklinian Basin of North Greenland

A. K. Higgins, Jon R. Ineson, John S. Peel, Finn Surlyk and Martin Sønderholm

The Franklinian Basin extends from the Canadian Arctic Islands to eastern North Greenland, a distance of approximately 2000 km. In the North Greenland segment about 8 km of Lower Palaeozoic strata are well exposed and permit the recognition of 7 stages in the evolution of the basin. With the exception of the first stage of basin initiation, which occurred close to the Precambrian-Cambrian boundary, each stage is differentiated into a southern shelf and slope, and a northern deep-water trough. The position of the boundary between the shelf and trough was probably controlled by deep seated normal faults and, with time, the basin expanded southwards leading to a final foundering of the shelf areas during the Silurian.

The 7 stages in the evolution of the Franklinian Basin in North Greenland are: 1, Late Proterozoic? – Early Cambrian shelf (basin initiation); 2, Early Cambrian carbonate platform and incipient trough; 3, Early Cambrian siliciclastic shelf and turbidite trough; 4, Late Early Cambrian – Middle Ordovician carbonate shelf and starved trough; 5, Middle Ordovician – Early Silurian aggradational carbonate platform, starved slope and trough; 6, Early Silurian ramp and rimmed shelf, and turbidite trough; 7, Early – Late Silurian drowning of the platform.

Basin evolution and sedimentation patterns in the eastern part of the Franklinian Basin were strongly influenced by the closure of the Iapetus Ocean and Caledonian orogenic uplift in eastern North Greenland. The Franklinian Basin in North Greenland was finally closed in Devonian – Early Carboniferous times, resulting in strong deformation of the northern part of the Franklinian trough sequence during the Ellesmerian Orogeny.

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Lower Palaeozoic strata exposed across North Greenland from Kronprins Christian Land in the east to Washington Land and Inglefield Land in the west (Figs 1–4 and Map 1) form the eastern part of the Franklinian Basin of the Canadian Arctic Islands (cf. Trettin, 1989). Strata assigned to this succession in North Greenland outcrop in an east-west belt almost 1000 km long, with a maximum preserved north-south width of about 200 km; the sedimentary column attains a thickness of about 8 km. The main part of the succession is of Cambrian-Silurian age, but the basin probably also contains strata of latest Precambrian and earliest Devonian age.

The Franklinian Basin in North Greenland contains a southern shelf succession and a northern deep-water trough succession, also recognised in adjacent Ellesmere Island. Indeed, variations in facies with time show close parallels in the two regions such that lithostratigraphic correlation is often possible across Nares Strait (Troelsen, 1950; Peel & Christie, 1982; Peel *et al.*, 1982).

A craton composed of Precambrian crystalline basement rocks overlain by late Precambrian sedimentary and volcanic rocks lies to the south of the Franklinian Basin (Sønderholm & Jepsen, 1991). This is now exposed along the margin of the Inland Ice, and more extensively in eastern North Greenland (Fig. 1). During Early Palaeozoic time this craton was fringed to the north by an east-west trending shallow-marine shelf. Two main facies belts characterise the shelf, a shallow-water carbonate-dominated platform (*sensu* Schlager,

Bull. Grønlands geol. Unders. 160, 71–139 (1991)

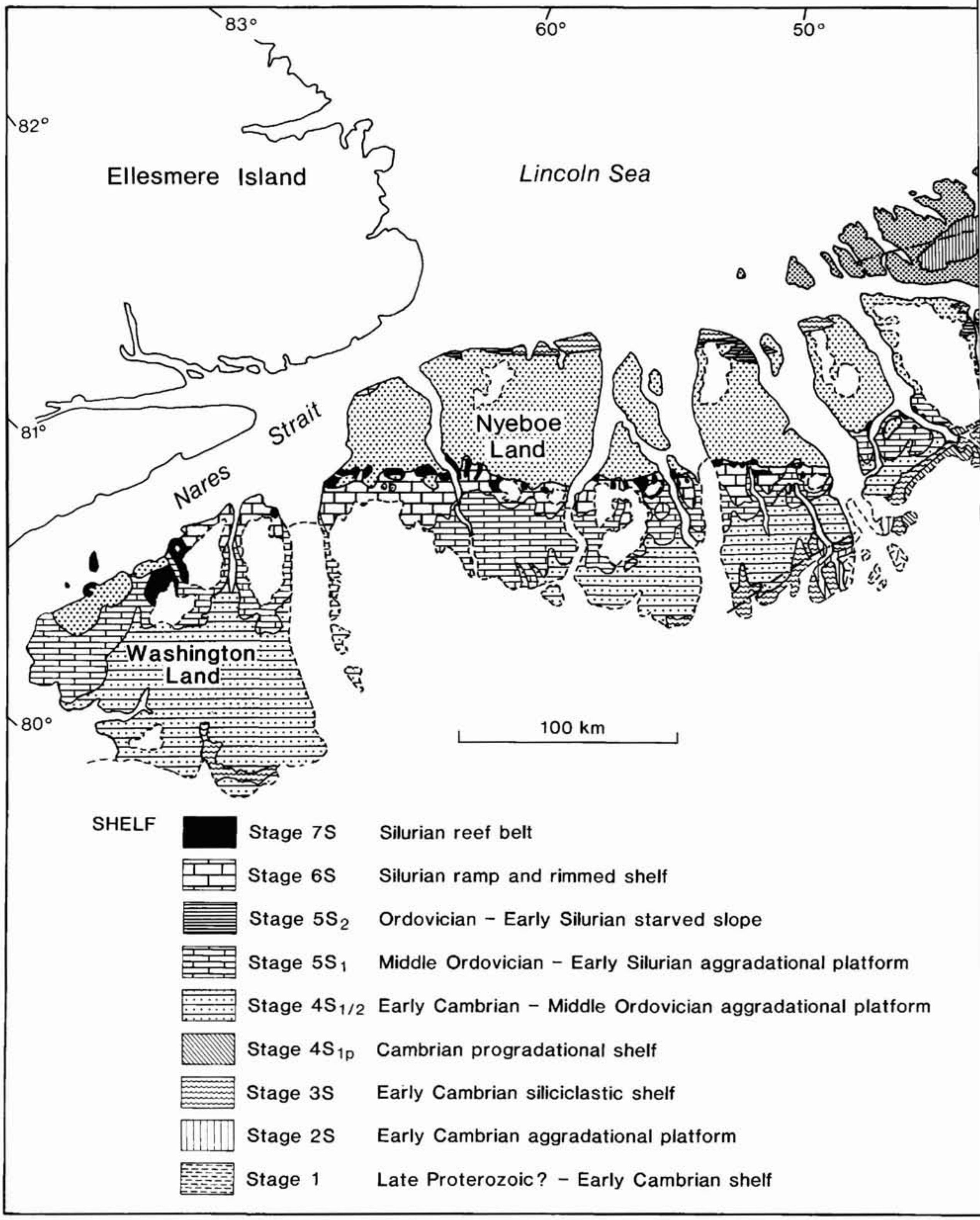
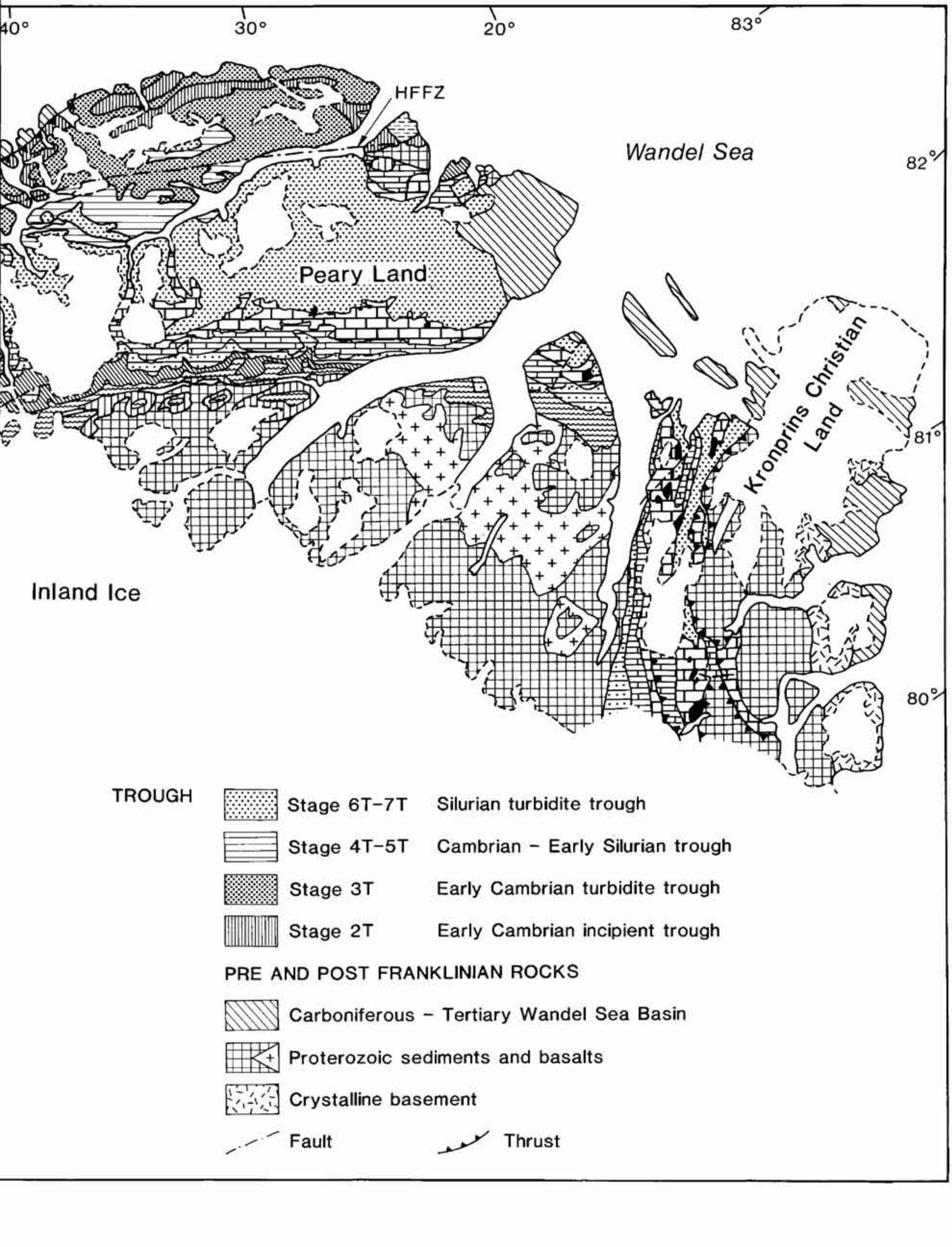
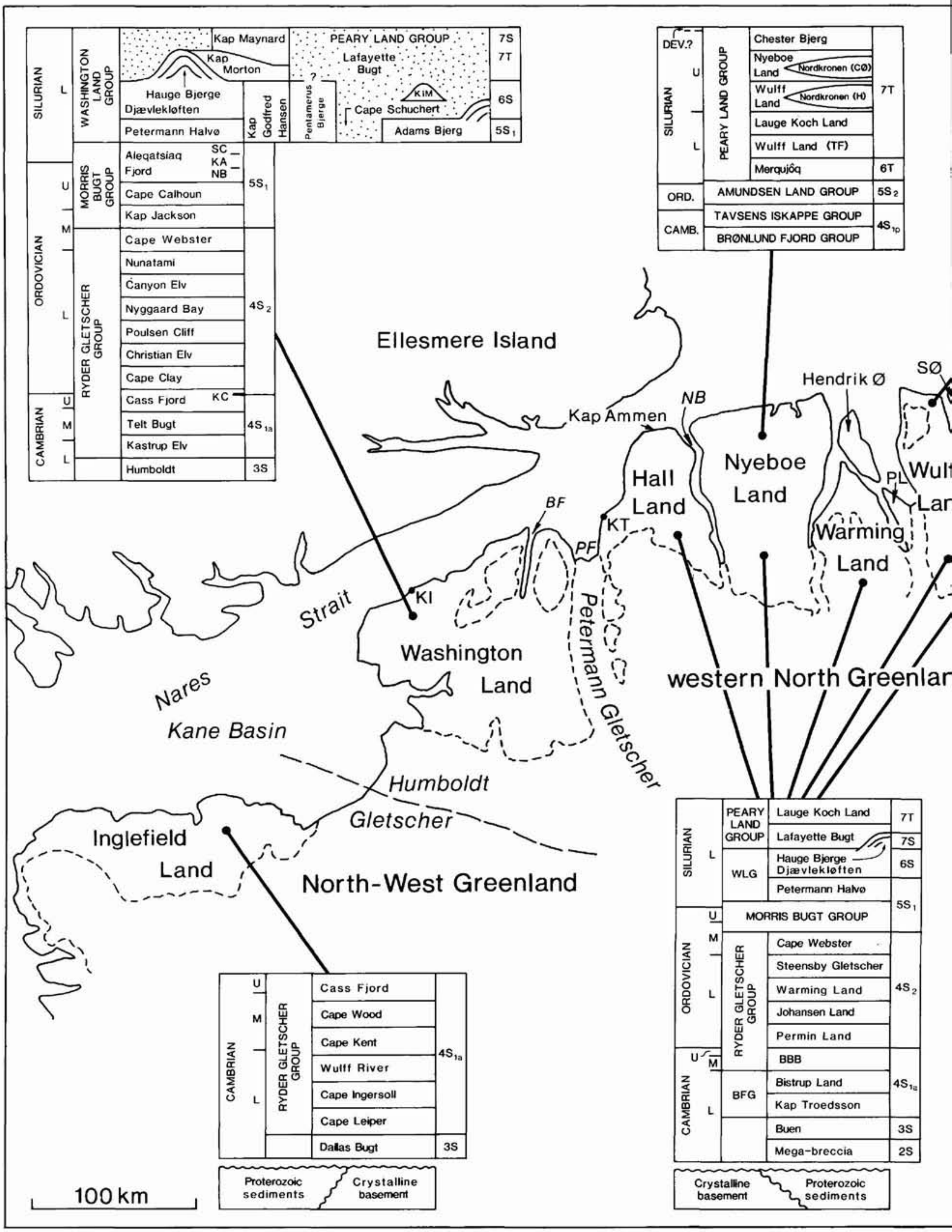


Fig. 1. Geological map showing the subdivision of the Franklinian Basin sequence in North Greenland. See Figs 2–4 and Map 1. HFFZ, Harder Fjord fault zone.


40°
30°
20°
83°
HFFZ
Wandel Sea
82°
Peary Land
Kronprins Christian Land
81°
Inland Ice
80°
TROUGH
Stage 6T–7T Silurian turbidite trough
Stage 4T–5T Cambrian – Early Silurian trough
Stage 3T Early Cambrian turbidite trough
Stage 2T Early Cambrian incipient trough
PRE AND POST FRANKLINIAN ROCKS
Carboniferous – Tertiary Wandel Sea Basin
Proterozoic sediments and basalts
Crystalline basement
Fault
Thrust


SILURIAN
L
WASHINGTON LAND GROUP
Kap Maynard
Kap Morton
Hauge Bjerge
Djævlekløften
Petermann Halvø
Kap Godfred Hansen
Pentamerus Bjerge
PEARY LAND GROUP
Lafayette Bugt
KIM
Cape Schuchert
Adams Bjerg
7S
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6S
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Aleqatsiaq Fjord
SC
KA
NB
Cape Calhoun
Kap Jackson
RYDER GLETSCHER GROUP
Cape Webster
Nunatami
Canyon Elv
Nyggaard Bay
Poulsen Cliff
Christian Elv
Cape Clay
Cass Fjord
KC
Telt Bugt
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Humboldt
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Chester Bjerg
Nyeboe Land
Nordkronen (CØ)
Wulff Land
Nordkronen (H)
Lauge Koch Land
Wulff Land (TF)
Merqujôq
7T
6T
ORD.
AMUNDSEN LAND GROUP
$5S_2$
CAMB.
TAVSENS ISKAPPE GROUP
BRØNLUND FJORD GROUP
$4S_{1b}$
Ellesmere Island
Hendrik Ø
SØ
NB
Kap Ammen
Nyeboe Land
Hall Land
PL
Wulf
Lan
BF
KT
PF
Warming Land
KI
Strait
Washington Land
Petermann Gletscher
western North Greenlan
Nares
Kane Basin
Humboldt Gletscher
Inglefield Land
North-West Greenland
CAMBRIAN
U
M
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RYDER GLETSCHER GROUP
Cass Fjord
Cape Wood
Cape Kent
Wulff River
Cape Ingersoll
Cape Leiper
Dallas Bugt
$4S_{1a}$
3S
Proterozoic sediments
Crystalline basement
100 km
SILURIAN
L
PEARY LAND GROUP
Lauge Koch Land
Lafayette Bugt
WLG
Hauge Bjerge
Djævlekløften
Petermann Halvø
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Steensby Gletscher
Warming Land
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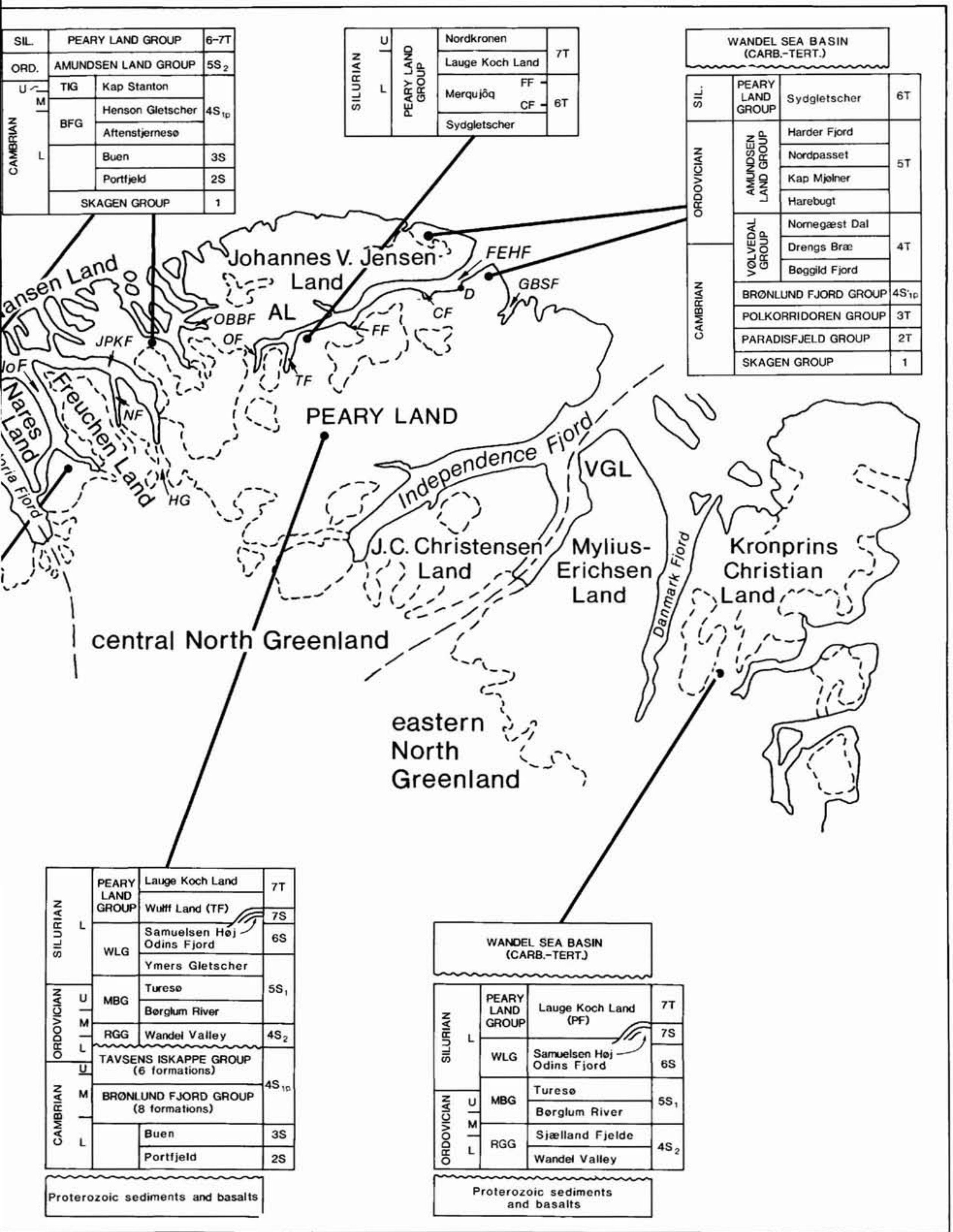
Crystalline basement
Proterozoic sediments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Nordkronen
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WANDEL SEA BASIN
(CARB.-TERT.)
SIL.
PEARY LAND GROUP
Sydgletscher
6T
ORDOVICIAN
AMUNDSEN LAND GROUP
Harder Fjord
Nordpasset
Kap Mjølner
Harebugt
5T
VØLVEDAL GROUP
Nornegæst Dal
Drengs Bræ
Bøggild Fjord
4T
CAMBRIAN
BRØNLUND FJORD GROUP
4S1p
POLKORRIDOREN GROUP
3T
PARADISFJELD GROUP
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Johannes V. Jensen Land
FEHF
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Nares Land
Freuchen Land
PEARY LAND
Independence Fjord
VGL
J.C. Christensen Land
Mylius-Erichsen Land
Danmark Fjord
Kronprins Christian Land
central North Greenland
eastern North Greenland
SILURIAN
L
PEARY LAND GROUP
Lauge Koch Land
7T
Wulff Land (TF)
7S
WLG
Samuelsen Høj
Odins Fjord
6S
Ymers Gletscher
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Turesø
Børglum River
5S1
RGG
Wandel Valley
4S2
CAMBRIAN
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TAVSENS ISKAPPE GROUP
(6 formations)
BRØNLUND FJORD GROUP
(8 formations)
4S1p
Buen
3S
Portfjeld
2S
Proterozoic sediments and basalts
WANDEL SEA BASIN
(CARB.-TERT.)
SILURIAN
L
PEARY LAND GROUP
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Børglum River
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Wandel Valley
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Proterozoic sediments
and basalts

1981), and a shale-dominated shelf. The boundary between these two regimes fluctuated considerably; in some periods the platform was almost drowned, while in others the platform prograded and the platform margin coincided with the shelf-slope break. A deep-water basin, or trough, characterised by deposition of fine-grained sediments, sand turbidites, and carbonate conglomerates was situated north of this zone. Shelf-parallel turbidite transport directions suggest that the deep-water basin was two-sided for most of its existence (Surlyk *et al.*, 1980; Surlyk & Hurst, 1984); for this reason the term trough is used in the following description. There is no direct evidence in North Greenland, however, of a northern margin to the Franklinian Basin.

Deposition in the trough was brought to a close in North Greenland, as in northern Ellesmere Island, by the mid-Palaeozoic Ellesmerian Orogeny. In Greenland this produced the North Greenland fold belt. Deformation is largely confined to the trough succession, and was intense in the extreme north where it was accompanied by low amphibolite facies metamorphism. Deformation decreases southwards, and dies out in a belt of thrusts and monoclines located slightly north of the early Silurian shelf-trough transition.

Due to the remoteness of North Greenland much geological work until recent years has been on a reconnaissance level. Dawes (1971, 1976) has summarised this early work, producing a geological map and synthesis of North Greenland geology. Other reviews are given by Troelsen (1949, 1950), Dawes & Soper (1973), Dawes & Peel (1981), Dawes & Christie (1982), Peel (1982a) and Christie & Dawes (in press; see also Henriksen & Higgins, 1991).

In 1978–80 and 1984–85 regional systematic mapping and general geological investigations were carried out as part of the North Greenland Project of the Geological Survey of Greenland (GGU; see Henriksen & Higgins, 1991). The current paper presents a synthesis of the Lower Palaeozoic sedimentary succession in North Greenland, examination of which culminated with the North Greenland Project. An earlier version was given by Higgins *et al.*, in press.

Lower Palaeozoic shelf stratigraphy in North Greenland (Fig. 2) has been described by Christie & Peel (1977), Fortey & Peel, 1989; Hurst (1980a, 1984), Ineson & Peel (1987, in prep.), Peel (1982a, 1985, 1988a, b, 1990), Peel *et al.* (1981), Peel & Smith, 1988; Smith *et al.*, 1989; Sønderholm & Due (1985); Sønderholm *et al.* (1987) and Sønderholm & Harland (in prep.).

The lithostratigraphy of the Lower Palaeozoic deep-water succession has been outlined within a framework of six groups by Friderichsen *et al.*, (1982; Fig. 2). Preliminary descriptions of the Cambrian and Ordovician deposits are given by Bengaard *et al.* (1987), Davis & Higgins (1987), Higgins *et al.* (1981), Soper *et al.* (1980) and Surlyk & Ineson (1987a). The stratigraphy of the Cambrian-Ordovician deep-water sequence in Peary Land was established by Surlyk *et al.* (in prep.), while Silurian deep-water stratigraphy was described by Hurst (1980a), Hurst & Surlyk (1982), Larsen & Escher (1985, 1987, 1991) and Surlyk & Ineson (1987b).

Biostratigraphical and palaeontological studies of the Lower Palaeozoic in North Greenland include: Armstrong (1990), Bjerreskov (1981, 1986, 1989), Conway Morris & Peel (1990), Fortey & Peel (1983, 1989, 1990), Grahn & Nøhr-Hansen (1989), Lane (1972, 1979), McLean (1977), Nøhr-Hansen & Koppelhus (1988), Norford (1973), Palmer & Peel (1981), Peel (1979, 1980, 1982b, 1986, 1988a, b, 1990), C. Poulsen (1927, 1934, 1941, 1943, 1958, 1974), V. Poulsen (1964, 1969, 1974), Robison (1984, 1988), Smith (in press) and Troedsson (1926, 1928).

The petroleum geology of the Franklinian Basin in North Greenland is described by Christiansen (1989, 1990).

The main aspects of the tectonic-sedimentological evolution of the Early Palaeozoic shelf sequence in North Greenland were described by Hurst & Surlyk (1983b). The evolution of the contemporaneous deep-water basin has been related to intrabasinal tectonic lineaments which govern, or influence, the boundaries of the shelf, slope, and trough of the basin at different times (Surlyk & Hurst, 1983, 1984; Figs 3–5).

Fig. 2. Stratigraphy of the Franklinian Basin sequence in North Greenland. Individual units are assigned to the stages in basin evolution described in the text; see also Figs 1, 3, 4. AL, Amundsen Land; BBB, Blåfjeld, Brikkerne and Blue Cliffs Formations; BF, Bessels Fjord; BFG, Brønlund Fjord Group; CF, Citronen Fjord, also Citronens Fjord Member; CØ, Castle Ø Member; D, Depotbugt; FEHF, Frederick E. Hyde Fjord; FF, Freja Fjord, also Freja Fjord Member; GBSF, G. B. Schley Fjord; HG, Henson Gletscher; H, Hendrik Ø Member; JPKF, J. P. Koch Fjord; KA, Kap Ammen Member; KC, Kap Coppinger Member; KI, Kap Independence; KIM, Kap Independence Member; KT, Kap Tyson; MBG, Morris Bugt Group; NB, Newman Bugt, also Newman Bugt Member; NF, Navarana Fjord; NoF, Nordenskiöld Fjord; OBBF, O. B. Bøggild Fjord; OF, Odin Fjord; PF, Profilfjeldet Member; PL, Permin Land; RGG, Ryder Gletscher Group; SC, Store Canyon Member; SØ, Stephenson Ø; TF, Thor Fjord, also Thors Fjord Member; VGL, Valdemar Glückstadt Land; WLG, Washington Land Group.

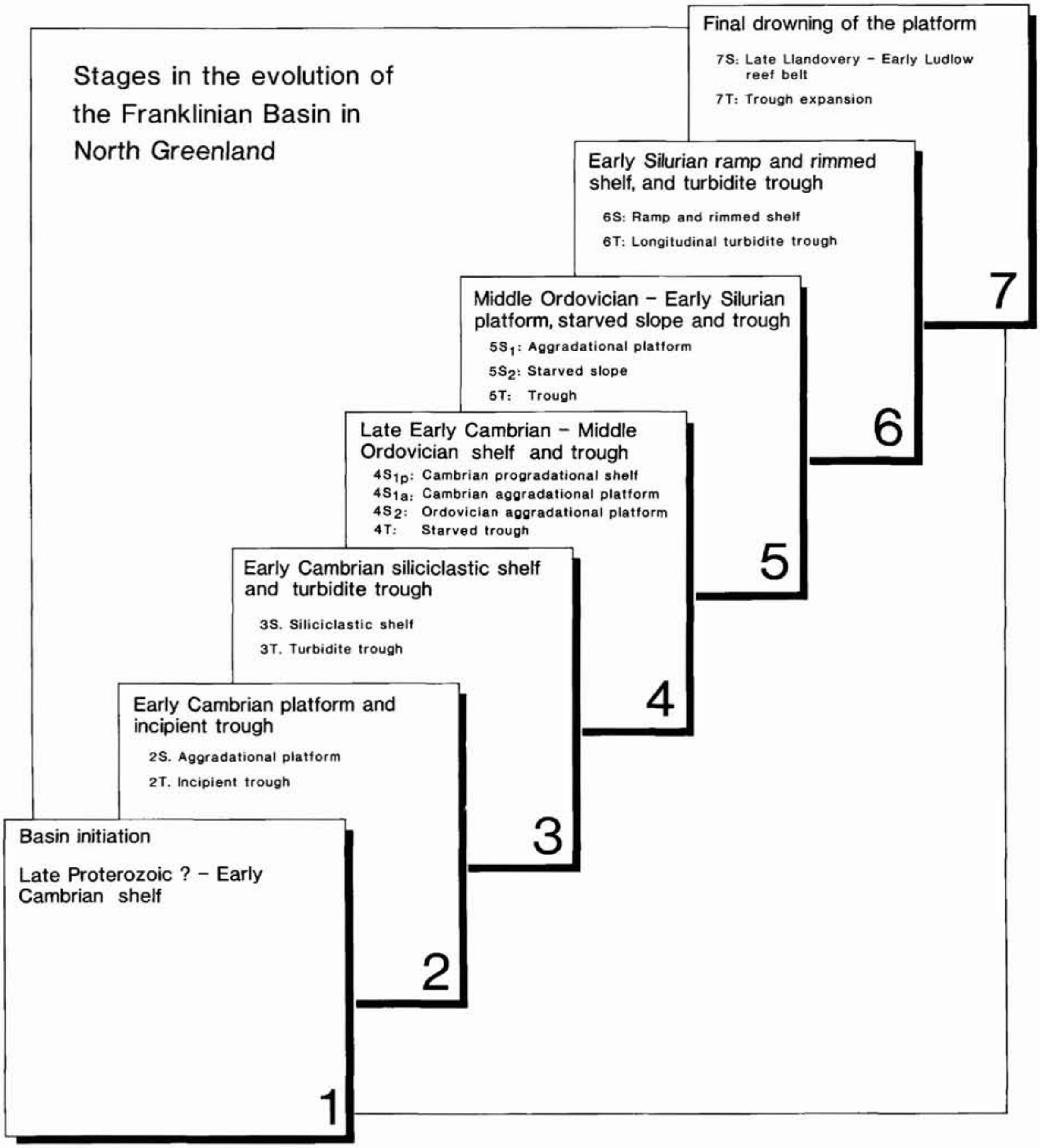
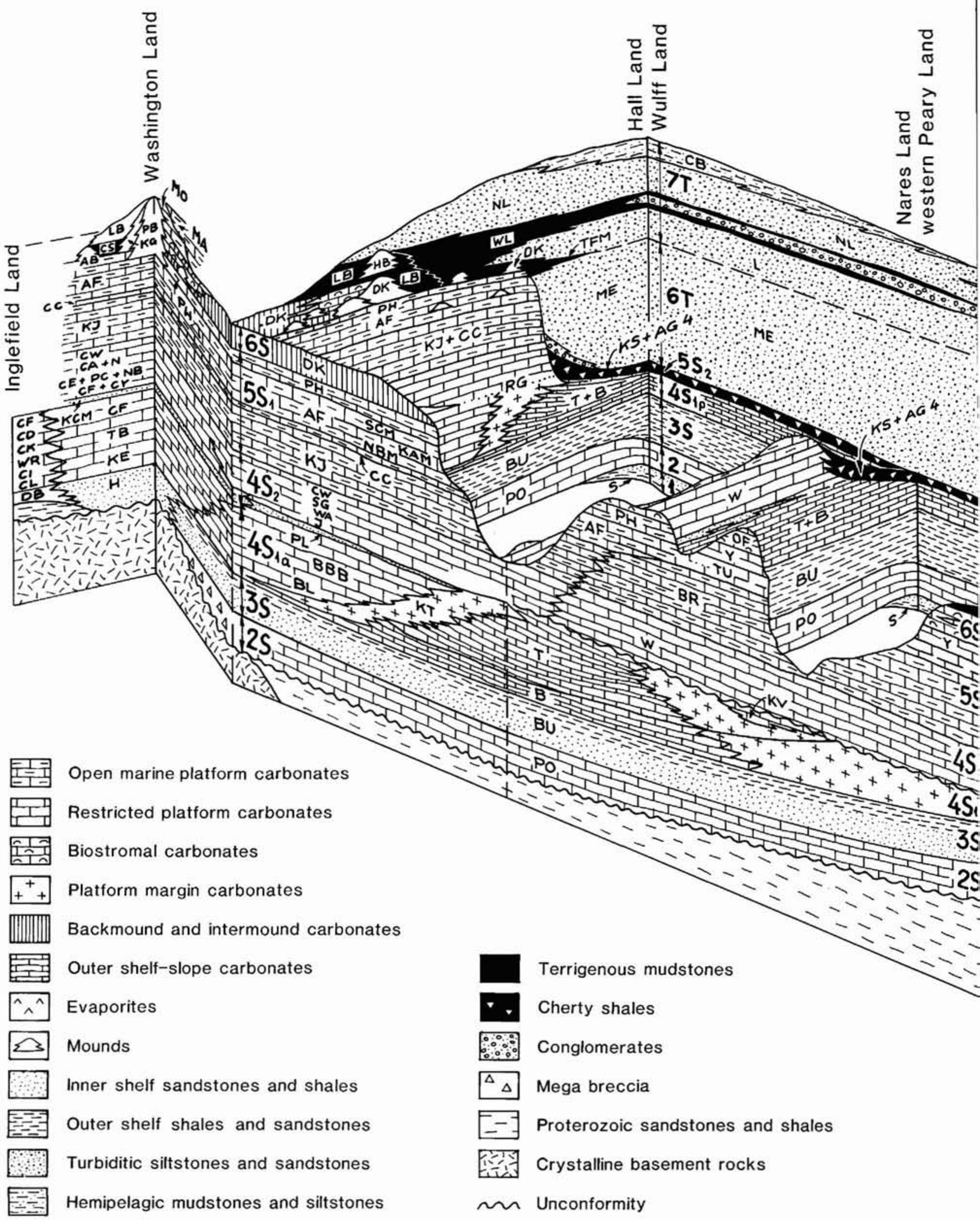


Fig. 3. Stages in the evolution of the Franklinian Basin in North Greenland.

Tectonic lineaments

The evolution of the North Greenland Early Palaeozoic basin and its differentiation into a southern shelf and a northern trough was interpreted in terms of control by tectonic lineaments by Surlyk *et al.* (1980), a model elaborated and presented in more detail by Surlyk & Hurst (1983, 1984). It is envisaged that the basin expanded in several episodes by southward shift of the southern margin to new E-W trending lineaments. The shifts are accompanied by major changes in sedimentary regimes. This concept is adopted here, permitting the recognition of a number of stages in the evolution of the basin (Figs 3–5). These stages form the basis for the


Inglefield Land
Washington Land
Hall Land
Wulff Land
Nares Land
western Peary Land
7T
6T
6S
5S₁
5S₂
4S₂
4S₁a
4S₁p
3S
2S
Open marine platform carbonates
Restricted platform carbonates
Biostromal carbonates
Platform margin carbonates
Backmound and intermound carbonates
Outer shelf-slope carbonates
Evaporites
Mounds
Inner shelf sandstones and shales
Outer shelf shales and sandstones
Turbiditic siltstones and sandstones
Hemipelagic mudstones and siltstones
Terrigenous mudstones
Cherty shales
Conglomerates
Mega breccia
Proterozoic sandstones and shales
Crystalline basement rocks
Unconformity

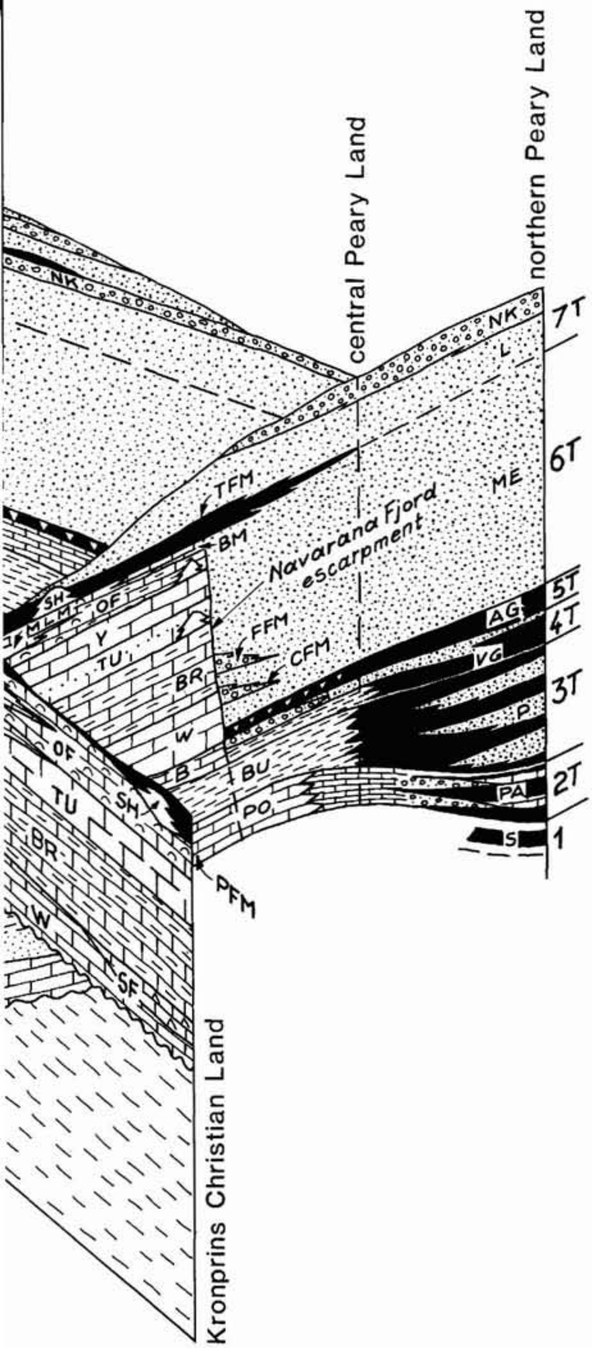


Fig. 4. Fence diagram showing the interpreted relationships of shelf, slope and trough deposits of the various stages in the evolution of the Franklinian Basin sequence of North Greenland (see Figs 1–3). Abbreviations denote formations unless otherwise specified. AB, Adams Bjerg; AF, Aleqatsiaq Fjord; AG, Amundsen Land Group; AG4, unit 4 of Amundsen Land Group; B, Brønlund Fjord Group; BBB, Blåfjeld, Brikkerne and Blue Cliffs Formations; BL, Bistrup Land; BM, Bure Iskappe Member; BR, Børglum River; BU, Buen; CA, Canyon Elv; CB, Chester Bjerg; CC, Cape Calhoun; CD, Cape Wood; CE, Christian Elv; CF, Cass Fjord; CFM, Citronens Fjord Member; CI, Cape Ingersoll; CK, Cape Kent; CL, Cape Leiper; CS, Cape Schuchert; CW, Cape Webster; CY, Cape Clay; DB, Dallas Bugt; DK Djævlekløften; FFM, Freja Fjord Member; H, Humboldt; HB, Hauge Bjerge; J, Johansen Land; KAM, Kap Ammen Member; KCM, Kap Coppinger Member; KE, Kastrup Elv; KG, Kap Godfred Hansen; KJ, Kap Jackson; KS, Kap Stanton; KT, Kap Troedsson; KV, Koch Væg; L, Lauge Koch Land; LB, Lafayette Bugt; MA, Kap Maynard; ME, Merqujôq; MLM, Melville Land Member; MO, Kap Morton; N, Nunatami; NB, Nygaard Bay; NBM, Newman Bugt Member; NK, Nordkronen; NL, Nyeboe Land; OF, Odins Fjord; OI, Offley Island; P, Polkorridoren Group; PA, Paradisfjeld Group; PB, Pentamerus Bjerge; PC, Poulsen Cliff; PFM, Profilfjeldet Member; PH, Petermann Halvø; PL, Permin Land; PO, Portfjeld; RG, Ryder Gletscher Group; S, Skagen Group; SCM, Store Canyon Member; SF, Sjælland Fjelde; SG, Steensby Gletscher; SH, Samuelsen Høj; T, Tavsens Iskappe Group; TB, Telt Bugt; TFM, Thors Fjord Member; TU, Turesø; VG, Vølvedal Group; WA, Warming Land; W, Wandel Valley; WL, Wulff Land; WR, Wulff River; Y, Ymers Gletscher.

integrated description of shelf and trough successions presented in this paper.

Some of the lineaments responsible for control of sedimentation during the Early Palaeozoic are easily defined. The identity of others, however, is not clear, since some of the structures have been shown to be main elements of Ellesmerian thin-skinned thrust zones or Eurekan (Tertiary) fault systems. These later thrusts and faults may have had precursors which were active in the Early Palaeozoic and influenced sedimentation.

The earliest stage of the Franklinian Basin recognised in North Greenland (Skagen Group) is loosely dated as Late Precambrian – Early Cambrian and its base is not known. Later in the Early Cambrian it is possible to define a facies boundary between the shelf carbonates of the Portfjeld Formation and the equivalent trough carbonates of the Paradisfjeld Group (Figs 2–5). This boundary runs from Depotbugt in the east, westwards to outer J. P. Koch Fjord and along the northern coast of Greenland as far as northern Nyeboe Land (Figs 3–5, stage 2). However, the original position of this linea-

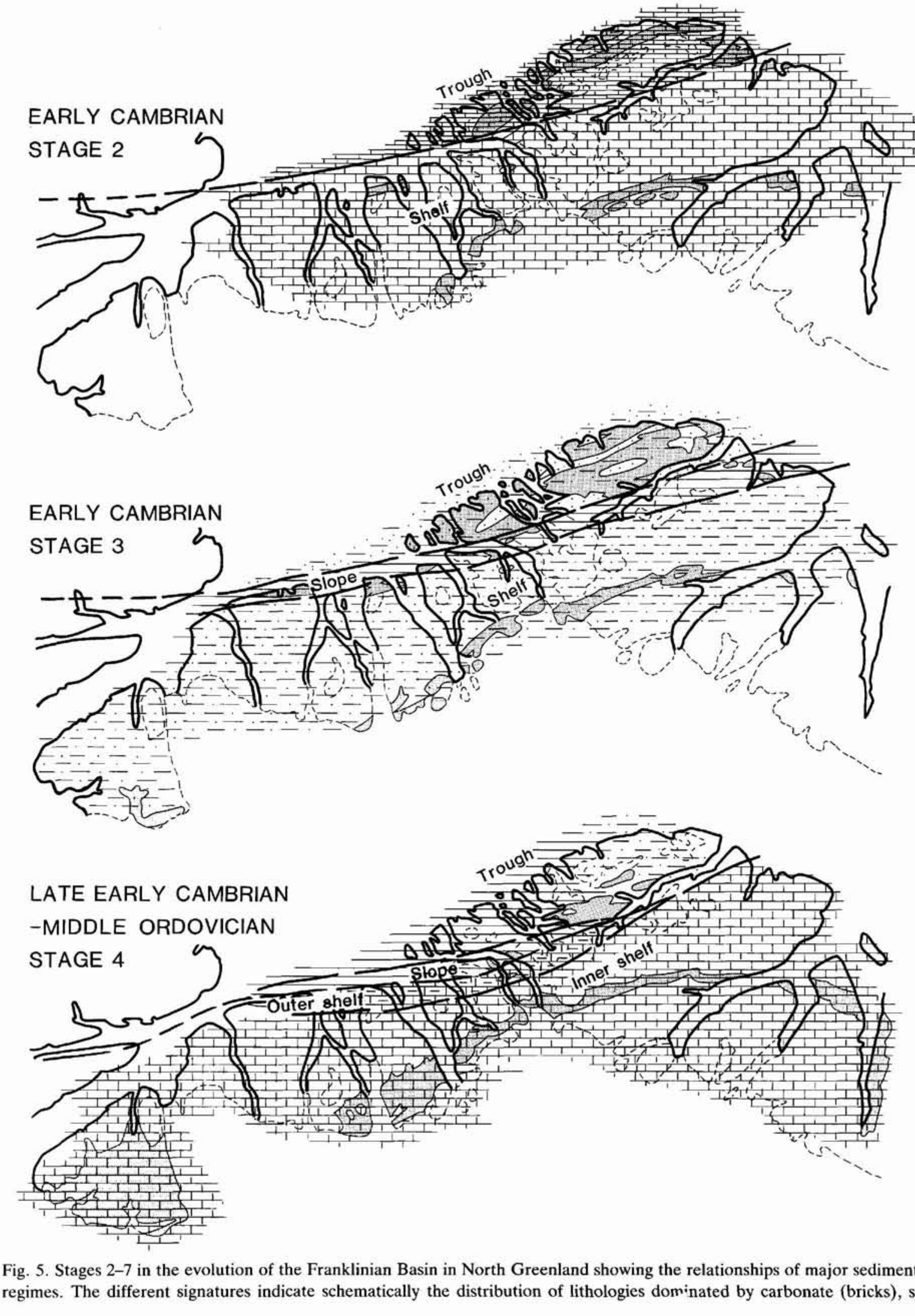
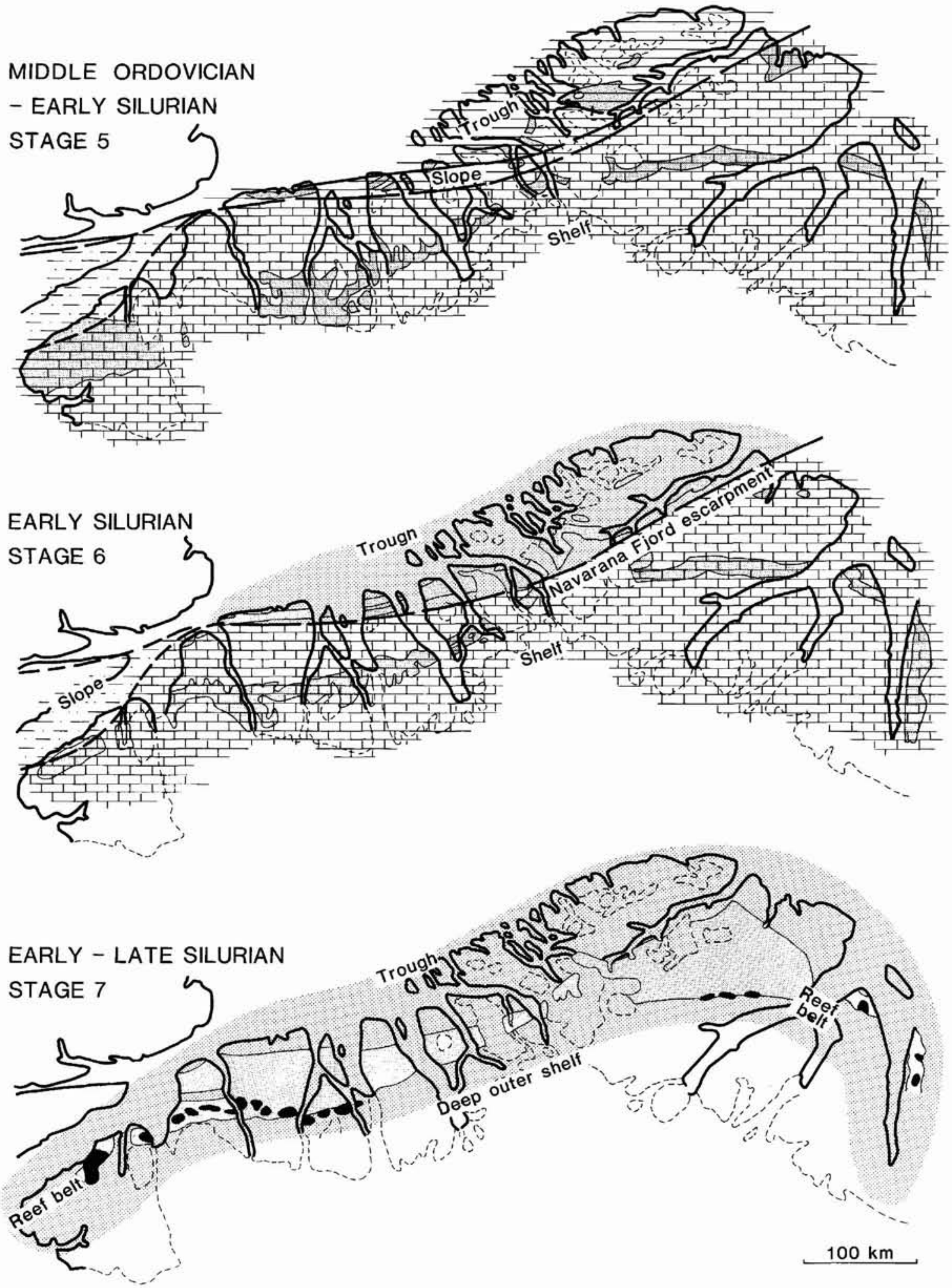


Fig. 5. Stages 2–7 in the evolution of the Franklinian Basin in North Greenland showing the relationships of major sedimentary regimes. The different signatures indicate schematically the distribution of lithologies dominated by carbonate (bricks), sand



(dots) and mud (horizontal lines). Dense dotting indicates present day exposures. The position of the Navarana Fjord escarpment is shown in stage 6.

ment is obscured by the N-S shortening due to Ellesmerian thrusting; it may have been sited farther north, corresponding to a precursor of the present Harder Fjord fault zone (Surlyk *et al.*, 1980; Surlyk & Hurst, 1984; Soper & Higgins, 1987). The present distribution of succeeding deposits of the Buen Formation (shelf sandstones and shales) and Polkorridoren Group (trough turbidites) suggests that the shelf margin was located slightly further south (Fig. 5, stage 3); in logged sections deeper water, more offshore facies overlie shallow shelf facies. The original position of the shelf margin lineament, however, is again obscured by Ellesmerian thrusting.

Carbonate platform accumulation resumed on the inner shelf in the late Early Cambrian and continued through the Ordovician, while shale deposition dominated in the outer shelf-slope area which can be characterised as 'starved'. In some areas the total succession deposited on the outer shelf and slope during this period is less than 100 m thick; 300–500 m is more normal. The trough deposits, up to 1200 m thick, are only known from northern Peary Land (Johannes V. Jensen Land) where they include thickly developed turbiditic units of the Vølvedal Group. Two lineaments seem to have determined the boundaries between shelf and trough deposition during this period. The northernmost of these, running from Depotbugt to Nyeboe Land, may have marked the north margin of the shelf during the first part of this period (Fig. 5, stage 4). The turbidites of the Vølvedal Group occur only north of this line. The southern lineament is the Navarana Fjord lineament which is expressed as a platform margin escarpment in the Navarana Fjord – J. P. Koch Fjord area (Figs 4–5, Escher & Larsen, 1987; Surlyk & Hurst, 1984; Surlyk & Ineson, 1987 a, b). It extends eastwards to the vicinity of Depotbugt and westwards beneath younger rocks to northern Nyeboe Land and just offshore Hall Land. Carbonate-dominated outer shelf sediments accumulated in the area between the two lineaments during the early part of the period (Fig. 5, stage 4), but these are overlain by deeper water slope or trough sediments (Amundsen Land Group and equivalent chert/shale deposits) suggesting that the basin margin had retreated southwards in the Ordovician to the Navarana Fjord lineament (Fig. 5, stage 5).

In the Late Ordovician and Early Silurian the Navarana Fjord lineament was a major basinal and facies boundary separating shelf carbonate deposition to the south from turbidite deposition of the Peary Land Group to the north (Fig. 5, stage 6). The lineament took the form of a pronounced escarpment and the lowest formations of the turbiditic Peary Land Group (Sydgletscher and Merqujôq Formations) occur only north of the escarpment. In late Llandovery time, the outer platform foundered, probably in response to loading of the trough by the thick turbidite sequences and to orogenic activity in eastern North Greenland. The trough filled to the brim with turbidites and expanded southwards to cover most of what is now North Greenland (Fig. 5, stage 7) (Hurst & Surlyk, 1982; Hurst *et al.*, 1983; Surlyk & Hurst, 1984). A new shelf-trough boundary was established farther to the south, corresponding to the line of impressive carbonate mounds running from central Hall Land to Kronprins Christian Land. The shelf was almost totally drowned at about the Llandovery-Wenlock boundary and carbonate deposition only persisted in a few isolated mounds. The succession of formations in the Peary Land Group – Wulff Land Formation (mudstones), Lafayette Bugt Formation (mudstones and carbonate conglomerates), Lauge Koch Land Formation (sandstone turbidites), Nordkronen Formation (mainly turbiditic chert pebble conglomerates) and Chester Bjerg Formation (turbiditic mudstones and siltstones) – reflect facies variations governed by the supply of detritus to the deep-water trough from the source areas in the east, principally the rising mountains of the East Greenland Caledonides (Hurst *et al.*, 1983; Surlyk, 1982; Surlyk & Hurst, 1984).

Evolution of the Franklinian Basin in North Greenland

The development of the Franklinian Basin in North Greenland is described here in terms of 7 stages (Figs 3–5) which are defined on the basis of sedimentary infill, position and structural style of the shelf-trough boundary (cf. Surlyk & Hurst, 1983, 1984). The stages are broadly analogous to seismic stratigraphic sequences (Mitchum *et al.*, 1977; Vail *et al.*, 1977; Van Wagoner *et al.*, 1988) or to groups of temporally related depositional systems (e.g. Galloway & Hobday, 1983). The stages are described below in ascending order; in each stage description of the shelf development is followed by description of the equivalent slope and deep-water trough development.

Stage 1: Basin initiation, Late Proterozoic? – Early Cambrian shelf

The oldest representative of the Early Palaeozoic sedimentary cycle is the Skagen Group (Figs 1–4, 6–7). It is recognised in north-east Peary Land, Johannes V. Jensen Land and in northern parts of central and western North Greenland, notably northern Wulff Land (Fig. 6). The base of the group is not seen although stratigraphic relationships in north-east Peary Land suggest that it may rest unconformably on Proterozoic quartzites and volcanics (Christie & Ineson, 1979). In its northern outcrop in Johannes V. Jensen Land, the Skagen Group is overlain by relatively deep-water carbonates of the Paradisfjeld Group (see stage 2, below) whereas south of Frederick E. Hyde Fjord and in central and western North Greenland, it is overlain by platform carbonates of the Portfjeld Formation. The age of the Skagen Group is uncertain, but an Early Cambrian (Atdabanian) fauna has been collected from the Kennedy Channel Formation of Ellesmere Island (Long, 1989a) from strata considered by Dawes & Peel (1984) to be equivalent to the Skagen Group of northern Wulff Land.

In its type area in north-east Peary Land the Skagen Group consists of tightly folded quartzitic sandstones and mudstones divided into three units by Friderichsen *et al.* (1982); the depositional environment is not known, but upper beds of the succession in the G. B. Schley Fjord area include stromatolitic and dessication-cracked dolomites of peritidal origin. The lowest unit comprises structureless quartzitic sandstones, the middle unit dark phyllitic mudstones, and the upper unit consists of thick-bedded quartzitic sandstones with phyllitic mudstone interbeds and rare pebble conglomerates. The upper unit is also exposed on the north side of the mouth of Frederick E. Hyde Fjord where it has a conformable, but highly deformed, contact with the overlying Paradisfjeld Group.

Higgins & Soper (1985) suggested similarities between the Skagen Group and the siliciclastic sequence which underlies the Portfjeld Formation between northern Wulff Land and J. P. Koch Fjord. This sequence is included in the Skagen Group (Surlyk & Ineson, 1987a). In northern Wulff Land, where deformation is less intense, the Skagen Group consists of over 500 m of mudstones, sandstones and dolomites. The lower half of the group is dominated by mudstones with thin, cross-laminated, fine-grained to medium-grained sandstones. Sandstone bed thickness increases upwards and hummocky cross-stratification becomes more common towards the middle of the group. This lower interval records sedimentation on an offshore, storm-influenced shelf. It is succeeded by a more varied sequence of coarse pebbly sandstones, hummocky cross-stratified sandstones, mudstones and intraclastic oolitic dolomites, reflecting shallow-water, inshore environments. The coarse sandstones show large-scale trough cross-bedding and parallel, even lamination of storm-dominated shoreface and possibly beach origin. Grey, hummocky cross-stratified oolitic-intraclastic dolomites

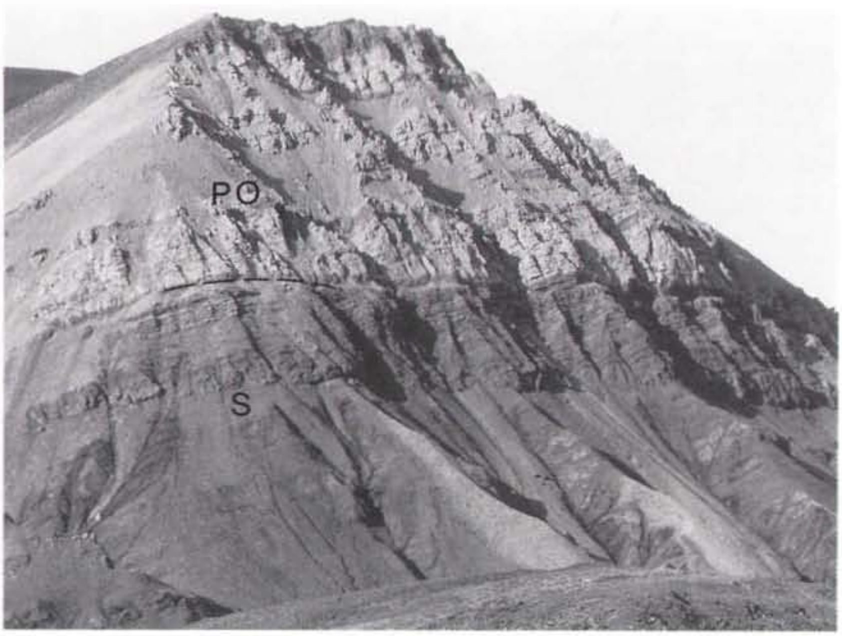


Fig. 6. Mudstones, sandstones and dolomites of the Skagen Group (S, stage 1) overlain by a 340 m thick sequence of light coloured Portfjeld Formation dolomites (PO, stage 2S), northern Wulff Land.

Fig. 7. Hummocky cross-stratified dolomites forming the top part of the Skagen Group (stage 1). Northern Wulff Land.

dominate in the upper 100 m of the group (Figs 6, 7) and grade up into massive pale dolomites of the Portfjeld Formation (see stage 2 below).

The Skagen Group probably represents the earliest phase in the development of the Franklinian Basin in North Greenland. It records the initial subsidence and transgression of Proterozoic basement to produce a storm-dominated shelf that was restricted to the northernmost parts of North Greenland. The succession reflects an overall shallowing and the first differentiation of the shelf into a carbonate platform and a mainly siliciclastic storm influenced shelf leading to the development of a stable carbonate platform represented by the Portfjeld Formation (stage 2S) (Surlyk & Ineson, 1987a).

Stage 2: Early Cambrian platform and incipient trough

The transition from the first to the second stage in basin evolution is marked by the change from mainly siliciclastic to carbonate sediments, and by a clear differentiation into shelf and deeper water trough environments (Figs 3–5, stage 2).

This stage in the evolution of the region is represented by the Portfjeld Formation on the shelf and the Paradisfjeld Group in the trough (Figs 1–4).

2S: Aggradational platform

The Portfjeld Formation crops out across central North Greenland but is not known to the west of Wulff Land or to the east of Danmark Fjord. In its northern outcrop it conformably overlies the shelf sediments of the Skagen Group (Fig. 6); farther south it rests unconformably on Proterozoic strata (Figs 2, 8). The formation is poorly fossiliferous but has yielded remains of cyanobacteria of probable Early Cambrian age (Peel, 1988c).

The Portfjeld Formation is 200–280 m thick in southern Peary Land (O'Connor, 1979) and typically comprises cross-bedded oolitic and intraclastic dolomites, flat-pebble conglomerates, wave-rippled silty dolomites and algally laminated dolomites displaying planar, crinkly, domal, digitate and columnar stromatolites. Dark grey, bituminous, cherty dolomites form a distinctive, laterally persistent unit (10–15 m thick) near the base of the formation in this area. Oncolitic and pisolitic dolomites are present at some levels, and desiccation cracks and irregular, brecciated palaeokarst surfaces occur locally. The latter are sometimes associated with breccias containing well-rounded quartz grains in a dolomitic matrix. Together with intervals of well-rounded, medium to coarse-grained sandstones, they probably represent periods of regression and local emergence (Hurst & Surlyk, 1983b). The association of facies suggests deposition in shallow subtidal and intertidal environments on a marine carbonate platform. Ooid and intraclast grainstones were deposited on subaqueous carbonate sand banks in shallow turbulent water while fetid and algally laminated carbonate muds and silts accumulated in protected shallow subtidal and low to moderate-energy intertidal environments.

The Portfjeld Formation thickens appreciably towards the north. In north-east Peary Land it is 400–700 m thick (Christie & Ineson, 1979); in the north-west

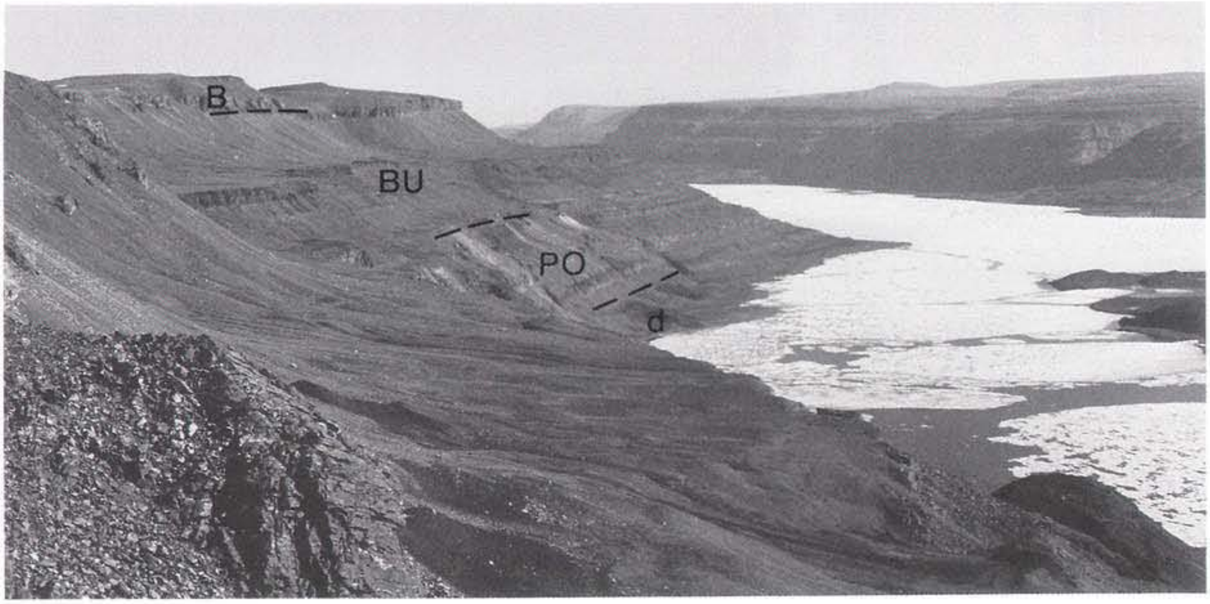


Fig. 8. Stable platform dolomites about 200 m thick of the Portfjeld Formation (PO, stage 2S) unconformably overlying Proterozoic red sandstones with dark weathering dolerite intrusions (d), looking eastward along Øvre Midsommersø, southern Peary Land. Succeeding siliciclastic sediments of the Buen Formation (BU, stage 3S) can be divided into a lower, inshore, sandstone unit and an upper unit of outer shelf mudstones and siltstones. The cliff is capped by carbonates of the Brønlund Fjord Group (B, stage $4S_{1p}$).

Peary Land region the formation thickens dramatically northwards over less than 20 km from 260 m at Navarana Fjord (Fig. 9) to 500–700 m east of J. P. Koch Fjord. In these northern exposures the formation is composed almost entirely of dolomitised ooid-intraclast grainstones, locally showing hummocky cross-stratification, with rare intervals of columnar and hemispherical stromatolites and oncolitic grainstones. This thickened succession of high energy carbonates in the north clearly represents the outer rim of the platform which accreted rapidly in response to greater subsidence adjacent to the platform/trough boundary. The thickness difference and the occurrence of mixed carbonate-siliciclastic deposits in the upper part of the underlying Skagen Group

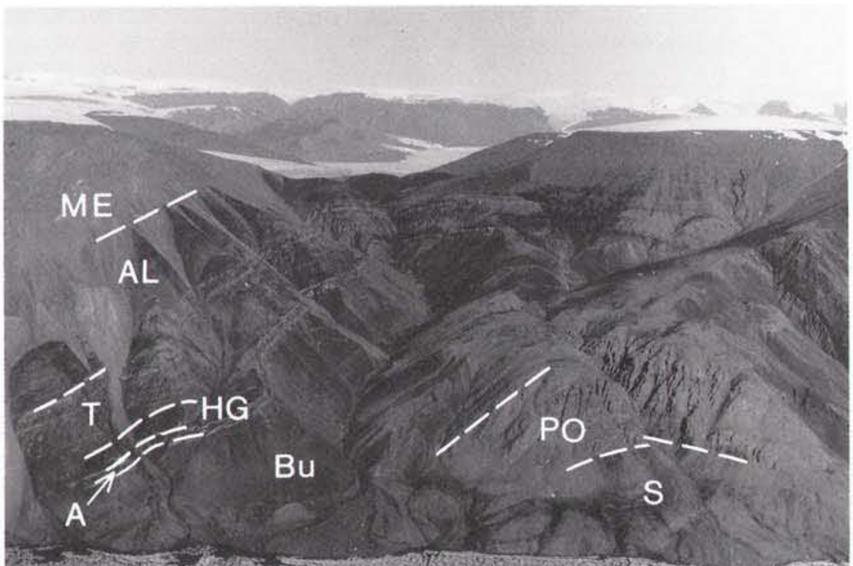


Fig. 9. Navarana Fjord anticline on the eastern side of Navarana Fjord, exposing Skagen Group (S, stage 1) in the core, overlain by Portfjeld Formation dolomites (PO, stage 2S), dark coloured sandstones and shales of the Buen Formation (BU, stage 3S), and outer shelf representatives of the Aftenstjernesø Formation (A), Henson Gletscher Formation (HG) of the Brønlund Fjord Group, and Tavsens Iskappe Group (T), (all stage $4S_{1p}$). The uppermost dark unit comprises dark cherts and cherty shales of a new formation of the Amundsen Land Group (AL, stage 5T) and is overlain by turbiditic sandstones of the Merqujôq Formation (ME, stage 6T). Plateau icecap is 1100 m high.

further south may suggest that deposition of Portfjeld Formation carbonates was initiated in the outer shelf while the inner shelf still received terrigenous sand and mud (Surlyk & Ineson, 1987a). Farther north, the Portfjeld Formation is replaced by the carbonate dominated, relatively deep-water Paradisfjeld Group (see below).

The Portfjeld Formation is overlain by siliciclastic sediments of the Buen Formation without angular discordance (Fig. 8). The contact is sharp and upper levels of the Portfjeld Formation in several areas are brecciated and stained red (Davis & Higgins, 1987); clasts of Portfjeld Formation are locally incorporated into the base of the Buen Formation (O'Connor, 1979). It is likely that this contact records subaerial exposure and the resulting demise of much of the carbonate platform; siliciclastic sedimentation was established following renewed submergence of the platform (see stage 3, below).

The Portfjeld Formation can be readily correlated with the Ella Bay Formation of Ellesmere Island to which it shows striking similarities in both facies and evolution (Peel & Christie, 1982; Long, 1989b). The local unconformity between the Ella Bay Formation and overlying siliciclastic sediments was interpreted by Long (1989b) as a breakup unconformity.

An important event along the southern outcrop margin of the Franklinian Basin in western North Greenland is reflected by the occurrence of a remarkable mega-breccia around the head of Victoria Fjord (Surlyk & Ineson, 1987a). This unit varies from 85–270 m in thickness and was essentially formed by the collapse, break-up and mass transport of the entire Portfjeld Formation (Fig. 10). It rests upon an irregular topography of crystalline basement or thin remnants of the Upper Proterozoic Moræneso Formation; it is itself overlain by undisturbed sandstones and mudstones of the Buen Formation. The breccia consists mainly of blocks and large slabs of various types of dolomite and cherty dolomite of the Portfjeld Formation, together with large clasts of quartzite, gneissic basement rocks and red siltstone, set in a carbonate matrix containing abundant, very well rounded quartz grains. Clasts are angular and very poorly sorted. The largest slabs are more than 100 m long and may be tens of metres thick; they are mainly subhorizontal but show all degrees of deformation, from weak bending and doming to strong folding, faulting and shearing. Slabs may have sharp boundaries or they may pass both upwards and laterally into progressively more deformed strata and eventually into disorganised matrix-supported conglomerate.

In spite of the ubiquitous occurrence of folded and tilted slabs, directional phenomena are not immediately obvious in the field. However, measurements of fold axes and the general southerly dip of slab surfaces suggest a transport direction approximately toward the north.

It is envisaged that violent earthquake activity associated with faults along the southern hinge line of the Franklinian Basin in North Greenland shattered and mobilised Proterozoic sediments and the already partly lithified and probably karstified Portfjeld Formation, generating a mega-debris flow which moved down-slope to the north. Neither the geographic location nor the geological origin of the presumed faults are known. However, a major fault zone postdating all Lower Palaeozoic strata and with downthrow generally to the south extends ENE-WSW from eastern Peary Land, crossing Henson Gletscher, the head of Jungersen Gletscher, the land area south of Nares Land and southern Wulff Land to Ryder Gletscher (see Fig. 58 in Christiansen, 1989; Map 1). This fault lies just to the north of most outcrops of the mega-breccia, but may indicate an older zone of structurally weakness possibly associated with generation of the breccia. The geometry of the mega-breccia and its relationship to undisturbed Portfjeld Formation are likewise uncertain; undisturbed Portfjeld Formation is known as far west as Nordenskiöld Fjord, with isolated outcrops in fold cores in northern Freuchen Land and northern Wulff Land. The mega-breccia extends north-eastward to the central part of the land area south of Nares Land, some 15 km north-east of a zone of large-scale deformation, with upright folds of high amplitude, which may represent a major ruck near the down-slope termination of the debris sheet.

2T: Incipient trough

The Paradisfjeld Group (Friderichsen *et al.,* 1982), a sequence of calcareous mudstones, dolomites and conglomerates at least 1 km thick, is the deep-water equivalent of the Portfjeld Formation (Surlyk *et al.,* 1980). This group is widely exposed in Johannes V. Jensen Land and Nansen Land (Figs 1–5, Map 1), where it is strongly deformed and outcrops generally in anticlinal fold cores. Along strike from east to west there are few facies changes, whereas more marked variations occur from south to north. The group is probably entirely of Early Cambrian age, although fossils (*Chancelloria* and inarticulate brachiopods) are only known from the upper part (Peel & Higgins, 1980). A two fold division can be recognised in most of the region of outcrop (Fig. 11): a thick, lower unit of dark grey, uniform, carbonate rocks, and a thinner upper unit of light coloured, more varied carbonate lithologies (Friderichsen *et al.,* 1982). Preliminary descriptions of the group were given by

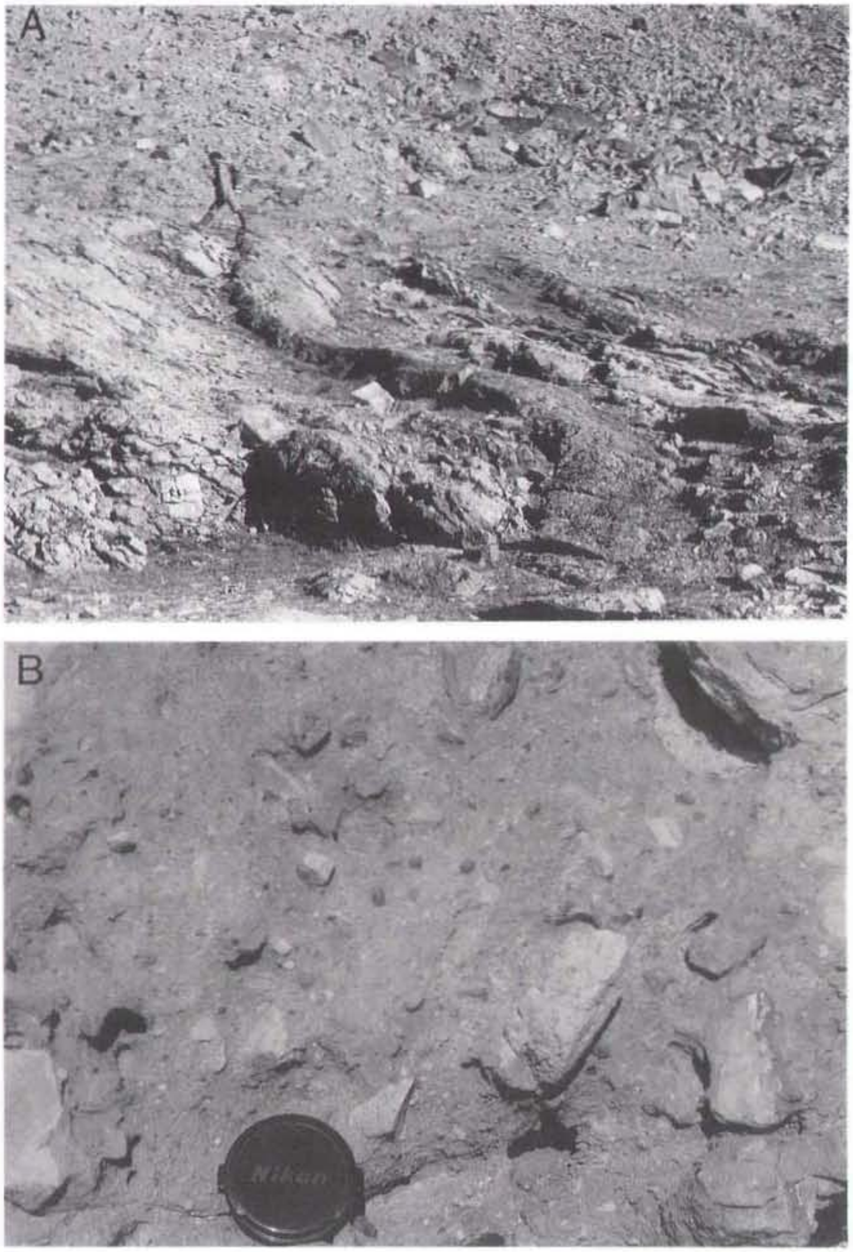


Fig. 10. A, large bent and folded slabs of dolomite derived from the Portfjeld Formation (stage 2S). Southern Wulff Land. Note figure for scale. B, disorganised matrix supported conglomerate, which itself forms the matrix between the large slabs shown in A.

Dawes & Soper (1973), Friderichsen & Bengaard (1985), Higgins *et al.* (1981) and Soper *et al.* (1980).

The lower division comprises largely dark coloured, rubbly weathering carbonates and calcareous mudstones. The dark carbonates show poor bedding; textures are often deformed and recrystallised, but many seem to have been poorly sorted calcarenites. The overall uniform nature of the lower division is occasionally relieved by bands of light coloured calcareous turbidites and calcareous shales, but these are not sufficiently continuous to permit any subdivision. Limestone conglomerates with outsize blocks (up to 50 m across) occur locally.

The upper unit is conspicuous on account of its yellow and orange weathering colours and varied lithologies; the generally well bedded sequence includes light grey and yellow dolomites, calcareous turbidites, a succession of up to six limestone conglomerate beds, and a transitional 20–40 m unit of orange-weathering calcareous shales and siltstones which passes up into the overlying Polkorridoren Group.

Calcareous shales appear and become increasingly

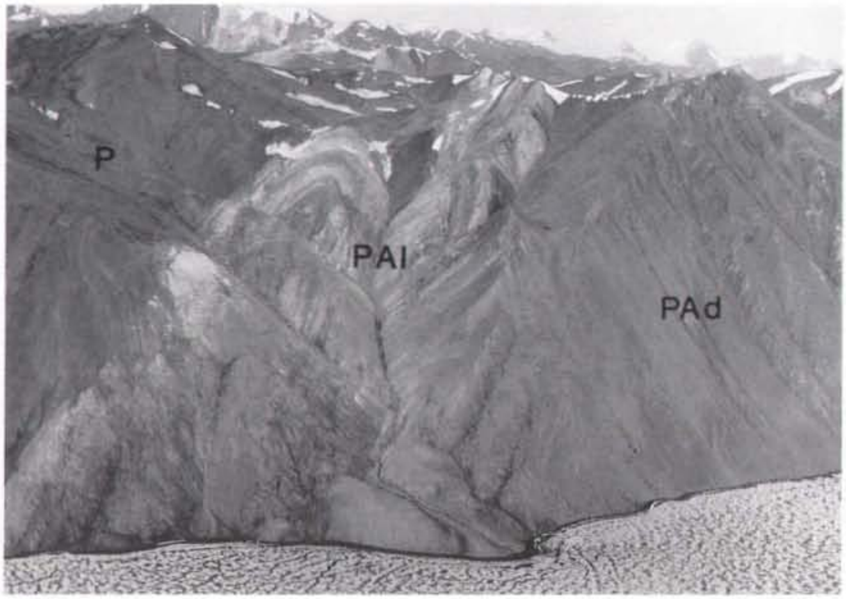


Fig. 11. Major, northerly overturned folds in eastern Nansen Land. The Paradisfjeld Group (stage 2T) is divided into a lower sequence of dark rubbly carbonates (PAd) and an upper sequence of light coloured dolomites (PAl). Overlying dark weathering rocks are siltstones and sandstones of the Polkorridoren Group (P, stage 3T). The near summits are 650 m above the fjord.

important in the Paradisfjeld Group towards the north, whereas the conglomerates thin out and disappear. However, details of the lithological variations are difficult to untangle in the extreme north due to the intense deformation.

Limestone conglomerates occur in the higher parts of the upper division in a broad belt over a length of 250 km along the southern limit of the group. Both clast supported and matrix supported types are present, the latter dominating and showing a greater variety of clast size. Clasts are mainly of light grey or pale grey carbonate, usually from a few centimetres to tens of centimetres in length, set in a fine-grained carbonate matrix; deformed rip-up clasts occur in some areas. The highest conglomerate bed characteristically has a quartz sand matrix. The beds are planar, with sharp, often erosive, boundaries, and grading is common. Bed thickness normally varies between 15 cm and 3 m, but composite units as much as 15 m thick have been observed. The sum of the sedimentary features suggests transport by high-density turbidity currents and debris flows. The original pebble fabric commonly has a strong tectonic overprint, and transport directions have not been measured. Lithology and distribution, however, clearly indicate a source area of the conglomerates in the southern carbonate platform area.

The facies association of mainly grey limestones with calcareous turbidites and related deposits points towards a relatively deep-water slope and incipient trough environment.

The southward transition of the Paradisfjeld Group into the shallow marine sediments of the Portfjeld Formation of the carbonate shelf has not been directly observed. The present line of demarcation between outcrops of the two units (Fig. 5, stage 2) coincides with the location of a low angle Ellesmerian thrust zone, and the transition is hidden beneath the hanging wall sequence (see Figs 65–67). A strong tectonic control of the original carbonate shelf margin, which was probably an escarpment, has been suggested, and may have coincided with a precursor to the present Harder Fjord fault zone (Surlyk *et al.*, 1980; Surlyk & Hurst, 1984; see Fig. 1).

Huge olistoliths derived from the Portfjeld Formation occur in the lower part of the turbiditic Polkorridoren Group (Fig. 12; Friderichsen & Bengaard, 1985). Thus the Portfjeld Formation scarp persisted or was revived by later faulting so that parts of it were still exposed in Buen Formation – Polkorridoren Group times. Subsequent to burial beneath the Ellesmerian thrust sheets, the ancient fault line may have been reactivated in Post-Ellesmerian time to form the present Harder Fjord fault (Soper & Higgins, 1987).

Stage 3: Early Cambrian siliciclastic shelf and turbidite trough

The passage from the second to the third stage in basin evolution is characterised by marked differential subsidence, leading to the formation of a deep-water turbidite trough. This was accompanied by the southward shift of the shelf-trough boundary to a position possibly controlled by new faults (Fig. 5, stage 3). The resultant shift in facies belts caused slope and trough margin deposits of the Paradisfjeld Group to be over-

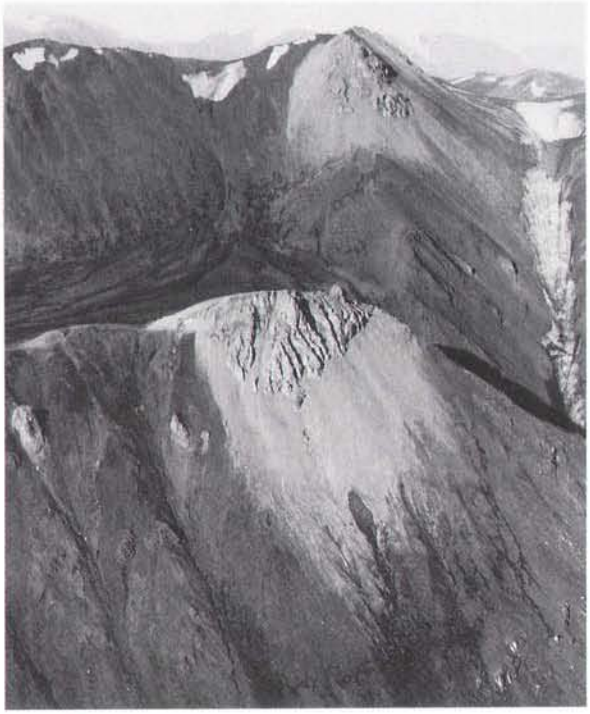


Fig. 12. Yellow weathering dolomite olistoliths of the Portfjeld Formation (stage 2S) within a siltstone sequence of the Polkorridoren Group (stage 3T), Nansen Land. The largest blocks are 150 m across.

lain by true deep-water trough deposits of the Polkorridoren Group, whereas the slope area retreated southwards. The marked increase in subsidence correlates with an interruption of carbonate shelf deposition. The water depth over the shelf, however, was not very great, and the area still formed a well-defined shelf contrasting with the deeper slope and trough environments. The tectonic-sedimentological setting at this stage can thus be visualised as follows:

Outside a shelf area receiving terrigenous mud and sand, a wide slope was formed, characterised by deposition in a well-oxygenated environment of red and green mudstones with occasional thin turbidites. Coarse clastic material was probably funnelled across the shelf into submarine canyons that still remain to be found. This material was deposited by turbidity currents onto several submarine fans, the outer parts of the fans showing deflection westward following the east-west axis of the basin.

3S: Siliciclastic shelf

The shelf record of stage 3 is represented by siliciclastic sediments of the Buen Formation (Jepsen, 1971) in the region between Warming Land and Danmark Fjord, and the Humboldt and Dallas Bugt Formations in Washington Land and Inglefield Land, respectively (Figs 1–4; Map 1; Peel & Christie, 1982; Peel *et al.*, 1982). Northwards these Lower Cambrian shelf deposits grade into the turbiditic Polkorridoren Group (see below). The shelf sediments overlie the platform carbonates of stage 2 in the area east of Wulff Land (Figs 8, 9), but are seen to overstep onto Proterozoic sedimentary rocks and Archaean gneisses to the south-west in Inglefield Land (Peel *et al.*, 1982); their extent in the north-western part of the basin is not known as only younger rocks are exposed in these areas. Shelf sediments of stage 3 are conformably overlain by carbonates of stage 4 throughout North Greenland.

The Buen Formation (middle-late Early Cambrian) ranges between 425 and about 500 m in thickness in its southern outcrop, and about half this amount in the outer shelf outcrops at Navarana Fjord and in northern Wulff Land. The sediments of this stage thicken rapidly northwards into the slope and the deep-water trough (see below). They consist of a succession of sandstones and mudstones, with rare conglomerates, and typically can be subdivided into a lower, sandstone-dominated unit and an upper, recessive, mudstone-dominated unit (Fig. 8). In general, the proportion of sandstone in the formation decreases northwards; hence, the formation is sandstone-dominated in south-east Peary Land and southern Wulff Land (Jepsen, 1971; Hurst & Peel, 1979; Bryant & Pickerill, 1990) but consists mainly of a thick mudstone-dominated succession in the north-east Peary Land to northern Nyeboe Land area (Christie & Ineson, 1979; Davis & Higgins, 1987; Soper & Higgins, 1985; Surlyk & Ineson, 1987a). The sandstone unit contains minor conglomerate and silty mudstone interbeds. In its southern outcrop, medium to coarse-grained sandstones show abundant cross-stratification; large-scale compound sets are common and locally show siltstone drapes along low-angle foresets (3°–15°); compound sets characteristically show a unimodal (northward) palaeocurrent pattern whereas thin to medium-bedded, glauconitic sandstones often show herring-bone cross-bedding. Bioturbation is common, particularly within thin-bedded heterolithic facies from which Bryant & Pickerill (1990; see also Bergström & Peel, 1988) described a varied ichnofauna; *Skolithos* is locally abundant near the top of the sandstone unit. Hummocky cross-stratified sandstones occur at certain levels in southern outcrops but are the dominant facies in northern Wulff Land. The upper fine-grained member is composed mainly of laminated or bioturbated, grey-green silty mudstones with subordinate interbeds (2–50 cm thick) of medium to fine-grained sandstone showing parallel and ripple cross-lamination and hummocky cross-stratification.

The Buen Formation represents a siliciclastic marine shelf environment, the sandstone unit recording inshore environments influenced by tides and high energy storms, whereas the mudstone unit reflects a low-energy, outer shelf environment in which episodic high-energy events were the result of storm-induced currents. The ubiquitous upward transition from sand-dominated inner shelf to fine-grained outer shelf facies reflects a regional sea-level rise during this depositional phase.

The Dallas Bugt Formation (25–150 m) of Inglefield Land clearly records the marine transgression of stage 3 during a period of abundant sediment supply. Feldspathic, coarse-grained pebbly red sandstones of fluviatile origin unconformably overlie Proterozoic siliciclastic sediments and crystalline basement rocks and are succeeded by well sorted, white, large-scale cross-bedded sandstones with reactivation surfaces and massive beds with *Skolithos*, deposited under tidal influence. The sandstones become interbedded with bioturbated siltstones with *Cruziana* prior to grading up into dolomites of the overlying Cape Leiper Formation (Peel *et al.*, 1982; Bergström & Peel, 1988). The Dallas Bugt Formation is also recognised in immediately adjacent Ellesmere Island, where it comprises the Bache Peninsula and Sverdrup Members of Christie (1967; see Peel *et al.*, 1982). Correlative strata in southern Washington Land are referred to the Humboldt Formation.

3T: Turbidite trough

The change in trough sedimentation from the Paradisfjeld Group carbonates to the Polkorridoren Group sandstone turbidites and mudstones is a major step in the evolution of the trough and reflects a dramatic increase in subsidence, probably controlled by trough-parallel faulting (Surlyk & Hurst, 1984). The corresponding change on the shelf from the Portfjeld Formation dolomites to the Buen Formation siliciclastic sediments was initiated by shallowing of the shelf sea and exposure of much of the carbonate platform (see above). The earliest Polkorridoren Group sandstones and mudstones may correspond to a hiatus at the base of the Buen Formation (Davis & Higgins, 1987).

The Polkorridoren Group is widely exposed in Johannes V. Jensen Land and Nansen Land, in the intensely deformed part of the North Greenland fold belt. The total thickness of the group is estimated to be 2–3 km, and it is considered to be entirely of Early Cambrian age (Surlyk *et al.*, 1980; Friderichsen *et al.*, 1982). Two main facies associations are present: black, green and purple mudstones, and sandy turbidites. No formal lithostratigraphic subdivision has yet been made.

The alternation of mud-dominated and sand-dominated units, generally on a scale of 100–500 m thick, has proved useful in defining local, informal stratigraphies (Fig. 13). A subdivision into six or seven parts has been possible in eastern Johannes V. Jensen Land and the islands east of Nansen Land (Soper *et al.*, 1980;

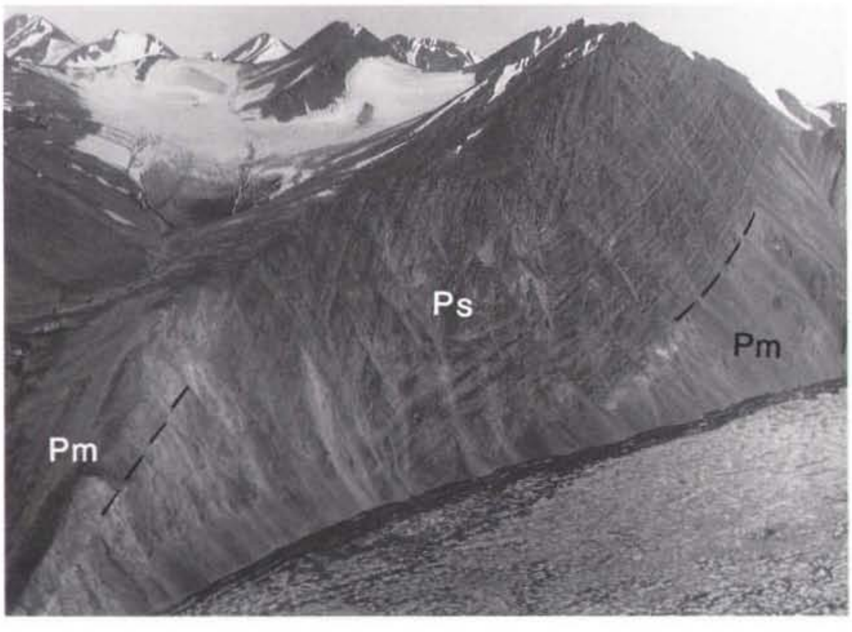


Fig. 13. Regularly bedded sandstone turbidite sequence (Ps) overlying recessive siltstone and mudstone sequence (Pm), Polkorridoren Group (stage 3T), north-east Nansen Land. Folds are overturned northwards. Highest summits reach 1100 m.

Higgins *et al.*, 1985). Correlation of these units between regions is difficult, however, and in some areas, such as western Johannes V. Jensen Land, thinly bedded, finer grained units are poorly developed and the sand-dominated sequence can be indivisible. Sand-rich units typically consist of thick, often structureless beds that are commonly amalgamated; fining-upward cycles on a scale of 50–100 m are recognised locally. Intervening mudstone units include thin-bedded sandstone turbidites which may show abundant trace fossils at some levels (Pickerill *et al.*, 1982). Lateral variation in thickness can be marked, and sand-rich units locally coalesce or wedge out laterally. Carbonate conglomerate beds occur at several levels in the sequence and sometimes form persistent mapping units (see below).

The uppermost unit of the group, the Frigg Fjord mudstone (Fränkl, 1955; Dawes & Soper, 1973; Friderichsen *et al.*, 1982), has a more widespread, regional distribution and can be recognised in various guises between Johannes V. Jensen Land and south-east Nansen Land. Along the southern trough margin, where the sandstone turbidites have wedged out, the Frigg Fjord mudstone extends stratigraphically further downwards. This distinctive unit is up to 400 m thick and consists mainly of purple and green mudstones. A sequence of similarly coloured mudstones and thin, flaser-bedded siltstones and sandstones which forms the uppermost unit in north-west Nansen Land, is probably the lateral equivalent of the Frigg Fjord mudstones.

Palaeocurrent readings from Johannes V. Jensen Land show three distinct modes towards the west, north and, less commonly, east. The longitudinal transport towards the west is interpreted as representing a deflection of the outer parts of northerly directed submarine fans along the basin axis. In Nansen Land palaeocurrent readings give a dominant northward mode, with a narrow range between north-east and north-west.

A persistent and spectacular carbonate conglomerate level occurs about 600 m above the base of the Polkorridoren Group, and is traceable over a distance of 125 km throughout southern Nansen Land and the islands to the east and west (Friderichsen & Bengaard, 1985). Individual clasts range from tens of centimetres in size to outsize blocks up to 300 m in diameter (Fig. 12); many blocks can be identified as Portfjeld Formation lithologies. The yellow-weathering dolomite blocks, which have been described as olistoliths, are totally enveloped by dark-weathering siltstones of the Polkorridoren Group. Relationships between the blocks and the surrounding sediments are masked, however, by the strong deformation. Most of the large blocks occur in two clusters in southern Nansen Land, spread over distances along strike of 2–3 km and 8 km, respectively. Friderichsen & Bengaard (1985) suggested that the blocks may have been derived from a submarine canyon excavated in Portfjeld Formation dolomites at the trough/shelf transition, whereas Soper & Higgins (1987) consider their wide east-west distribution more indicative of a line source, such as a precipitous, possibly faulted platform margin.

Strong deformation precludes detailed facies analysis and environmental reconstruction in many areas. The general picture, however, is clear. At the shelf-slope break the black and green mudstones of the upper part of the Buen Formation gradually give way to variegated, thickly developed Frigg Fjord mudstone facies characterising the wide slope area. Further north thin sandstone turbidites start to appear in the Frigg Fjord mudstones reflecting the approach of the transition of the base-of-slope area and the trough floor.

Sand was funnelled from the shelf across the slope probably through a number of canyons. These have not been observed in the field, however, most likely due to the intense deformation of the Frigg Fjord mudstones or due to cover by younger rocks. Many of the sandy turbidites were deposited in a system of relatively small borderland fans which were deflected towards the west or less commonly towards the east along the trough axis. Thick sequences of poorly-sorted, massive sandstone turbidites occur in some areas and possibly represent rapid sediment dumping in a channel mouth – proximal lobe setting (Fig. 14). The dominance of sandstones in areas such as western Johannes V. Jensen Land and Nansen Land would then represent major depositional lobe systems of individual fans while intervening mudstone-dominated areas reflect interfan and basin plain environments.

Stage 4: Late Early Cambrian – Middle Ordovician shelf and starved trough

From the late Early Cambrian to the Early Ordovician, sedimentation in North Greenland was influenced by two major tectonic developments: 1, differential subsidence and southward expansion of the east-west deep-water trough;, and 2, uplift in eastern North Greenland, probably the effect of an early Caledonian event. The influence of the latter was most pronounced in eastern North Greenland and decreased westwards (Fig. 4).

The evolution of the shelf from the late Early Cambrian to earliest Ordovician is best envisaged in terms of two components: a progradational shelf in the eastern areas (stage $4S_{1p}$) influenced by uplift in south-eastern Freuchen Land, Peary Land and Kronprins Christian Land (recorded by the Brønlund Fjord and Tavsens

Fig. 14. Thick, poorly or non-graded mid-fan sandstone turbidites of the Polkorridoren Group (stage 3T), central Johannes V. Jensen Land. Note person for scale.

Iskappe Groups; Figs 2–4), and a western, uniformly subsiding, aggradational shelf (stage $4S_{1a}$) in areas west of Nordenskiöld Fjord (represented mainly by the Ryder Gletscher Group; Figs 2–4, 15). During the Early Ordovician (stage $4S_2$), following the end of active uplift in eastern North Greenland, the shallow-water aggradational shelf persisted in western areas and expanded in the late Early Ordovician to cover the entire North Greenland shelf (Fig. 15).

$4S_{1p}$: Progradational Cambrian shelf

The eastern Cambrian shelf succession is dominated by the Brønlund Fjord and Tavsens Iskappe Groups which are a complex, diachronous array of prograding carbonates with subordinate siliciclastic sediments (Figs 15–17A). The Middle(?) Cambrian Koch Væg Formation is the only Cambrian representative of the Ryder Gletscher Group in this area. The Brønlund Fjord and Tavsens Iskappe Groups attain their maximum development (900 m in thickness) in south-west Peary Land and south-east Freuchen Land and range in age from late Early Cambrian to earliest Ordovician (Fig. 2; Ineson & Peel, 1980, in prep.; Peel, 1982c). The succession in the type area of southern Peary Land and south-eastern Freuchen Land is subdivided into twelve formations divided equally between the two groups (Fig. 16). Two additional formations of the Brønlund Fjord Group are recognised from south-west Freuchen Land to Warming Land (see stage $4S_{1a}$) and a further two formations are known from highly faulted outcrops in north-east Peary Land, around G. B. Schley Fjord (Fig. 16 and Map 1). The Brønlund Fjord and Tavsens Iskappe Groups also outcrop in anticlinal fold cores in the northern coastal regions from Nyeboe Land, in the west, to the J. P. Koch Fjord area, in the east (Figs 1, 9, 16). The two lowest formations of the Brønlund Fjord Group in its type area are recognised in these northern outcrops, while an overlying new formation (Kap Stanton Formation, unit 3 of Higgins & Soper, 1985) is assigned to the Tavsens Iskappe Group (Fig. 16).
16).

To the east of Freuchen Land, progressive uplift and erosion resulted in an unconformity at the base of the

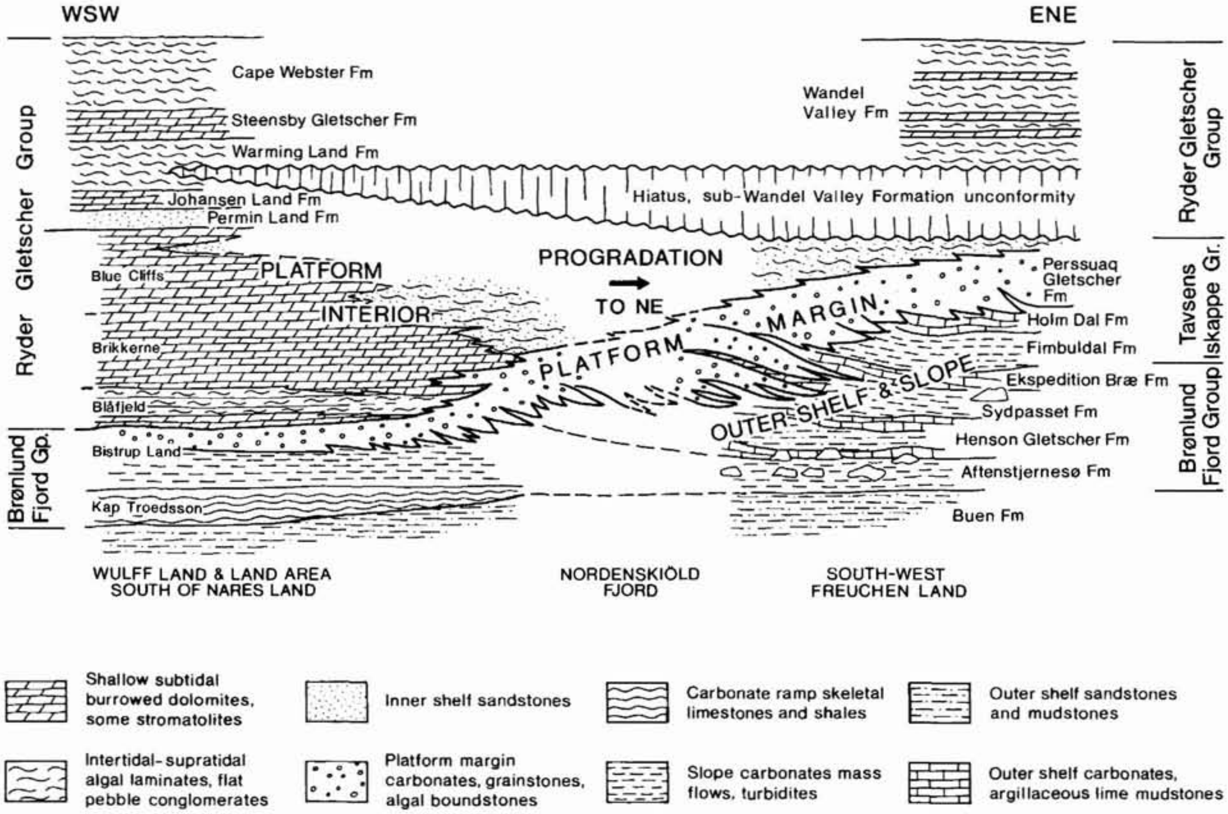


Fig. 15. Schematic cross-section showing relationships between platform interior, platform margin and outer shelf-slope rocks of stage $4S_{1-2}$ at the head of Nordenskiöld Fjord.

succeeding Wandel Valley Formation (Early-Middle Ordovician), which consequently oversteps eastwards on to older units of the Brønlund Fjord and Tavsens Iskappe Groups to ultimately rest on Proterozoic strata in eastern North Greenland (Figs 4, 15). Thus, the Tavsens Iskappe Group has been eroded or was never deposited in areas to the east of central southern Peary Land, while the Brønlund Fjord Group persisted eastward to Independence Fjord (see Map 1).

The complex nature of the lithostratigraphic scheme applied to the sediments of the Brønlund Fjord and Tavsens Iskappe Groups (Figs 15, 16) reflects the rapid lateral facies variations within the succession (Ineson, 1985). Three major environments are recognised: *starved ramp, platform margin* and *outer shelf-slope*.

Starved ramp facies form a distinctive unit at the base of the Brønlund Fjord Group, marking the transition from the siliciclastic-dominated marine shelf (Buen Formation, stage 3S) to the succeeding carbonate regime. The remainder of the Brønlund Fjord Group and Tavsens Iskappe Group forms a progradational platform margin – outer shelf system (Fig. 15). Platform interior rocks are rarely preserved within this regressive succession and are represented only by the Koch Væg Formation of the Ryder Gletscher Group (Fig. 17A, see also Fig. 20).

The starved ramp deposits at the base of the Aftenstjernesø Formation consist of a 2–7 m thick unit of phosphoritic, glauconitic skeletal grainstones, packstones and wackestones (and dolomitised equivalents) with subordinate burrowed terrigenous siltstones (Fig. 18). Bioturbation is widespread and bedding is typically nodular or wavy; sedimentary structures such as shell imbrication and current ripple cross-lamination are preserved locally. Black or dark brown phosphorite occurs as detrital grains in winnowed shell lags, as irregular nodules and within impregnated, pyritic hardground surfaces (Frykman, 1980).

This highly condensed interval clearly records a period of sediment starvation on the Cambrian shelf (Hurst & Surlyk, 1983b; Ineson, 1985). As the supply of terrigenous sediment declined due to transgression and drowning of sediment sources, carbonate production gradually took over. The starved, muddy carbonate

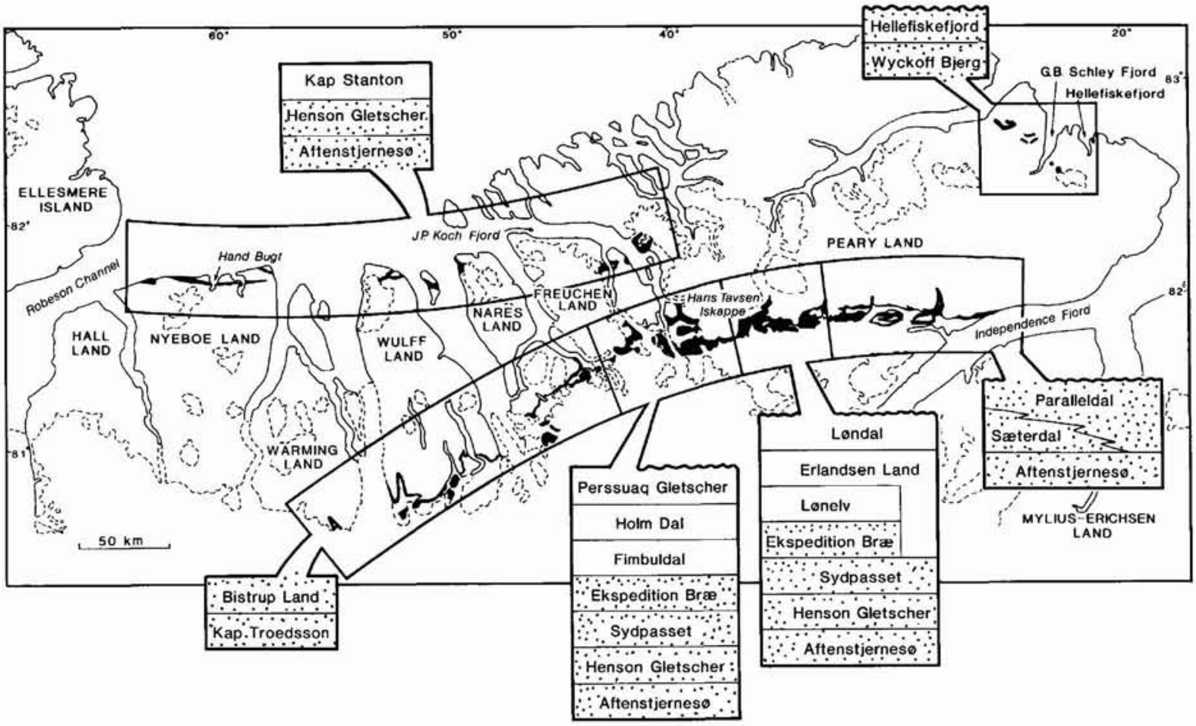


Fig. 16. Map showing the distribution (black) of the Brønlund Fjord and Tavsens Iskappe Groups in North Greenland, and their component formations (Brønlund Fjord Group stippled). These stratigraphic groups consist of platform margin and outer shelf rocks forming the Cambrian progradational succession (stage $4S_{1p}$) in eastern areas and along the northern coast. West of southern Freuchen Land, outer-shelf and platform margin rocks are restricted to the Kap Troedsson and Bistrup Land Formations at the base of a thick Cambrian and Ordovician aggradational succession of platform interior carbonates (Ryder Gletscher Group, stages $4S_{1a-2}$).

ramp represents the transitional phase, preceding the establishment of a flat-topped carbonate platform. This interval is equivalent to the ramp facies of the Kap Troedsson Formation in the western area (stage $4S_{1a}$; Figs 15, 17B).

As carbonate sedimentation became established, the shelf environment was resolved into a shallow-water platform that passed northwards via a carbonate slope into a deeper water, outer shelf region. Rocks of the platform interior (Ryder Gletscher Group) pass northwards into thick bedded or massive dolomites of the carbonate *platform margin* (Figs 15, 17A, 19). Typically, these dolomites are trough cross-bedded, well-sorted, ooid, peloid and intraclast grainstones that record sedimentation in a high-energy, shallow-water setting at the outer margin of the platform. Associated facies in this setting include archaeocyathid-algal biostromes in the Lower Cambrian Paralleldal Formation and thrombolitic algal mounds in Upper Cambrian sandy foreslope deposits of the Perssuaq Gletscher Formation. Mature quartzitic sandstones with well rounded grains form a large proportion of the latter formation, particularly in more northerly localities, where trough cross-bedded, medium-grained sandstones alternate with bioturbated parallel-laminated sandstones and sandy mass-flow deposits (Fig. 21; Surlyk & Ineson, 1987a).

The transition from platform edge to outer shelf-slope is often marked by spectacular foreslope deposits that show northward primary dips of up to 30°. The foreslope grainstones and carbonate mass-flow deposits wedge out northwards, interdigitating with dark carbonates of the slope and outer shelf; this transition is superbly illustrated within the Perssuaq Gletscher, Løndal and Bistrup Land Formations, at the transition from the western aggradational platform to the eastern succession (Figs 15–17A, 20, 21).

Outer shelf and slope rocks make up over two-thirds of the Brønlund Fjord and Tavsens Iskappe Groups (Figs 15, 16, 22), forming continuous sections up to 450 m thick in south-western Peary Land. Typically, they consist of thinly bedded, dark, hemipelagic lime mudstones and nodular limestones, interbedded with graded limestones and chaotic carbonate breccia beds. Secondary dolomitisation affects nearly three-quarters of the succession, and occurs preferentially within thick-bed-

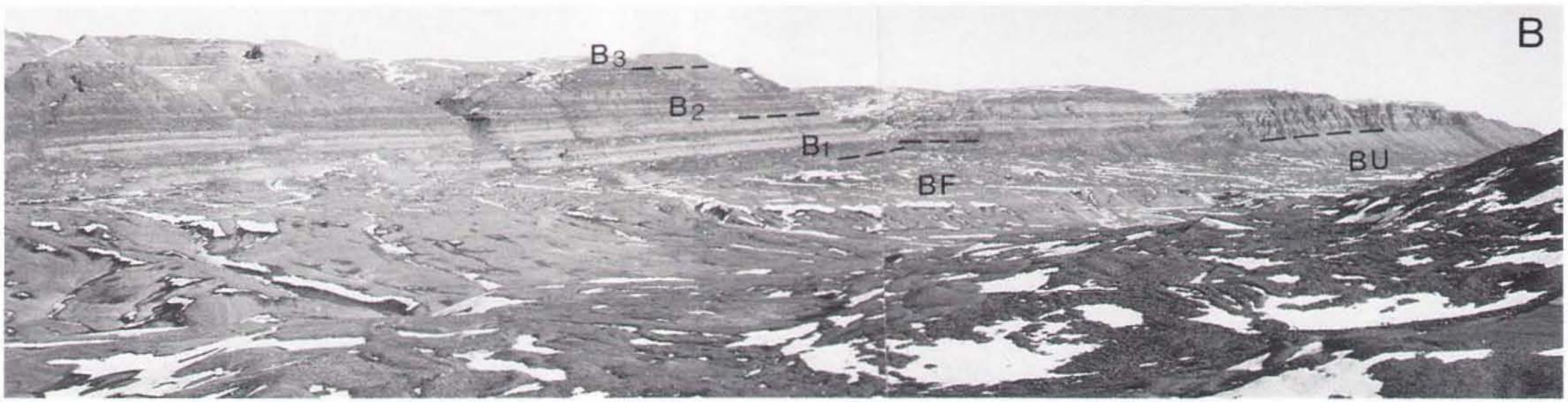


Fig. 17. A, Sequence of prograding platform margin carbonates (stage $4S_{1p}$) on the east side of Henson Gletscher, western Peary Land. Foreslope and margin sediments of the Perssuaq Gletscher Formation (PG) of the Tavsens Iskappe Group are overlain by restricted platform interior carbonates of the Koch Væg Formation (KV) and Wandel Valley Formation (W) of the Ryder Gletscher Group (stage $4S_{1a}$). Northward progradation of units within the Perssuaq Gletscher Formation produced the inclined depositional surfaces seen to the right. A dolomite mound (m) to the left is well bedded dolomites and siltstones of the Koch Væg Formation which are overlain by dolomites of the Wandel Valley Formation. The cliff is 600 m high, and is cut by a draped by dyke (d). B, Platform carbonates and siltstones of the Blåfjeld (B_1), Brikkerne (B_2) and Blue Cliffs (B_3) Formations of the Ryder Gletscher Group overlying dolomites of the Brønlund Fjord Group (BF, Kap Troedsson and Bistrup Land Formations; stage $4s_{1a}$) and recessive siliciclastics of the Buen Formation (BU, stage 3S), south-west Wulff Land. The Blåfjeld Formation is 100 m thick.

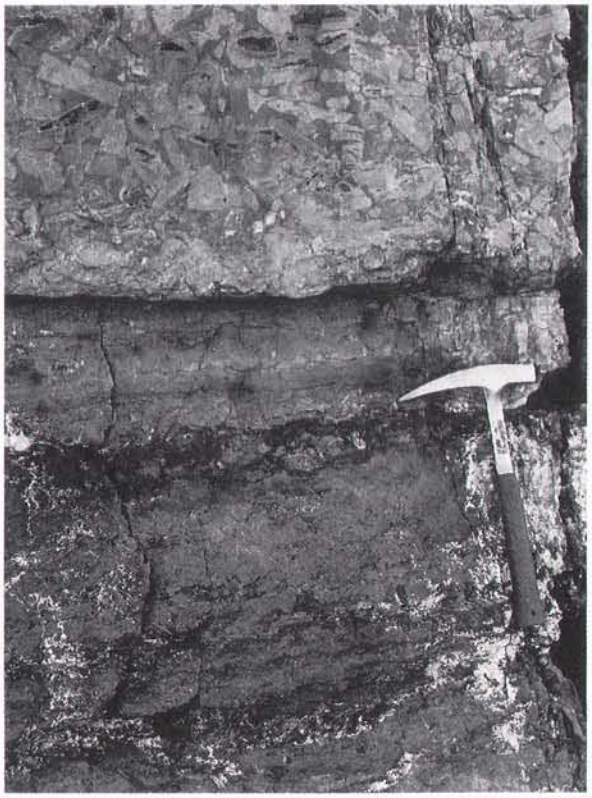


Fig. 18. Nodular glauconitic dolomites with black phosphorite nodules and hardgrounds of the starved deep ramp, overlain by mass-flow brecia representing the prograding carbonate slope. Basal Aftenstjernesø Formation (stage $4S_{1p}$). Hammer for scale.

ded coarse-grained intervals. The hemipelagites are commonly bituminous, argillaceous and cherty and often contain small phosphatic brachiopods, trilobites and sponge spicules; this facies is typical of the Henson Gletscher, Ekspedition Bræ, Erlandsen Land and Holm Dal Formations (Figs 16, 22, 23). Even, parallel, occasionally micrograded, lamination is the dominant sedimentary structure. *Chondrites* burrows occur at certain levels. Some sections show a regular, cyclic alternation of burrowed and non-burrowed, laminated carbonate mudstones, reflecting rhythmic variations in the degree of oxygenation of bottom waters. The interbedded graded limestone beds range from silty lime mudstones less than 5 cm thick, to thick-bedded (<60 cm), coarse-grained peloidal grainstones showing Tab and Tabc Bouma divisions; they are the deposits of low-density turbidity currents derived from the upper slope and platform margin.

Very thinly bedded, nodular carbonates are a striking feature of the outer shelf and slope rocks, and are particularly well-developed in the Aftenstjernesø, Sydpasset and Fimbuldal Formations (Figs 15, 16). Now composed mainly of dolomite or neomorphic calcite spar, these beds show a complex, platy, nodular banding that probably reflects primary interbedding of turbiditic and hemipelagic lime mud, enhanced by early diagenetic, differential cementation. Interstratal sliding within such partially lithified sediments resulted in a spectacular array of slope creep structures. These range from pull-aparts, boudins, microfaults and discontinuous, locally discordant interstratal breccias to folds and hummocks with relief of up to 10 m and wavelength up to several tens of metres (Fig. 24; Ineson, 1985).

Carbonate breccia beds, often dolomitised, range from 0.2 to 45 m in thickness and are mainly sheet-like, non-channellised deposits. Typically clast-supported, these beds are internally unstratified, chaotic and poorly sorted, with an interstitial carbonate mud matrix; they are interpreted as the deposits of submarine debris flows (Ineson, 1980, 1985). Platform-derived blocks of ooid grainstone up to several tens of metres across are prominent in some breccia beds, particularly within the Aftenstjernesø, Sydpasset, Lønelv and Fimbuldal Formations (Figs 5, 16, 19). More commonly, however, the breccias consist of coarse pebble to cobble-sized, platy, angular fragments derived from slope environments (Fig. 25). All stages of slope mass wastage are preserved in the succession from slope creep through sliding and slumping to mass flow.

A siliciclastic sand wedge, up to 124 m thick, interrupts the outer shelf-slope carbonates at around the Early to Middle Cambrian boundary, forming the Sæterdal Formation and much of the Henson Gletscher Formation (Figs 15, 16). The sand wedge is persistent along depositional strike (roughly east-west) for over 300 km, from northern Nyeboe Land to central Peary Land and, despite a general northward thinning, it extends over 40 km from south to north normal to depositional strike. It consists of pale-weathering, thin to very thick-bedded, fine-grained sheet sandstones, interbedded with burrowed, laminated sandy siltstones (Figs 19, 22). Although commonly structureless, some sandstone beds show dewatering structures, parallel lamination and hummocky cross-stratification. The sand was probably transported seawards during severe storms, but subsequent remobilisation and mass flow transport farther down the slope can be documented in several cases.

Coeval outermost shelf and slope rocks of late Early Cambrian to Early Ordovician age outcrop between northern Nyeboe Land and J. P. Koch Fjord in a series of anticlinal fold cores (Figs 2, 4, 16). This succession was initially described in terms of three provisional units by Higgins & Soper (1985); their fourth unit, equivalent to the Amundsen Land Group, forms part of stage $5S_2$.

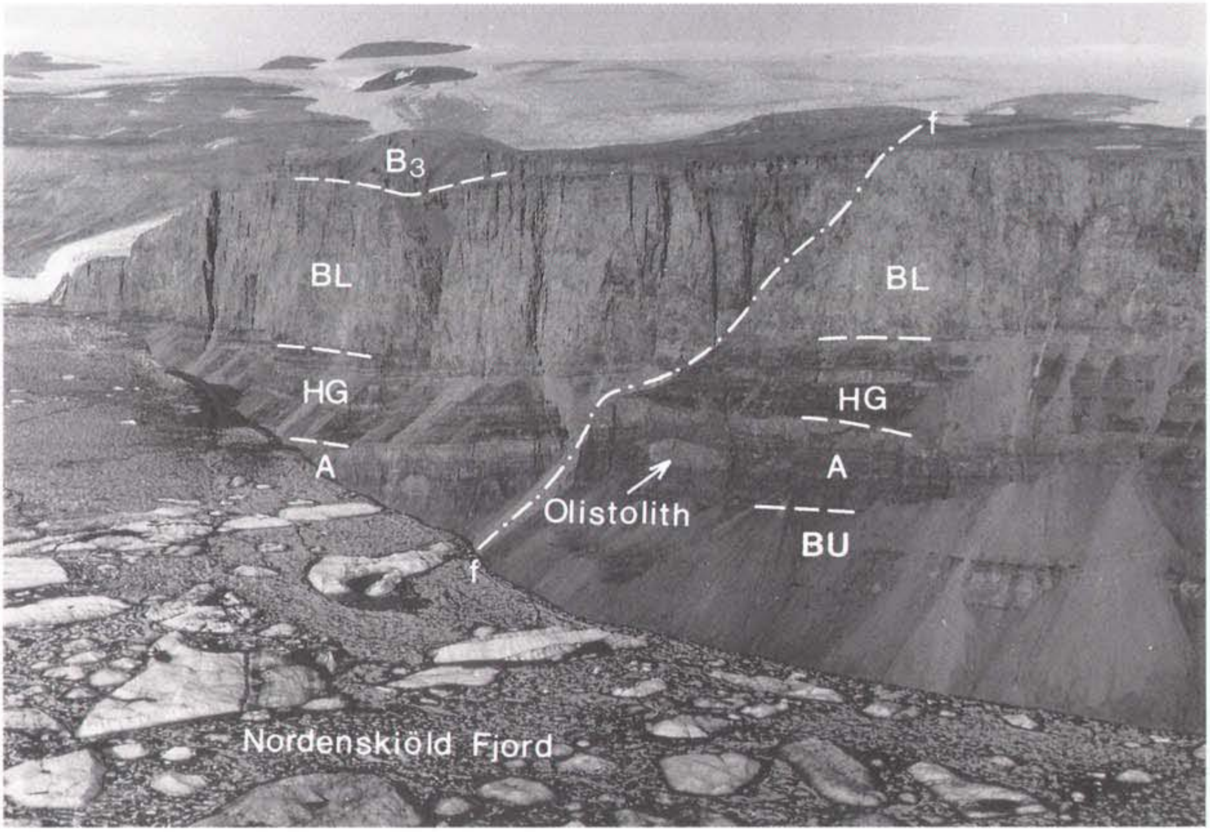


Fig. 19. Cambrian platform margin sequence at the head of Nordenskiöld Fjord. Outer shelf sandstones and mudstones of the Buen Formation (BU, stage 3S) are overlain by slope carbonates and debris flow units of the Aftenstjernesø (A) and Henson Gletscher (HG) Formations of the Brønlund Fjord Group (stage $4S_{1p}$) with conspicuous olistoliths. Succeeding platform margin carbonate grainstones of the Bistrup Land Formation (BL, Brønlund Fjord Group, stage $4S_{1a}$) are overlain by platform carbonates and siliciclastic rocks of the Blue Cliffs Formation (B_3) of the Ryder Gletscher Group, stage $4S_{1a}$). Cliff is 700 m high. f-f: fault.

The lower two units are distal, outermost shelf representatives of the Aftenstjernesø and Henson Gletscher Formations. The third unit (upper Middle Cambrian – lowermost Ordovician) is considered to be a new formation of the Tavsens Iskappe Group (Kap Stanton Formation; Ineson & Peel, in prep.), and shows a somewhat different development from its more proximal shelf equivalents (Fig. 26). It is generally between 150 m and 300 m thick, and is mainly composed of dark lime mudstones, although lime turbidites in beds from 10 cm to 1 m thick are conspicuous in eastern outcrops. Alternations of thin-bedded, grey, nodular or banded limestones and yellow-orange dolomites dominate in western outcrops, while carbonate breccia beds are common in every section.

Traced northwards towards the limit of exposure, in northern Nares Land, northern Freuchen Land and along the east side of central J. P. Koch Fjord, the division into the Aftenstjernesø, Henson Gletscher and Kap Stanton Formations fails and the total thickness of this succession is less than 100 m. The deposits in these areas consist almost entirely of chert and cherty shale, indicating a starved deep shelf or slope environment throughout the late Early Cambrian to Early Ordovician. Farther north still, in southern Johannes V. Jensen Land the succession thickens again, but now represents the trough deposits of the Vølvedal Group (see stage 4T).

It is clear from Fig. 15 that the Brønlund Fjord and Tavsens Iskappe Groups together reflect a major, shallowing-upward, progradational episode, probably controlled by regional uplift of eastern North Greenland during the Middle and Late Cambrian. Fine-grained outer shelf-slope rocks dominate the succession but are everywhere overlain by, and grade southwards into, platform carbonates (Figs 15–17A, 19–22), reflecting northward progradation of shallow-water environments. In southern Peary Land, palaeocurrents, palaeoslopes and facies patterns indicate progradation towards the north-north-west, whereas in south-west

Fig. 20. Northward prograding platform margin carbonates (stage $4S_{1p}$) of the Perssuaq Gletscher Formation (PG; Tavsens Iskappe Group) overlain by platform interior carbonates of the Koch Væg Formation (KV) and Wandel Valley Formation (W; note basal unconformity) of the Ryder Gletscher Group (stage $4S_{1a-2}$). Note the lenticular, sigmoidal form of individual stratal units within the progradational interval. East side of Henson Gletscher; representing the central part of Fig. 17A.

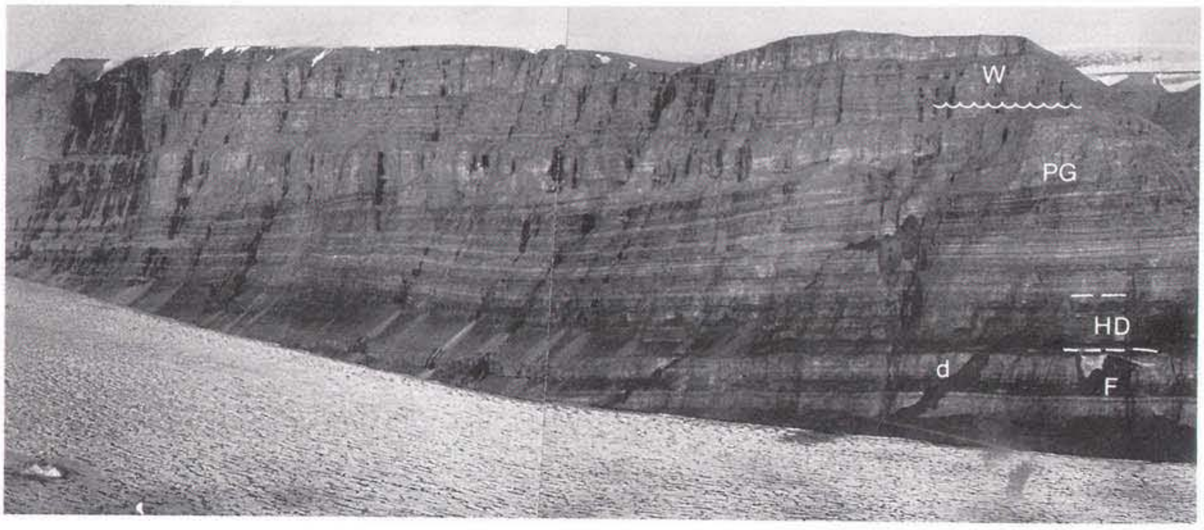


Fig. 21. Prograding siliciclastics and carbonates of the Perssuaq Gletscher Formation (PG) overlying outer shelf carbonates and shales of the Holm Dal (HD) and Fimbuldal (F) Formations (all Tavsens Iskappe Group, stage $4S_{1p}$). Platform dolomites of the Wandel Valley Formation (W, stage $4S_2$) unconformably overlie the Perssuaq Gletscher Formation. East side of J. P. Koch Fjord, western Peary Land. Height of cliff about 1000 m; d, dyke.

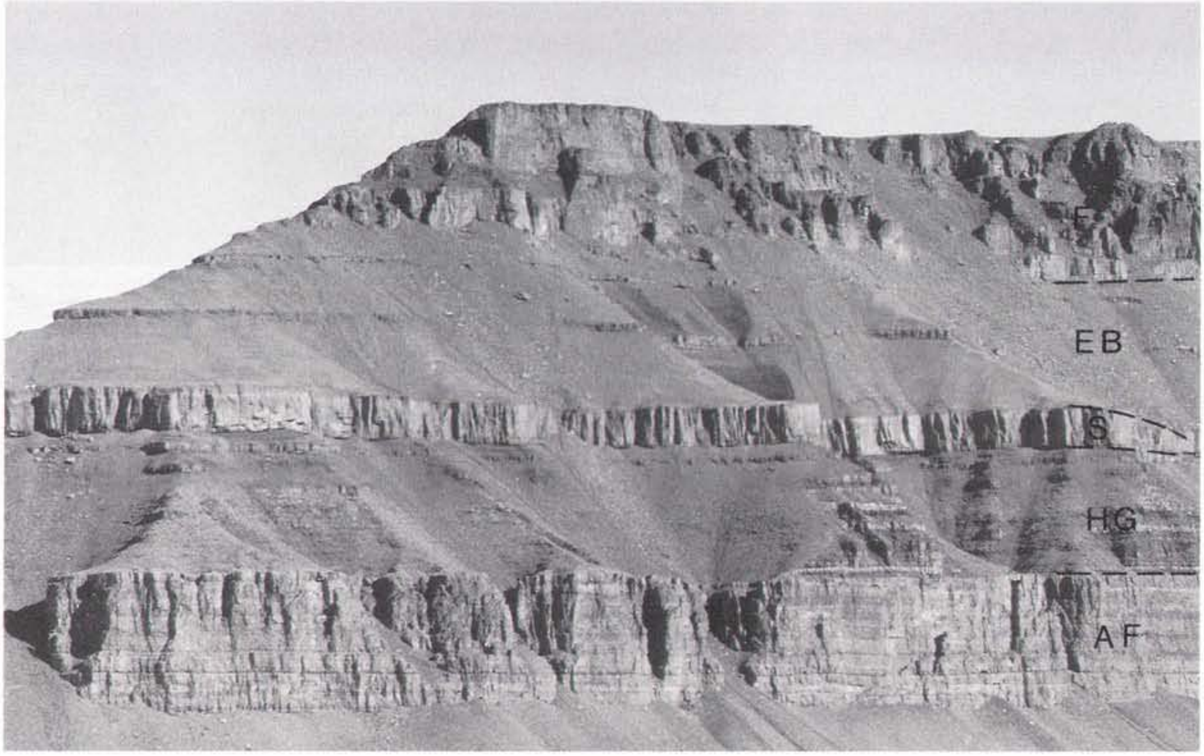


Fig. 22. Slope and outer shelf carbonate and siliciclastic sediments of the Brønlund Fjord and Tavsens Iskappe Groups (stage $4S_{1p}$; see Fig. 16) east of J. P. Koch Fjord. Note the cyclic alternation between cliff-forming carbonate formations and recessive, mixed siliciclastic-carbonate formations; light-coloured sheet sandstones in the Henson Gletscher Formation (HG) are also visible in Fig. 19. AF, Aftenstjernesø Formation; S, Sydpasset Formation; EB, Ekspedition Bræ Formation; F, Fimbuldal Formation.

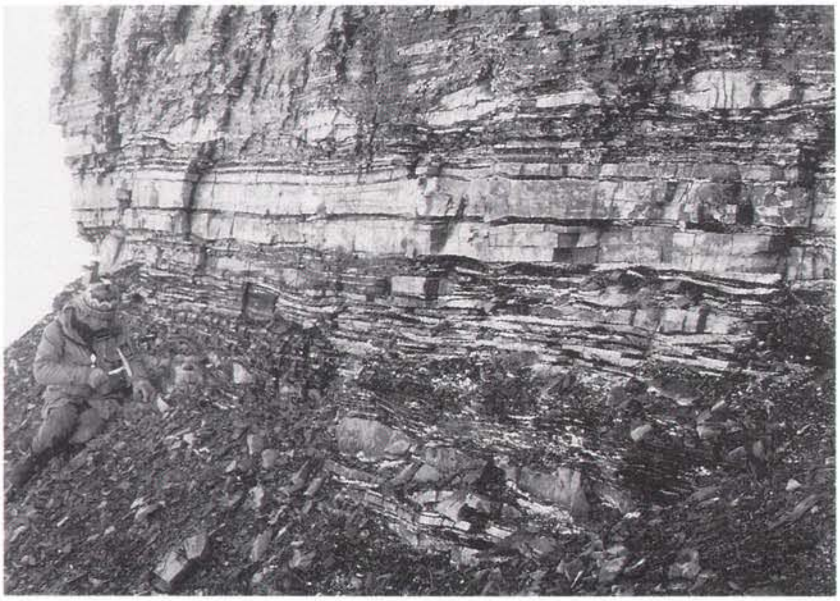


Fig. 23. Outer shelf bituminous silty dolomites of the Henson Gletscher Formation (stage $4S_{1p}$) west of J. P. Koch Fjord. Note the well-developed parallel lamination and nodular structure.

Fig. 24. Spectacular hummocks within thin-bedded slope carbonates of the Aftenstjernesø Formation (AF; Brønlund Fjord Group stage $4S_{1p}$) formed by interstratal slope creep and incipient sliding. Arrow indicates the plane of detachment. Southern Freuchen Land. HG, Henson Gletscher Formation. Height of cliff is about 100 m.

Fig. 25. Intraformational breccia (debris flow) formed of platy light and dark coloured lime mudstones; this rock type is abundant in the outer shelf equivalent of the Tavsens Iskappe Group (stage $4S_{1p}$) of northern Nyeboe Land.

Fig. 26. Brønlund Fjord and Tavsens Iskappe Groups exposed south-west of Hand Bugt, northern Nyeboe Land; the type locality of the Kap Stanton Formation (KS). The inverted succession youngs to the right (south). BU, Buen Formation; A, Aftenstjernsø Formation; HG, Henson Gletscher Formation.

Freuchen Land the platform prograded towards the north-east, at least locally. Superimposed on this overall regressive trend is a well-developed reciprocal sedimentation pattern, recording periods of extensive carbonate platform development alternating with periods of mixed carbonate-siliciclastic sedimentation (Ineson, 1988).

$4S_{1a}$: Aggradational Cambrian platform

The western part of the Cambrian shelf is represented by a thick and varied succession of carbonates, mainly of restricted platform aspect (*sensu* Wilson, 1975) with subordinate siliciclastic sediments and evaporites, which are assigned to the Brønlund Fjord Group and the lower part of the Ryder Gletscher Group (Figs 2, 15, 17B). In the Warming Land – Nares Land area, this succession conformably overlies the fine-grained siliciclastic sediments of the Buen Formation (stage 3S). In Inglefield Land and Washington Land, to the west, the Brønlund Fjord Group is not recognised and the Ryder Gletscher Group succeeds siliciclastic sediments of stage 3S (the Dallas Bugt and Humboldt Formations; Fig. 2).

The Kap Troedsson and Bistrup Land Formations of the Brønlund Fjord Group record the evolution from the siliciclastic outer shelf (Buen Formation, stage 3S) to the shallow-water aggradational shelf (Ryder Gletscher Group) in outcrops between south-west Freuchen Land and Warming Land (Figs 15, 17B). The argillaceous lime mudstones and skeletal grainstones of the Kap Troedsson Formation (maximum thickness 65 m) represent a storm-dominated carbonate ramp that developed during the initial stages of carbonate sedimentation on the shelf. The succeeding formation (Bistrup Land Formation, 80 m thick) consists essentially of a lower unit of dolomitised mass-flow carbonate breccias and carbonate turbidites overlain by an upper succession of trough cross-bedded and hummocky cross-stratified carbonate grainstones. This formation records the progressive development and northward progradation of a flat-topped, rimmed carbonate platform with a high-energy margin and flanking carbonate slope deposits. In south-west Freuchen Land, at the transition from the western aggradational platform into the outer shelf-slope succession (stage $4S_2$), the platform margin facies thickens markedly (Figs 15, 19) and includes a 200 m thick sequence of dolomitised algal boundstones with archaeocyathans.

The Ryder Gletscher Group is sedimentologically best known in its type area, namely the Warming Land – Nares Land region, where the Cambrian portion (Figs 2, 4) attains a total thickness of about 470 m (Bryant & Smith, 1985; Ineson & Peel, 1987; Peel & Wright, 1985). Within the eastern shelf succession the group is represented within the Cambrian only by the Middle(?) Cambrian Koch Væg Formation (Figs 17A, 20). Earlier stratigraphic nomenclature is based on sections in Inglefield Land and Washington Land where the complete Cambrian sequence of the Ryder Gletscher Group is approximately 590–680 m thick (summaries by Peel & Christie, 1982; Dawes, 1976; Peel, 1982a; Fig. 2).

Cambrian strata of the Ryder Gletscher Group are in the type area assigned to the Blåfjeld, Brikkerne and Blue Cliffs Formations (Fig. 17B). They consist of dessication cracked stromatolitic and cryptalgal dolomites, dark burrow-mottled dolomites, silty lime mudstones and flat-pebble conglomerates. Thrombolitic and stromatolitic bioherms with relief of several metres are developed at several levels in this sequence (Fig. 27). Dessication-cracked, wave-rippled and cross-bedded, fine to medium-grained sandstones and siltstones occur locally in the upper half of the Blue Cliffs Formation (RG6 of Peel & Wright, 1985). These poorly fossiliferous formations record sedimentation on a restricted

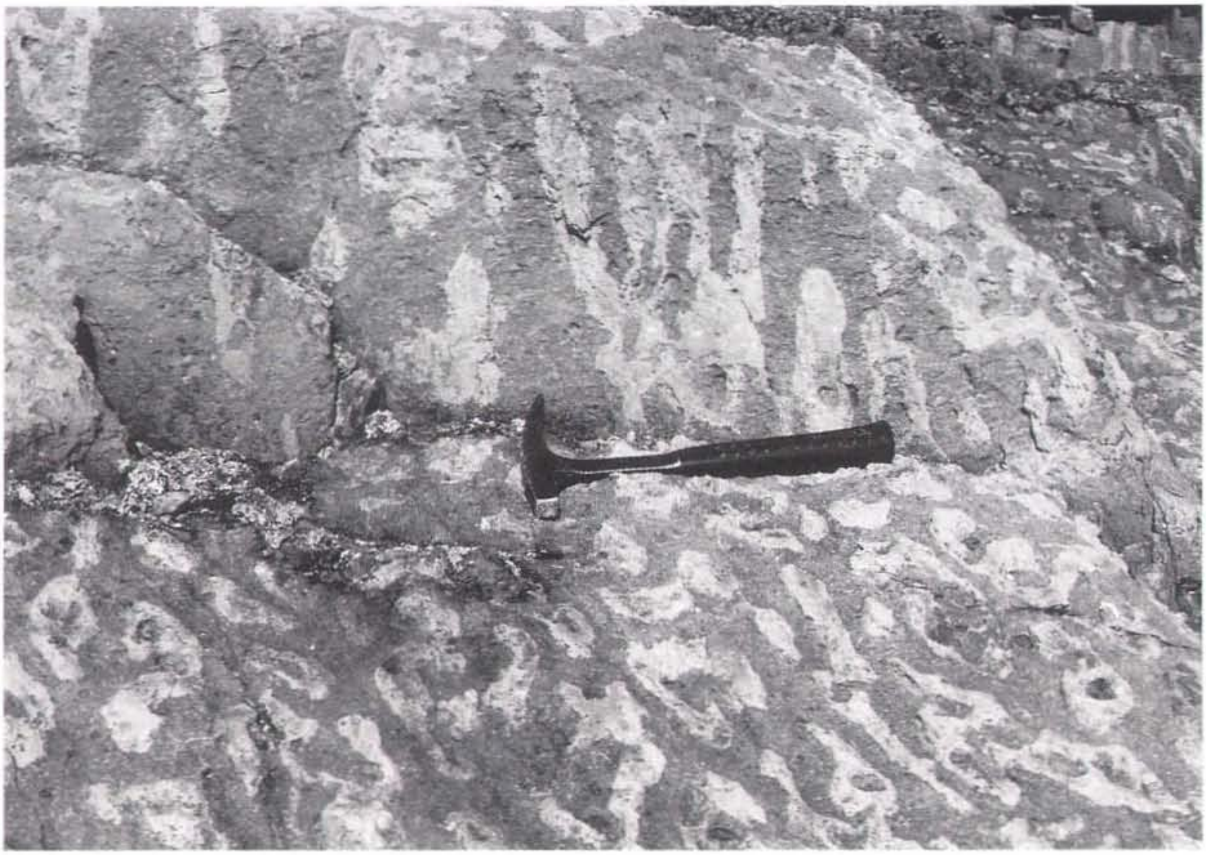


Fig. 27. Stromatolite mound within dolomites of the Brikkerne Formation (Ryder Gletscher Group; stage $4S_{1a}$). The horizontal and vertical sections illustrate the linked columnar form of the stromatolitic framework. South-western Wulff Land.

carbonate platform in shallow subtidal and intertidal environments. The increased siliciclastic content relative to the equivalent carbonates of the Cass Fjord Formation of Washington Land (Figs 2, 4) reflects proximity to the emergent eastern shelf in Late Cambrian times (see below and stage $4S_{1p}$).

Contemporaneous Cambrian platform strata of the Ryder Gletscher Group in Washington Land are assigned to the Kastrup Elv, Telt Bugt and Cass Fjord Formations (Henriksen & Peel, 1976; see Fig. 2). The Kastrup Elv Formation (Early-Middle Cambrian) is approximately 140 m thick and dominated by well-bedded, mottled, crystalline dolomites (Fig. 28A). Paler units of more finely crystalline, laminated dolomites, with stromatolites, occur in the upper part of the formation. The overlying Middle Cambrian Telt Bugt Formation (5–100 m) consists mainly of thin, irregularly bedded, mottled micritic limestones with a wavy silty lamination. The formation grades up into the overlying Cass Fjord Formation which is widely distributed in Washington Land, Inglefield Land and adjacent Ellesmere Island (Peel & Christie, 1982). The latter formation attains a thickness of 470 m in southern Washington Land, but this includes the Kap Coppinger Member (1–30 m) and overlying carbonates at the top of the formation, discussed below (Fig. 28B). The typical Cass Fjord lithology consists of thin, irregularly bedded, micritic limestones with a wavy, silty lamination; scours, ripple marks, dessication cracks and burrows are abundant. Laterally extensive beds of flat-pebble conglomerate up to 50 cm in thickness are common. Calcarenites, thinly bedded, finely recrystallised massive dolomites, thin beds of siltstone and well-sorted sandstone, rare oolites and thin beds of evaporites may be locally prominent.

The Kastrup Elv and Telt Bugt Formations resemble the Blåfjeld and Brikkerne Formations of Wulff Land and Nares Land, while the Cass Fjord Formation below the Kap Coppinger Member is very similar to the Blue Cliffs Formation. They represent environments ranging from restricted sub-tidal lagoons to intertidal and supratidal carbonate mud flats, locally evaporitic.

In Inglefield Land, large-scale cross-bedded to structureless dolomites of the Cape Leiper and Cape Ingersoll Formations (about 40 m) conformably overlie

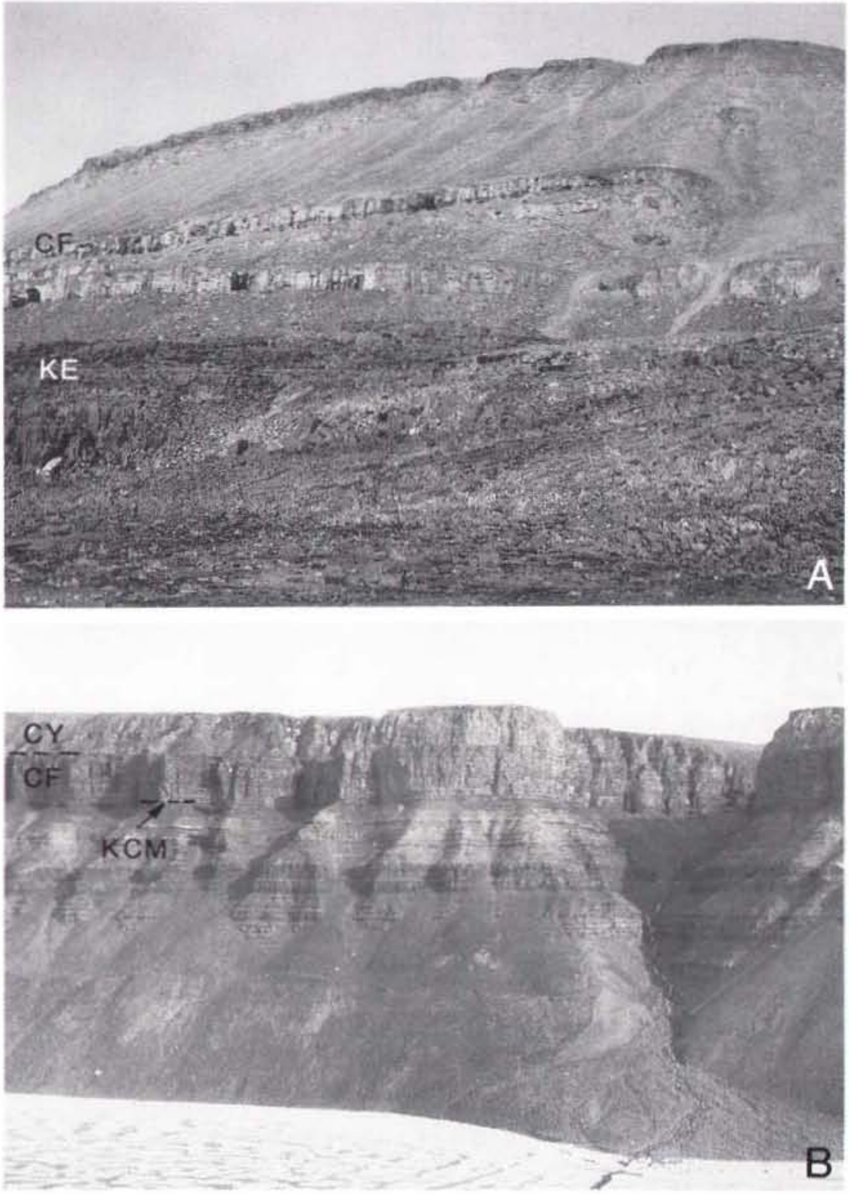


Fig. 28. A, Carbonate sediments of the Cambrian aggradational platform succession of the Ryder Gletscher Group (stage $4S_{1a}$) in southern Washington Land. Dolomites of the Kastrup Elv Formation (KE; Early-Middle Cambrian) are overlain by the Cass Fjord Formation (CF; Middle-Late Cambrian) of mainly micritic limestones. The intervening Telt Bugt Formation is only a few metres thick in this area, and outcrops are covered by talus. Ordovician strata forming the upper part of the Cass Fjord Formation are not visible. About 500 m of strata are exposed. B, Upper parts of the Cass Fjord Formation (CF) and overlying micritic limestones of the Cape Clay Formation (CY) of the Ryder Gletscher Group (stage $4S_{1a-2}$) in southern Washington Land. Quartzites of the Kap Coppinger Member (KCM; about 1.5 m) approximately delimit the Cambrian-Ordovician boundary. The dark unit forming the cliff top in A forms the prominent dark unit in the middle of the cliff. Height of cliff about 500 m.

siliciclastic sediments of the Dallas Bugt Formation (stage 3S; Fig. 2). Succeeding limestones of the Wulff River and Cape Wood Formations (Lower-Middle Cambrian; thickness about 150 m) are lithologically very similar to the Telt Bugt Formation of Washington Land (Peel & Christie, 1982; Peel, 1982a). The Cape Kent Formation (Lower Cambrian; thickness 5–10 m) lies between the latter two formations in Inglefield Land. It is a distinctive unit of oolitic limestone recognised on both sides of Kane Basin (Troelsen, 1950), and represents deposition on high energy ooid sand banks in shallow turbulent water.

The Permin Land Formation and its correlative Kap Coppinger Member of the Cass Fjord Formation form a conspicuous horizon across western North Greenland and broadly serve to separate Cambrian formations of the Ryder Gletscher Group from Ordovician formations of the same group (Figs 28B, 29). The Permin Land Formation conformably overlies the Blue Cliffs Formation between Warming Land and the land area south of Nares Land (Fig. 29) and is of earliest Ordovician age (Bryant & Smith, 1985, 1990). It comprises up to 53 m of well-sorted, well-rounded medium to fine-grained sandstones with subordinate grey dolomite and siltstone interbeds. Sedimentary structures include trough and tabular cross-bedding, wave-ripple lamina-

Fig. 29. Section from the upper part of the Blue Cliffs Formation (B$_3$), at base, through the Permin Land (PL), Johansen Land (J), Warming Land (WA), Steensby Gletscher (SG) and Cape Webster (CW) Formations, all Ryder Gletscher Group (stage 4S$_{1a-2}$) of platform interior origin. The Kap Jackson Formation (KJ) of the Morris Bugt Group (stage 5S$_1$) forms the top of cliff, which is 600 m high. Southern Permin Land.

tion and flat and low-angle lamination; palaeocurrent directions are widely dispersed (Bryant & Smith, 1985, 1990). The formation represents a shallow marine sand sheet of considerable lateral extent which can be traced westwards from south-western Freuchen Land into Washington Land where it forms the Kap Coppinger Member of the Cass Fjord Formation (Figs 2, 28B). This widespread clastic incursion during the earliest Ordovician is correlated with the time of maximum regression and exposure in eastern North Greenland (Fig. 4). Furthermore, Bryant & Smith (1990) propose that pulses of westward progradation of siliciclastic sediments can be correlated with eustatic sea-level lowstands. Broadly contemporaneous siliciclastic incursions also occurred in outer shelf environments (upper Tavsens Iskappe Group) and in trough environments (Vølvedal Group).

Outer shelf and slope facies of Cambrian and early Ordovician age in this western area are exposed intermittently along the northern coastline of western and central North Greenland between Nyeboe Land and Nares Land. These rocks are readily correlated with the more extensive outer shelf-slope rocks of the progradational eastern shelf and have been described briefly together with the eastern succession (see stage 4S$_{1p}$, above).

4S$_2$: Ordovician aggradational platform

Regional uplift of the eastern shelf was probably initiated as early as the late Early Cambrian (uppermost stage 3) and culminated in extensive exposure of the shelf during the latest Cambrian and earliest Ordovician. The resultant hiatus decreases in stratigraphic importance towards the west (Figs 2, 4, 15, 30, 31). Although the hiatus partly represents non-deposition due to progressive shelf exposure during the later part of the Cambrian, it also records extensive erosion of earlier Cambrian and late Precambrian strata. In eastern North Greenland, this erosion may have removed up to 1 km of section and the detritus was probably shed northwards, contributing to the North Greenland trough fill in the latest Cambrian and Early Ordovician (Hurst & Surlyk, 1983b; Surlyk & Hurst, 1984). In south-western Peary Land and Freuchen Land, shelf emergence was preceded by deposition of a thick succession of northward-prograding quartz-rich siliciclastic sediments (Perssuaq Gletscher Formation; Fig. 21) of Late Cambrian to earliest Ordovician age. This regressive clastic influx is represented farther west by the shallow marine siliciclastic sediments of the Permin Land Formation (see stage 4S$_{1a}$ and Fig. 15; Bryant & Smith, 1990) and to the north in the trough by the sandstone turbidites of the Vølvedal Group (Surlyk & Hurst, 1984; Surlyk *et al.*, in prep.). Migration of these regressive siliciclastic sediments over the exposed karstified platform in the east is recorded by sandstone infilling karstic fractures and vugs.

This episode of westward propagating, progressive regional uplift in eastern areas of North Greenland during the later part of the Cambrian and earliest Ordovician has been interpreted as the record of westward expansion of a peripheral bulge during an early collision event along the western margin of the Iapetus Ocean

Fig. 30. Lower Ordovician dolomites of the Wandel Valley Formation (W; Ryder Gletscher Group, stage $4S_2$) unconformably overlying Lower Cambrian dolomites of the Brønlund Fjord Group (BFG; Aftenstjernesø and Paralleldal Formations; stage $4S_{1p}$). The hiatus represented by the unconformity beneath the Wandel Valley Formation decreases in magnitude to the west such that angular discordance has not been recognised west of Nares Land (see Fig. 31). Southern Peary Land, with the base camp used during the first phase of the North Greenland Project. Bu, Buen Formation. Cliff is 600 m.

(Surlyk & Hurst, 1984). Uplift in central and eastern North Greenland ceased sometime in the Early Ordovician, and was followed by regional marine transgression in the late Early Ordovician, probably partly as a result of a eustatic sea-level rise. The previously exposed eastern portion of the North Greenland shelf thus became part of a continuous, mainly low-energy shallow marine aggradational shelf, extending across North Greenland. Platform sedimentation in the east is recorded by the Wandel Valley Formation (late Early – Middle Ordovician) and the Sjælland Fjelde Formation (early Middle Ordovician) of the Ryder Gletscher group (Figs 2, 4, 15, 17A, 20, 21, 30; Christie & Peel, 1977; Ineson *et al.*, 1986; Peel & Smith, 1988). In the western areas the Cambrian aggradational shelf continued its development into the Ordovician, as recorded by strata above the Permin Land Formation and its correlative Kap Coppinger Member (Figs 2, 4, 29, 31).

The Wandel Valley Formation (320–410 m) is dominated by pale dolomites. These may be burrow mottled with an irregular, parallel, discontinuous lamination, or exhibit cryptalgal and horizontal lamination, and wave and current formed cross-lamination, as well as dessication and water escape features. In the lower part of the formation dark, nodular, burrow mottled, pelletal lime mudstones containing *Ceratopea* and other gastropods are interbedded with the dolomites in 2–5 m, rarely up to 15 m, thick shallowing upwards cycles (Hurst & Surlyk, 1983b; Sønderholm & Due, 1985; Peel & Smith, 1988). The Wandel Valley Formation thus represents

Fig. 31. Restricted platform sediments of the Ryder Gletscher Group (stage $4S_2$) east of the southern tip of Nares Land, showing the western extension of the sub-Wandel Valley Formation unconformity (u) within the Warming Land Formation (WA). Basal beds of the latter, and of the underlying Johansen Land (J) and Permin Land (PL) Formations, are truncated over the crest of a shallow E-W trending anticline. B_3, Blue Cliffs Formation; SG, Steensby Gletscher Formation; CW, Cape Webster Formation. The Permin Land Formation is 23 m thick.

deposition in low-energy tidal flat and lagoonal environments on a slowly, but continuously subsiding platform.

In Kronprins Christian Land, the Wandel Valley Formation is overlain by the Sjælland Fjelde Formation (105 m) which in the lower part is dominated by bioturbated, skeletal lime mudstones and burrow mottled dolomites, with flat pebble conglomerates occurring throughout. The upper part is characterised by pale weathering, cryptalgally laminated dolomites. Spar-filled vugs and fenestrae, dessication cracks and stromatolite domes are common in places, as are bioturbation and halite pseudomorphs. The sediments reflect deposition in generally low-energy, shallow subtidal to low supratidal, locally evaporitic, environments (Ineson *et al.*, 1986; Peel & Smith, 1988).

The shallow marine sandstones of the Permin Land Formation in the western part of North Greenland mark a change from dominantly restricted carbonate platform deposits beneath (stage $4S_{1a}$) to an alternation of restricted and more open marine carbonate facies above (stage $4S_2$). This shift, which roughly coincides with the Cambrian-Ordovician boundary, was probably the result of a slight relative sea-level rise displacing the facies belts of the carbonate platform southwards.

The western part of the Ordovician succession assigned to the Ryder Gletscher Group can be regarded in terms of two major shallowing-upward cycles. Each cycle begins with carbonates, mainly of shallow subtidal aspect, which pass up into peritidal facies, often associated with evaporitic deposits. The thickness of these deposits increases from approximately 335 m in Nares Land to 850 m in Washington Land, reflecting decreasing influence of the area of uplift in the Peary Land region.

The lower, dominantly subtidal portion of the first cycle is represented by the Johansen Land Formation (15–35 m) in central and more western parts of North Greenland (Figs 29, 31) and by the uppermost Cass Fjord (30 m), Cape Clay (50 m) and Christian Elv (140 m) Formations in Washington Land (Henriksen & Peel, 1976; Sønderholm & Due, 1985; Fig. 28B). These mainly comprise burrow-mottled, nodular dolomites and lime mudstones with subordinate wave and current-rippled lime grainstones and flat-pebble conglomerates. Occasional algally laminated dolomites, columnar stromatolites, scalloped surfaces and siliciclastic intervals in the Washington Land sequence reflect periodic shallowing into the intertidal zone.

The upper portion of this cycle in the Warming Land – Nares Land area (Warming Land Formation; 50–150 m) consists of alternating dark and light grey fine-grained dolomites showing current and wave-ripple cross lamination, flaser and wavy bedding and abundant bioturbation (Fig. 32). Scalloped surfaces, cryptalgal dolomites with desiccation cracks and gypsum nucleation cones pseudomorphed by chert occur in places. These sediments were deposited on prograding tidal flats, dominated by very shallow subtidal to supratidal, locally probably evaporitic, environments (Sønderholm & Due, 1985). Farther west, in Washington Land, however, this interval is dominated by evaporitic deposits of the Poulsen Cliff (100–125 m) and Nygaard Bay (40 m) Formations (Figs 2, 4, 33) which are direct correlatives

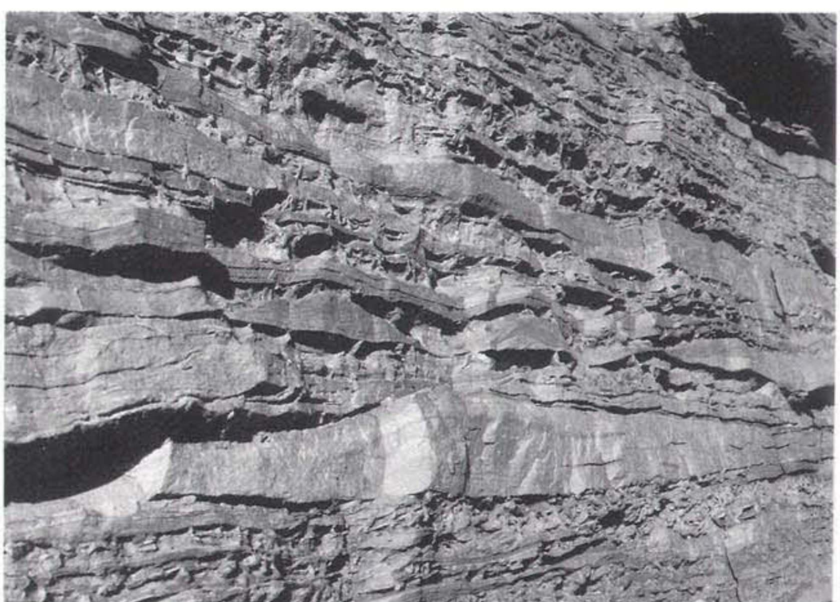


Fig. 32. Extensively burrowed, fine-grained dolomite showing wavy and flaser bedding (Warming Land Formation, stage $4S_2$). The ripples in the centre of the picture are 3 cm high. Eastern Warming Land.

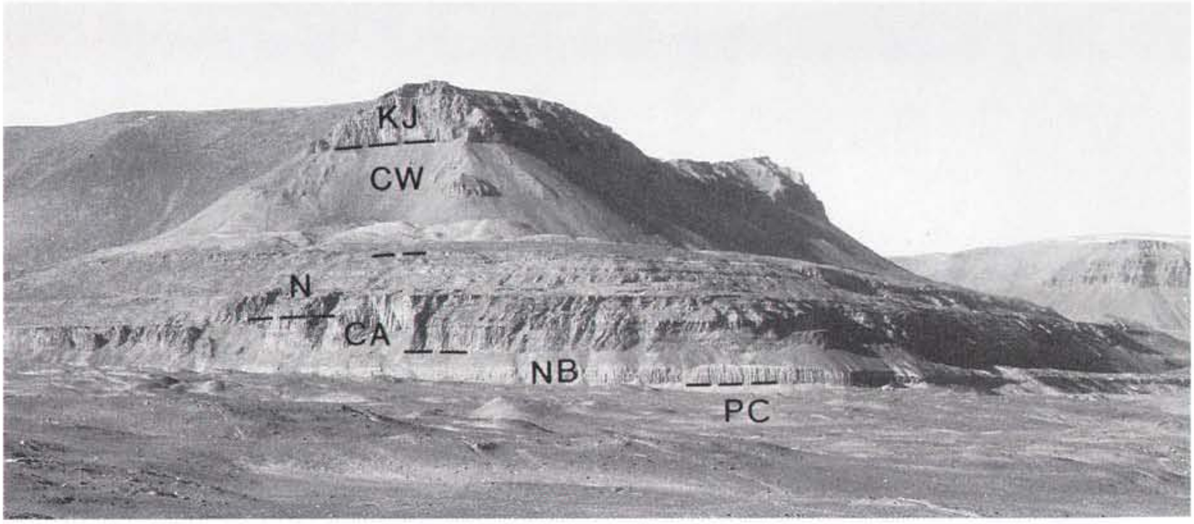


Fig. 33. Ryder Gletscher Group (stage $4S_2$) overlain by the Kap Jackson Formation (KJ) of the Morris Bugt Group (stage $5S_1$) in central Washington Land. The transition from recessive dolomitic sediments (stage $4S_2$) to cliff-forming limestones (stage $5S_1$) is a conspicuous marker traceable across most of the North Greenland shelf. PC: Poulsen Cliff Formation. N, Nunatami Formation; NB, Nygaard Bay Formation (45 m thick); CA, Canyon Elv Formation; CW, Cape Webster Formation.

of the thick evaporitic succession of Ellesmere Island (Baumann Fjord Formation; see Peel & Christie, 1982). These gypsum deposits may show fine irregular lamination, current or wave-ripple lamination or may consist of nodular or nodular-mosaic gypsum (Fig. 34); they commonly occur interbedded with laminated shaly dolomites on a 10 m scale. By analogy with the Ellesmere Island deposits (cf. Trettin, in press) these evaporites are probably subaqueous deposits that accumulated in a broad, shallow, possibly segmented saline basin. The lower half of the Nygaard Bay Formation is dominated by dark limestones with intraformational conglomerate interbeds and is probably of shallow subtidal or intertidal origin.

The basal portion of the second cycle represents a marked transgression of probable eustatic origin which can be traced from Ellesmere Island (Eleanor River Formation; Barnes, 1984) across Washington Land (Canyon Elv and Nunatami Formations; 40–60 m and 150 m, respectively) and the rest of western and central North Greenland (Steensby Gletscher Formation; 90–135 m) to eastern North Greenland (Wandel Valley Formation; 320–410 m). In the west the basal part of the second shallowing upward cycle is typified by dark, thick-bedded, burrow-mottled lime mudstones containing a rich open-marine fauna. These low-energy, subtidal deposits are dominant, but pale dolomites, locally algally laminated and dessication cracked, occur in some southern localities and towards the top of the Nunatami and Steensby Gletscher Formations (Peel & Cowie, 1979; Sønderholm & Due, 1985); they reflect periodic progradation of shallow subtidal to intertidal environments. The overlying Cape Webster Formation (175–280 m; see Fig. 33) marks the return to restricted conditions on the carbonate platform. It consists of grey to dark grey fine-grained dolomites with horizontal lamination, often with desiccation cracks and fluidisation features. Evaporites occur in the lower part of the formation in southern Washington Land and near the top in Nares Land, while breccias, possibly of solution origin, are common in Warming Land and central Washington Land (Sønderholm & Due, 1985).

4T: Starved trough

In southern Johannes V. Jensen Land the slope-and-rise red and green coloured Frigg Fjord mudstones at the top of the Polkorridoren Group are overlain by an outer slope and trough-floor sequence including dark mudstones, cherts, turbidites and base-of-slope conglomerates (Surlyk & Hurst, 1984). These upper Lower Cambrian to Lower Ordovician deposits are placed in the Vølvedal Group (Friderichsen *et al.*, 1982; Surlyk *et al.*, in prep.). The group differs markedly from the outer shelf and slope sequence described above by its much greater thickness, and by the presence of thick sandstone turbidite units. Higgins & Soper (1985) suggested that the turbidites of the Vølvedal Group did not extend much beyond the west point of Amundsen Land; it is possible that these deposits were in fact restricted to

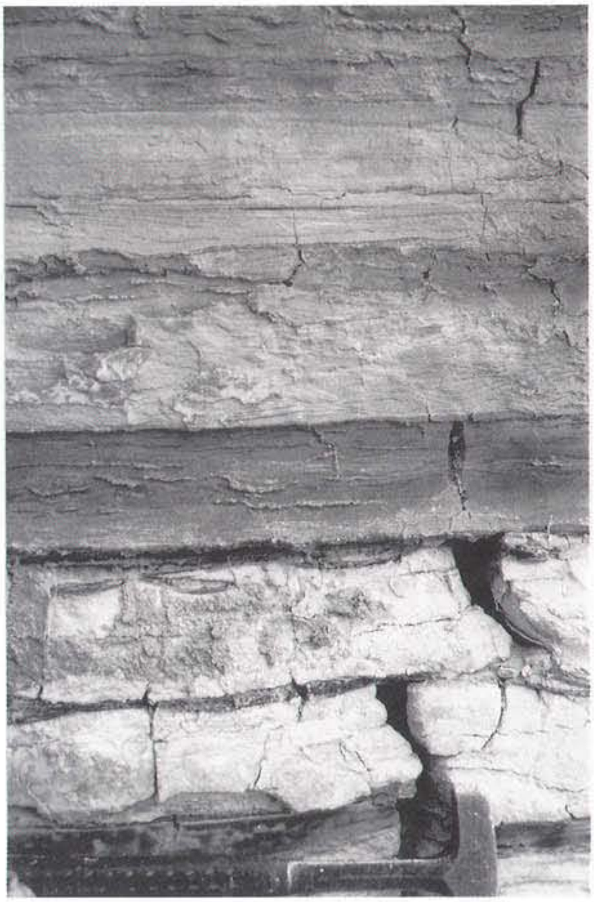


Fig. 34. Irregularly laminated, current and wave laminated, and massive gypsum deposits of the Poulsen Cliff Formation (stage $4S_2$). Hammer for scale. Central Washington Land.

the eastern part of the trough, if their deposition was linked to uplift of eastern areas in the Cambrian as suggested by Surlyk & Hurst (1984). However, the absence of outcrops of the trough sequence in Nansen Land makes this difficult to verify, and farther west in western North Greenland, this part of the basin is situated north of the present-day land areas. Comparable turbidites are not known from equivalent strata of the Hazen Formation in the outcrops of north-east Ellesmere Island.

The present outcrops of the Vølvedal Group are almost confined to southern Johannes V. Jensen Land, including Amundsen Land, and the region adjacent to Frederick E. Hyde Fjord (Fig. 35; Map 1). The group is generally 600–700 m thick. It begins with dark-grey and black non-bioturbated mudstones with thin-bedded turbidites comprising the Nornegæst Dal Formation. Deposition of the formation took place on the trough floor under poorly aerated conditions. Fine-grained sedimentation continued in the form of greenish chert, cherty mudstones and siltstones, locally with fine sandstone turbidites. These deposits form the approximately 50 m thick Drengs Bræ Formation.

The quiet, partly anoxic trough floor sedimentation was eventually interrupted by the influx from the south of medium-bedded to thick-bedded quartzitic turbidites of the Bøggild Fjord Formation (Fig. 36). The turbidites alternate with thin beds of black mudstones. The formation is approximately 240 m thick and is interpreted as representing one or more relatively small borderland fans prograding northwards into the trough, where black and green bedded cherts and black mudstones with thin-bedded fan fringe and basin-plain turbidites were deposited. The more proximal southern occurrences display channellised mid-fan and outer fan lobe features, and the turbidite units decrease dramatically in bed thickness and in sand/mud ratio towards the north (Fig. 37).

Along strike the fan turbidites pass into interfan mudstones of the trough floor. All mudstones and fine-grained, thin-bedded turbidites are chertified to varying degrees. In many cases the chertification is so intense that the original turbidite features are completely masked.

Towards the end of submarine-fan deposition the upper slope underwent slumping on a large scale. A composite debris sheet in southern Johannes V. Jensen Land is up to 20 m thick and can be traced along strike for 75 km. The mainly clast-supported conglomerates are composed largely of tabular, angular clasts of laminated carbonate that range in size from pebbles to boulders up to 1 m long, set in a lime mudstone matrix. Clasts often show varying degrees of plastic deformation, indicating that the parent rock was only partially lithified at the time of slumping and subsequent mass-flow transport. Clast lithologies suggest derivation from the upper slope and outer shelf rather than from the carbonate platform. One conspicuous boulder type comprises alternations of grey limestone and yellow dolomite, known to form thick developments in the equivalent Cambrian sequence of the outer shelf and slope (Kap Stanton Formation of the Tavsens Iskappe Group; unit 3 of Higgins & Soper, 1985).

There is little faunal control of the age of the Vølvedal Group, and the late Early Cambrian age of the base is fixed by comparison with the outer shelf and slope deposits. Early Ordovician graptolites are fairly common in mudstones in the middle and upper levels of the group.

A local development of the submarine fan sequence occurs in southern Johannes V. Jensen Land. It consists of thin to medium-bedded calcarenitic turbidites, carbonate conglomerates and black shales. The carbonate

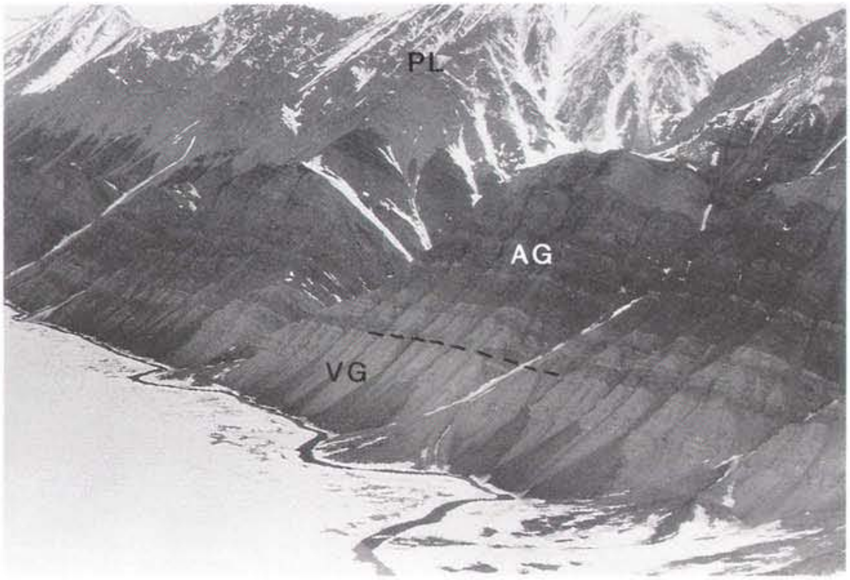


Fig. 35. North side of O. B. Bøggild Fjord showing turbidites of the Vølvedal Group (VG, stage 4T), overlain by black cherts and shales with carbonate and chert conglomerates of the Amundsen Land Group (AG, stage 5T), and by turbidites of the Merqujôq Formation, Peary Land Group (PL, stage 6T).

dominated lithology probably reflects the progressive uplift and erosion of the eastern platform region.

Stage 5: Middle Ordovician – Early Silurian aggradational carbonate platform, starved slope and trough

This stage in basin evolution is marked by a backstepping of the platform margin to approximately the line of the Navarana Fjord escarpment (Figs 3, 5; stage 5). Aggradational carbonate deposition continued to build up on the platform to the south with the platform margin forming a scarp-like feature (Figs 4, 38). North of the scarp the slope was starved receiving very restricted amounts of sediment. Farther north, in the deep-water trough, deposition was also slow, but considerably greater than in the slope areas. The relatively starved phase of slope and trough deposition lasted until the close of the Ordovician, when it was terminated by the abrupt commencement of turbidite deposition of the Peary Land Group (stage 6T).

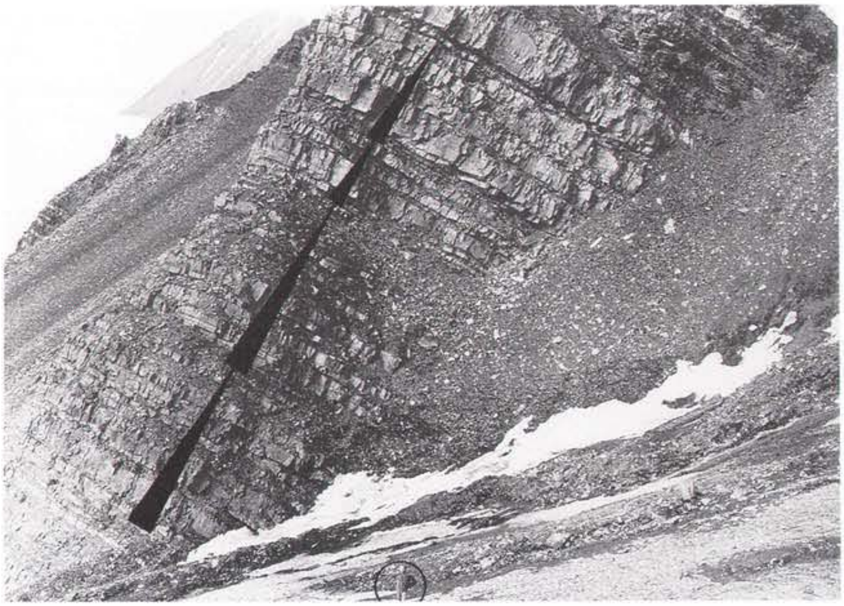


Fig. 36. Stacked, thinning-upwards turbidite sequences representing mid-fan channels. Vølvedal Group (stage 4T), O. B. Bøggild Fjord. Person for scale (ringed).

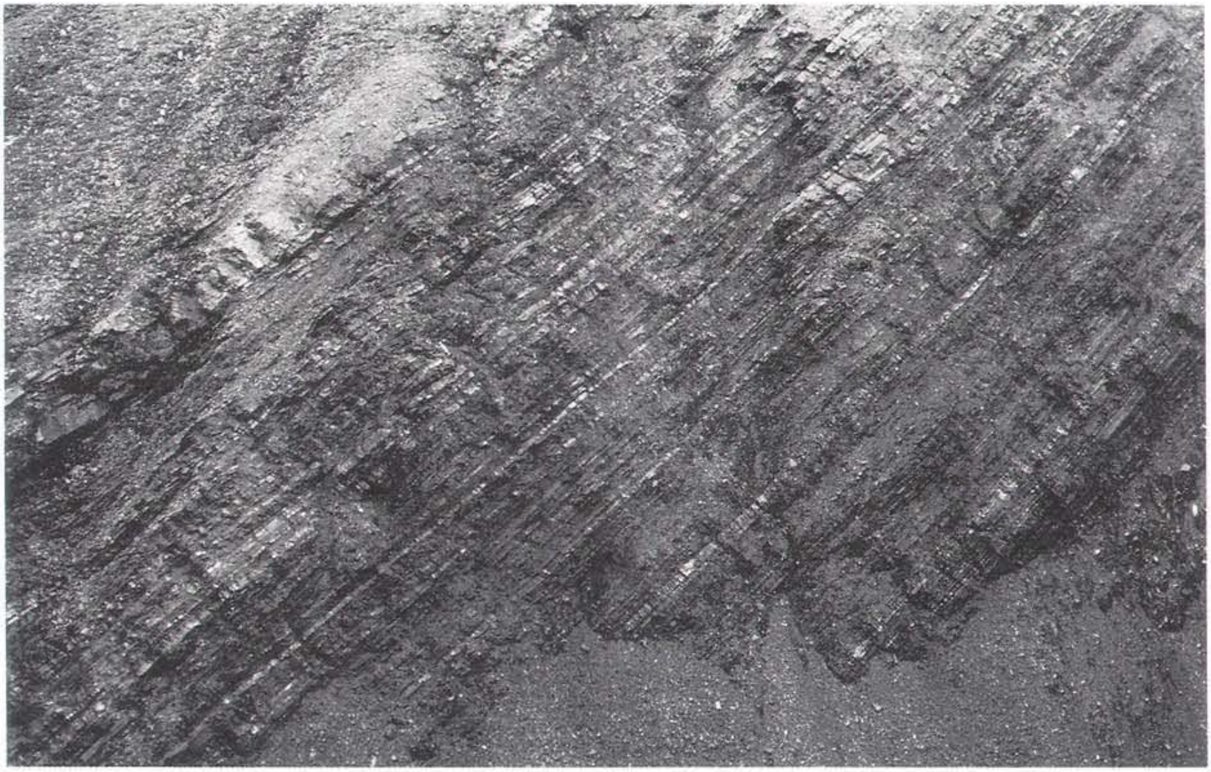


Fig. 37. Fan fringe and basin plain turbidites, black cherts and mudstones of the Vølvedal Group, stage 4T. Johannes V. Jensen Land. Thickness of consistent light beds in the middle of the section is about 10 cm.

$5S_l$: *Aggradational platform*

The phase in the evolution of the shelf recognised as stage 5 commenced with the late Middle Ordovician transgression (Christie & Peel, 1977; Fortey, 1984) and persisted into the Early Silurian (Early to Middle Llandovery). It is represented by the Morris Bugt Group and the basal part of the Washington Land Group (Hurst, 1980a; Hurst, 1984; Sønderholm *et al.*, 1987; Smith *et al.*, 1989, Sønderholm & Harland, in prep.) (Figs 2, 4).

The constant total thickness of these carbonate units throughout the region (*c.* 650 m) reflects uniform subsidence over the area (Smith *et al.*, 1989).

The shelf was bounded by an escarpment hundreds of metres high which can be seen in the inner parts of Navarana Fjord and at J. P. Koch Fjord (Fig. 38), where it forms an erosional sediment by-pass zone (Surlyk & Hurst, 1984; Surlyk & Ineson, 1987a). The extension of the escarpment further to the west as far as northern Nyeboe Land and north of Hall Land is inferred from stratigraphic considerations and from changes in the style of tectonic deformation (Escher & Larsen, 1987; Hurst & Surlyk, 1982; Larsen & Escher, 1985). Hurst & Kerr (1982) suggested that the isolated outcrop of carbonates around Kap Ammen in northern Hall Land (Figs 1, 2, 39) represented an Early Llandovery carbonate horst surrounded by deep-water shelf clastic sediments. However, the presence of the same facies and lithostratigraphic units in the southern part of Nyeboe Land seems to indicate that the carbonate shelf extended unbroken from the southern outcrop belt to northern Hall Land and Nyeboe Land until late in the Middle Llandovery (Dawes & Peel, 1984; Sønderholm *et al.*, 1987).

The shelf margin itself is only clearly exposed in the inner parts of J. P. Koch Fjord and Navarana Fjord (Figs 38, 40) and these outcrops also closely resemble the equivalent exposures at Kap Ammen in northern Hall Land (Fig. 39). Hurst & Surlyk (1983b) described mud mounds up to 200 m in diameter and 50–100 m high from the shelf margin at J. P. Koch Fjord. The mounds apparently had considerable relief above the surrounding level-bedded sediments.

Elsewhere in Peary Land, shelf margin facies equivalent to the Turesø Formation are only known from large blocks contained in contemporaneous base-of-slope conglomerates of the Citronens Fjord Member

(Figs 2–4), occurring along the southern coast of Frederick E. Hyde Fjord (Hurst & Surlyk, 1982; Hurst, 1984). The boulders consist of distinctive lithoclastic-bioclastic grainstones rich in fragments of virgianid brachiopods, stromatoporoids, gastropods and algae. Some small dolomite clasts are red stained. This suggests that the shelf was rimmed by high energy carbonate sand shoals; the abundance of algae may indicate the presence of algal reefs well within the photic zone with possible episodes of subaerial exposure (Hurst, 1984).

The sediments of the Kap Jackson Formation, together with the Cape Calhoun Formation and the Newman Bugt Member of the Aleqatsiaq Fjord Formation with a total thickness ranging from 300 to 390 m, and the corresponding Børglum River Formation (approximately 430 m) (Figs 2, 4, 38, 41) are dominantly dark, nodular, burrow mottled lime mudstones, skeletal wackestones and packstones. Epifauna and infauna are abundant and algal remains are common. These level-bedded sediments are of typical subtidal carbonate shelf aspect. The lack of grainstones suggests low energy environments probably below normal wave base, while the abundant fauna and algae indicate an oxygenated substrate within the euphotic zone.

This stable and uniform phase of deposition came to an end in latest Ordovician to earliest Silurian time as a result of a pronounced shallowing, followed by a later deepening of the entire shelf. The event is represented by the upper two units (the Kap Ammen and Store Canyon Members; 115–160 m) of the Aleqatsiaq Fjord Formation (Sønderholm & Harland, in prep.) and the 115–150 m thick Turesø Formation (Figs 2, 4; Hurst, 1984). The great lateral extent of these units and the timing of the shallowing and deepening may indicate eustatic events related to the late Ordovician glaciation (Brenchley & Newall, 1980; Fortey, 1984; McKerrow, 1979). The Kap Ammen Member of the Aleqatsiaq Fjord Formation consists of light grey, massively bedded, variably biostromal and coralliferous skeletal limestones. *In situ* stromatoporoids and corals are locally very abundant and contribute to the formation of small mounds in some areas, e.g. Bessels Fjord, Petermann Fjord, Newman Bugt and Kap Ammen (Fig. 39) (Sønderholm & Harland, 1989a). The sediments are interpreted as being of agitated, shallow, open shelf origin, reflecting a relative lowering of sea-level compared to the underlying unit. Towards the east, in the Nares Land to J. P. Koch Fjord region, the Kap Ammen Member becomes progressively more dolomitic and less fossiliferous, suggesting a more restricted environment (Sønderholm *et al.*, 1987). Farther to the east in Peary Land, it grades into the light weathering dolomites of the lower part of the Turesø Formation (Hurst, 1984).

The Turesø Formation in central Peary Land displays a well developed cyclicity (Fig. 42), each cycle varying from 2 to 20 m in thickness and consisting of burrow mottled, dolomitic wackestones with occasional calcsilt-ripples and rare benthic fauna, overlain by laminated and cryptalgally laminated or fenestral dolomites (Armstrong & Lane, 1981; Fürsich & Hurst, 1980; Hurst, 1984). The scarcity of intraclast conglomerates and shelly coquinas suggests that the whole succession was formed under very low energy conditions, and the possibility of periodically raised salinities has been discussed (Fürsich & Hurst, 1980; Hurst, 1984). In the G. B. Schley Fjord region to the north-east the environment again became more open marine. Here, the Turesø Formation is darker, less dolomitic and consists almost entirely of nodular lime wackestones.

The deepening which followed this phase of shallow-water deposition is represented by the sediments of the Store Canyon Member of the Aleqatsiaq Fjord Formation in the Washington Land to J. P. Koch Fjord region (Fig. 39) and the upper part of the Turesø Formation in Peary Land and Kronprins Christian Land (Figs 2, 4, 42). The Store Canyon Member is uniformly developed over the entire area and comprises very dark, strongly mottled, bituminous, fine-grained skeletal limestones with abundant large pentamerid brachiopods and frequent stromatoporoids and corals of Silurian age (Fig. 43). These sediments originated on an open, mainly low-energy, shelf. The upper part of the Turesø Formation in central Peary Land consists of dolomites much like the lower unit but dominated by the darker subtidal facies (Armstrong & Lane, 1981; Christie & Peel, 1977; Hurst, 1984). To the north-east, in the G. B. Schley Fjord region, the upper part of the Turesø Formation is more reminiscent of the Store Canyon Member of the Aleqatsiaq Fjord Formation, again suggesting a deepening of the shelf towards the east (Christie & Ineson, 1979).

This phase in the evolution of the stable platform came to a close during the Early Silurian which was a period of general shallowing of the platform sea, probably due to rapid vertical accretion. This period is represented by the Ymers Gletscher Formation in Peary Land, the Petermann Halvø Formation between J. P. Koch Fjord and Bessels Fjord (Fig. 39, see also Fig. 46) and parts of the Kap Godfred Hansen, Pentamerus Bjerge and Adams Bjerg Formations (Figs 2, 4) (Hurst, 1984; Sønderholm & Harland, in prep.).

The Ymers Gletscher Formation (25–45 m) comprises grey, thinly laminated and well bedded fenestral lime mudstones. Coquinas dominated by pentamerid brachiopods are present as well as desiccation cracks (Armstrong & Lane, 1981; Hurst, 1984). The sediments re-

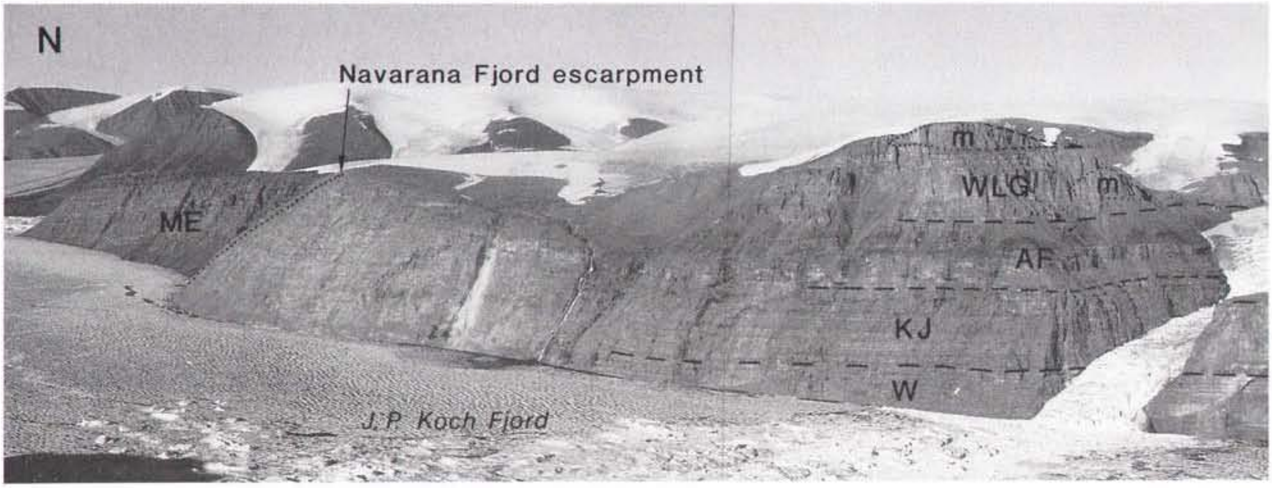
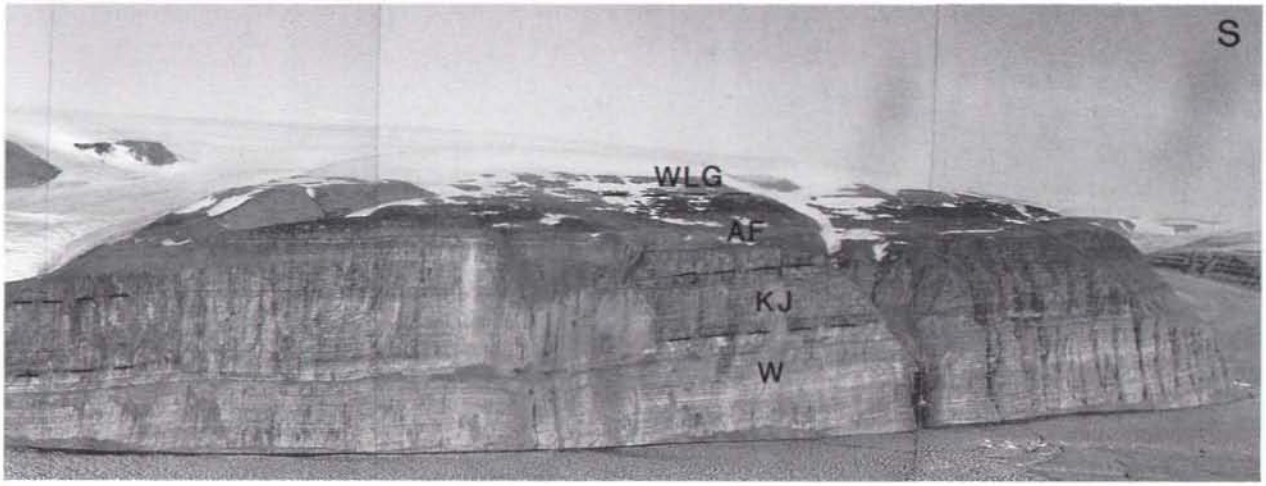


Fig. 38. Platform margin escarpment (Navarana Fjord escarpment) on the east side of J. P. Koch Fjord. Sandstone turbidites of the Merqujôq Formation (ME, stage 6T) abut against platform carbonates of stages $5S_1$ and 6S forming the escarpment. Note that bedding in the carbonates becomes diffuse as the escarpment is approached. W, Wandel Valley Formation, Ryder Gletscher

Fig. 39. Carbonate shelf sequence (stage $5S_1$ and 6S) at Kap Ammen, northern Hall Land close to the shelf margin. Dark open marine deposits of the Store Canyon Member (SC) of the Aleqatsiaq Fjord Formation (AF), are overlain by pale carbonates of the Petermann Halvø Formation (PH). Shelf edge mounds (m) with intermound deposits make up the overlying Djævlekløften Formation (DK). The shelf carbonates are overlain by deep sea fan turbidite sequences of the Peary Land Group (PL; stage 7T). In the distance, a linear belt of reefs (stage 7S) forms the Hauge Bjerge. KA, Kap Ammen Member; NB, Newman Bugt Member. Aerial photograph 546 K-S no. 2190. Copyright Kort- og Matrikelstyrelsen, Denmark; reproduced with permission A.200/87.



Group (stage $4S_2$); KJ, Kap Jackson Formation (stage $5S_1$); AF, Aleqatsiaq Fjord Formation (stage $5S_1$); WLG, Washington Land Group (stage $5S_1$ and 6S) with small mounds (m). Cliff 800 m.

Fig. 40. Platform margin relationships on the west side of Navarana Fjord. Top of the drowned Silurian platform margin scarp to the left (S, stage 6S), onlapped by turbidites of the Merqujôq Formation to the right (ME, stage 6T). Carbonate conglomerates of the Navarana Fjord Member (NF) drape the platform carbonates, interfinger with the highest turbidites of the Merqujôq Formation and are overlain by black shales and thin-bedded turbidites of the Thors Fjord Member (TFM) of the Wulff Land Formation and turbidites of the Lauge Koch Land Formation (L, stage 7T). The thickness of the Navarana Fjord Member is 80 m.

Fig. 41. Dark, cliff-forming carbonates of the Morris Bugt Group, representing the open marine shelf deposits of stage $5S_1$. KJ, Kap Jackson Formation; CC, Cape Calhoun Formation; NB, KA, Newman Bugt and Kap Ammen Members of the Aleqatsiaq Fjord Formation. The Steensby Gletscher (SG) and Cape Webster (CW) Formations of the Ryder Gletscher Group (stage $4S_2$) form the lower half of these 700 m high cliffs in southern Permin Land. Base camp of the Geological Survey of Greenland expedition 1984–85 in foreground.

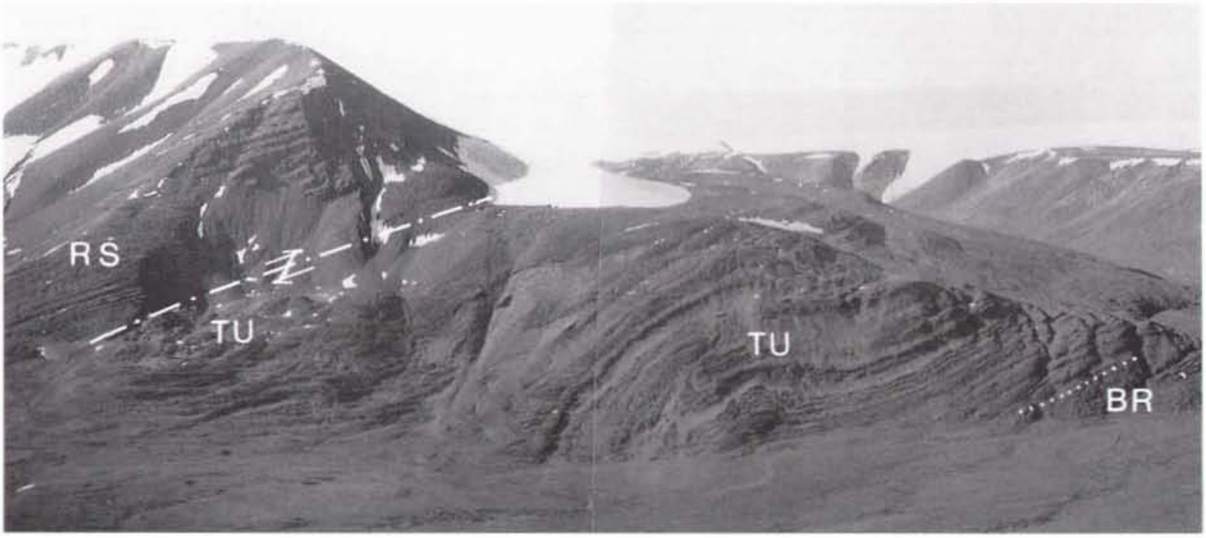


Fig. 42. Alternations of pale and dark coloured dolomitic limestones of the Turesø Formation (TU) overlying dark limestones of the Børglum River Formation (BR), central Kronprins Christian Land (both stage $5S_1$). Caledonian deformation has disturbed the sequence, and emplaced a thrust sheet of Proterozoic sandstone turbidites (RS: Rivieradal Sandstone) over the Turesø Formation. Cliff height 800 m.

Fig. 43. Strongly mottled, bituminous skeletal pentamerid limestone with frequent stromatoporoids (Aleqatsiaq Fjord Formation, Store Canyon Member, stage $5S_1$). Pencil is 15 cm long.

flect deposition in peritidal environments, possibly with raised salinities (Fürsich & Hurst, 1980). The sediments of the Petermann Halvø Formation (95–130 m) are dominated by light grey to dark, flat-bedded, skeletal limestones, usually rich in laterally extensive coral and stromatoporoid colonies with locally abundant crinoid debris. Facies variations within the Petermann Halvø Formation, reflect a slight deepening from peritidal, possibly partly emergent environments, in the south, to shallow outer platform in the north. Peritidal environments represented by cryptalgally laminated dolomites have only been recorded from the lower part of the Adams Bjerg Formation farthest to the south-west (Hurst, 1980a; Sønderholm *et al.*, 1987; Sønderholm & Harland, in prep.).

$5S_2$: Starved slope

The outer shelf and slope carbonates and mudstones of stage $4S_{1p}$ between northern Nyeboe Land and central J. P. Koch Fjord are overlain by a sequence of chert and cherty shales, with partly chertified successions of siltstones, black limestones and dolomitic mudstones (Fig 9; unit 4 of Higgins & Soper, 1985). This starved slope sequence is generally between 50 m and 150 m in thickness, and is assigned to a new formation of the Amundsen Land Group. Rich graptolite faunas occur throughout, and show an age range from Tremadoc to Late Llandovery.

Throughout the area between northern Nyeboe Land and central J. P. Koch Fjord, chert and mudstone deposition was brought to a close in the Late Llandovery with the incoming from the east of the first sand turbidites of the Peary Land Group (Higgins & Soper, 1985; Surlyk, 1982; Surlyk & Hurst, 1982). Deposition of fine grained turbidites was initiated slightly earlier, in latest Ordovician time towards the east in the Peary Land area. These distal turbidites are interbedded with black mudstones and cherts characteristic of stage 5T and they are accordingly not included in the Peary Land Group (Hurst & Surlyk, 1982; Surlyk *et al.*, 1980; Surlyk *et al.*, in prep.).

The Ordovician starved slope sequence passes downslope into similar, but more basinal and more thickly developed sediments of the same age which are only preserved in the type area of the Amundsen Land Group.

5T: Trough

The relatively small-sized borderland fans of the Vølvedal Group (stage 4T) were eventually abandoned and a long period of basin starvation and, at times, also stagnation set in (Surlyk & Hurst, 1984). In southern Johannes V. Jensen Land, including Amundsen Land, and the areas along the south side of Frederick E. Hyde Fjord, the deposits of this period are included in the Early Ordovician – Early Silurian Amundsen Land Group (Friderichsen *et al.*, 1982; Surlyk *et al.*, in prep.). The sedimentary facies are dominated by black and green radiolarian cherts and black and green mudstones; they include thin-bedded turbidites and thick carbonate conglomerates.

Turbidite deposition of the previous stage (Bøggild Fjord Formation of the Vølvedal Group) rapidly waned, and stage 5T was heralded by a change to slow sedimentation of mud and siliceous ooze mainly under anoxic conditions (Harebugt Formation of the Amundsen Land Group). In latest Tremadoc and Arenig times the quiet deposition of fine-grained sediments was interrupted by a period dominated by deposition of carbonate conglomerates and turbidites of the Kap Mjølner Formation which reaches a thickness of up to 200 m

Fig. 44. Sheet of base-of-slope carbonate conglomerates and calcarenites in the lower part of Amundsen Land Group, stage 5T. Individual beds are up to 10 m thick; the height of the wall is about 100 m. Southern Johannes V. Jensen Land.

in the southernmost localities around inner Frederick E. Hyde Fjord (Fig. 44). The conglomerates often form the base of fining-thinning upward cycles, considered to reflect waning deposition resulting from episodes of slumping and successive development of mass flows and turbidity currents. The conglomerate sheets can be traced over a wide area of Amundsen Land, but become less important westwards and northwards. The northernmost localities of the Amundsen Land Group, just north of the present Harder Fjord fault in Johannes V. Jensen Land, are characterised by thick units of black chert and mudstone, reflecting increasing stagnation of the trough.

The redeposited material represented by the Early Ordovician conglomerate sheets is of interest in the links that can be made with conditions in the source areas of the shelf (Surlyk & Hurst, 1984). The dominant clast composition of the conglomerates changes upward from flat pebble carbonates to black chert, reflecting a change in source area and lithology. Also, while boulder and cobble grades dominate the lower conglomerates, pebble grades become dominant in the higher parts of the conglomerate succession. The eroded material is considered to have been transported across the outer shelf and shelf-slope break in a series of debris flows. On the shelf to the south, a correlation can be made with a period of uplift and erosion preceding deposition of the Wandel Valley Formation (see above); the sub-Wandel Valley Formation unconformity overlies and oversteps rocks from Late Proterozoic to earliest Ordovician age (Figs 15, 17A, 30; Map 1). Although much of the hiatus is believed to be due to non-deposition, there was evidently significant Early Ordovician erosion.

Eventually conglomerate and turbidite deposition faded out and the quiet, slow sedimentation of fine-grained deposits was resumed. These include green and green-grey ribbon cherts, chertified mudstones and siltstones and thin-bedded silty turbidites, all referred to the Nordpasset Formation.

The youngest deposits of stage 5T include black cherts and mudstones, dark silty mudstones, siltstones and thin-bedded silty turbidites of the Harder Fjord Formation (Late Ordovician – Early Llandovery).

These deposits herald an important event in the evolution of the trough, with the starved basin deposition of the Amundsen Land Group being brought to a close in latest Ordovician to Early Silurian times (Hurst & Surlyk, 1982; Surlyk & Hurst, 1984). The abrupt onset of sandstone turbidite deposition of the Peary Land Group, however, seems to have started nearly everywhere in the Late Llandovery (Higgins & Soper, 1985; Hurst & Surlyk, 1982).

Stage 6: Early Silurian ramp and rimmed shelf, and turbidite trough

In the early Late Llandovery, deposition of a major system of sand turbidites derived from the rising Caledonian mountain belt to the east was initiated in the trough, although the earliest pulses of deposition of distal fine-grained turbidites took place in the latest Ordovician (see stage 5T). The trough filled rapidly. By about the Llandovery-Wenlock boundary, the Navarana Fjord escarpment which had formerly marked the platform margin was drowned and the trough expanded southwards (stage 7; Figs 3–5). The loading effect of the thick sequences of turbidites accumulating in the trough caused down-flexing of the outer part of the platform. Carbonate deposition continued during this general deepening of the shelf, but variation in facies became more complex, especially in the western part of the region.

6S: Ramp and rimmed shelf

The down-flexing of the outer shelf can be traced all across North Greenland, as a drowning event which occurred progressively later towards the west and covered the shelf with mudstones and turbidites of the Peary Land Group. In Washington Land this process started during the late Early Llandovery (stage 5S) but it is included here as the drowning was an integrated event which affected the entire shelf. In western North Greenland some outlying carbonate mounds survived the initial phase of drowning and continued to accrete, but only for a limited span of time. Concomitantly, the carbonate shelf margin retreated to a new, more southerly position. In this area shelf sediments of stage 6S are referred to the Djævlekløften, Kap Godfred Hansen and Pentamerus Bjerge (all Washington Land Group; Figs 2, 4; Hurst, 1980a; Sønderholm & Harland, in prep.); slope sediments are referred to the Lafayette Bugt and Cape Schuchert Formations of the Peary Land Group (Figs 2, 4; Hurst, 1980a; Hurst & Surlyk, 1983a). In Kronprins Christian Land and Peary Land the down-flexing resulted in a widespread deepening of the carbonate platform during the early Late Llandovery and deposition of the Odins Fjord Formation (Hurst, 1984).

The Odins Fjord Formation (200–350 m) comprises in the lower part dark, massive, nodular or wavy bedded skeletal wackestone and weakly laminated lime mudstones. Burrow mottling is common, whereas algal remains are rare. The sediments reflect deposition in low energy subtidal environments (Hurst, 1984).

In southern Peary Land peritidal environments prograded northwards, represented by the Melville Land Member (15–30 m), which consists of grey fenestral and laminated lime mudstones (Hurst, 1984). A further rise in relative sea-level took place in late Middle to early Late Llandovery (middle Odins Fjord Formation) and sediments of low-energy subtidal environments were deposited both in northern and southern shelf areas. In the Late Llandovery, continuing relative sea-level rise in the northern platform areas immediately south of the platform margin is indicated by the Bure Iskappe Member (30–60 m) which comprises cherty, thin-bedded, nodular wackestones, horizontally laminated lime mudstones and rare interbeds of terrigenous mudstones (Fig. 4). Algae have not been recorded from this member. These features suggest deposition in very low energy, relatively deep-water environments below the photic zone, possibly under partly anoxic conditions (Hurst, 1984). This event is probably contemporaneous with the final drowning of the outer platform further to the west (Sønderholm & Harland, in prep.), and records a general world-wide eustatic sea-level rise (Johnson *et al.*, 1985).

In the southern platform areas the contemporaneous sediments of the Odins Fjord Formation are much like the lower part of this formation, but contain abundant biostromal units rich in *in situ* stromatoporoids and skeletal debris. The units are lenticular on a kilometre scale, suggesting sedimentation on extensive high energy shoals in the euphotic zone, with smaller intervening lower energy, subtidal areas.

In similar fashion to the peritidal environments of the Melville Land Member, these large scale shoals did not prograde further north than to an east-west line running through central Peary Land, suggesting that some pre-existing shelf topography with an increase in dip at this line, prevented further progradation of the shallow marine facies (Hurst, 1984).

Sediments of the Odins Fjord Formation in the G. B. Schley Fjord region and in Kronprins Christian Land have not been investigated in detail but the environments were probably also here subtidal (Hurst, 1984).

The margin of the Peary Land shelf during this late stage is poorly known, but some information on the rim facies of the Odins Fjord Formation is yielded by boul-

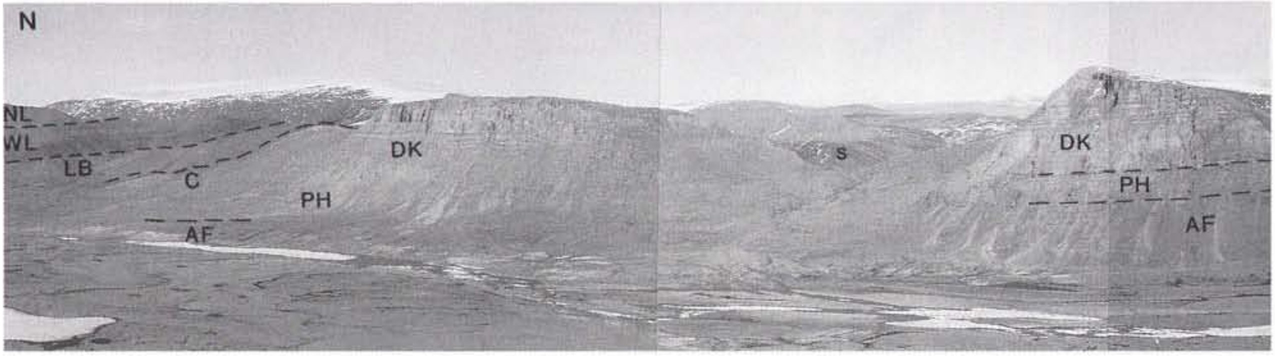
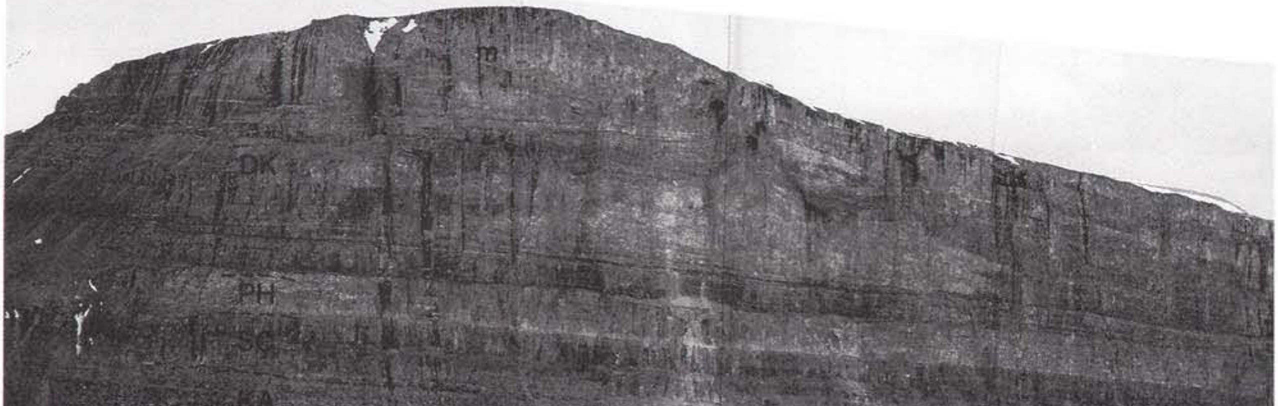


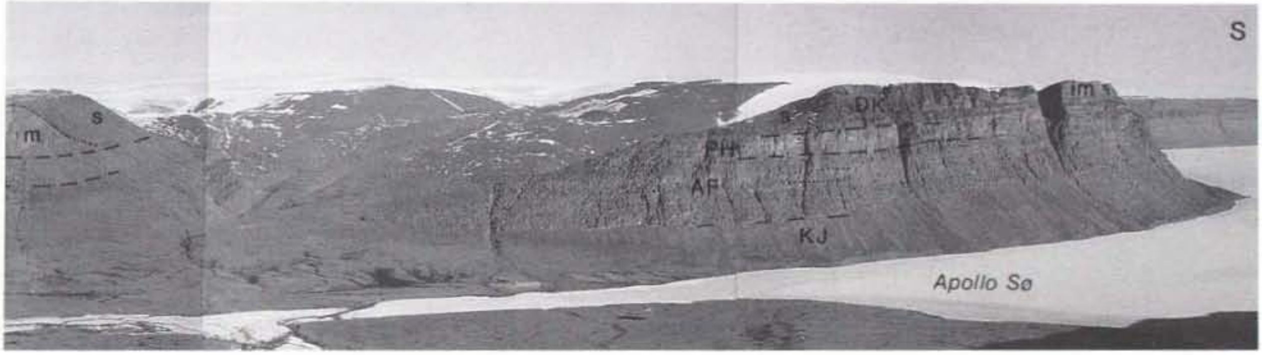
Fig. 45. Shelf-trough transition of stage 6, as developed in eastern Wulff Land. At the shelf edge pale weathering biostromal carbonates and mounds (m) of the Djævlekløften Formation (DK) form large promontories resulting in a steep and indented shelf margin. Between and behind the shelf margin carbonates of the Djævlekløften Formation dark shales (s) occur. Further back on the shelf dark weathering carbonate mud and wackestones occur with local developments of pale weathering intrashelf mounds (im). Carbonate conglomerates (c) surrounding foreslope mounds occur in a base-of-slope setting and together with interbedded

ders contained in contemporaneous base-of-slope conglomerates of the Freja Fjord Member (Fig. 2). These show clasts up to 10 m in diameter of grainstones and algal-bryozoan boundstones, suggesting that the platform was rimmed by a series of high-energy shoals and incipient algal-bryozoan reefs. The platform margin in Peary Land was still developed as the steep sediment by-pass zone of the Navarana Fjord escarpment, although stratigraphic considerations indicate that the height of the escarpment was gradually reduced due to trough infill during the Early Silurian (Hurst, 1984; Surlyk & Ineson, 1987a).

The drowning of the northern part of the shelf in western North Greenland was accompanied by a retreat of the shelf margin to a more southerly position running from south of Nares Land through central Wulff Land to central Hall Land (Figs 3, 45). As a consequence of the increased subsidence, the Petermann Halvø Formation (stage $5S_1$) is locally overlain by a series of mounds (basal mounds of the Djævlekløften Formation) which increase in size and numbers towards the north (Figs 38, 39). However, the mound complexes along the shelf margin did not form a complete barrier across the region and a steep indented margin developed with promontories hosting large slope mounds and re-entrants infilled with dark, cherty lime muds and shales. South of the shelf margin an essentially flat carbonate platform was maintained, probably sloping gently towards the north (Figs 2, 4, 45; Sønderholm & Harland, 1989b; Sønderholm & Harland, in prep.).

The Djævlekløften Formation (up to c. 600 m) preserves a complex array of facies, with dark, often shaly or cherty lime mudstone, variably coloured mound-related flank beds including skeletal limestone and biostromes, isolated mounds and mound complexes (Fig. 46). The southern part of the platform is dominated by dark grey to black, back-mound and inter-mound sediments (Fig. 47), which comprise thinly bedded, variably





mudstones form the Lafayette Bugt Formation (LB). Trough deposits (stage 7T) are represented by dark mudstones of the Wulff Land Formation (WL) and pale turbidites of the Nyeboe Land Formation (NL). Carbonate platform deposits of stage $5S_1$ are represented by the Kap Jackson Formation (KJ, with Cape Calhoun Formation on the top), the Aleqatsiaq Fjord Formation (AF, showing three-part member sub-division) and the Petermann Halvø Formation (PH). Height of mountain in centre about 900 m.

mottled, skeletal lime mudstones with thin interbeds of graded bioclastic limestones, pebble conglomerates and slump sheets. Chert layers and nodules occur throughout. These sediments drape on to, or terminate against, light grey to dark grey carbonate mound sediments. The mounds are mostly small, up to 200 m thick, patch reefs which especially to the north along the shelf margin may interconnect to form large mound complexes (Fig. 48). In western Washington Land these large mound complexes form part of the Pentamerus Bjerge and Kap Godfred Hansen Formations, while the Kap Jefferson mound of the Adams Bjerg Formation probably is an equivalent to the intrashelf mounds of the Djævlekløften Formation (Hurst, 1980a; Sønderholm & Harland, 1989b; Sønderholm & Harland, in prep.).

Around the major mounds and mound complexes, sequences of generally pale weathering, very variable limestones up to 200–450 m thick occur. These are typically associated with the upper parts of the mounds, spreading mainly southwards, and form the top of the Djævlekløften Formation in many areas. The limestones mainly comprise interbedded dark and light stromatoporoid and coral biostromes (Figs 45, 49). The dark beds contain *in situ* stromatoporoids and corals (Fig. 50), while the pale beds contain abundant reworked material. Crinoid material occurs virtually throughout, and beds up to 10 m thick consisting almost entirely of crinoid columnals are common. In exceptional cases, major mound complexes are flanked by up to 200 m thick successions almost exclusively composed of crinoid columnals.

Sedimentation patterns in Washington Land west of Bessels Fjord reflect a somewhat different evolution. In this area the carbonate platform of stage 5 developed into a homoclinal carbonate ramp during the late Early Llandovery. In the westernmost areas this event is represented by starved slope sediments of the Cape Schuchert Formation (55–80 m) which mainly consist of thin bedded, black, bituminous, cherty lime mudstones overlying the Aleqatsiaq Fjord Formation. Contemporaneously, fringing reefs and reef-derived sediments at the carbonate ramp margin represented by the Pentamerus Bjerge and Kap Godfred Hansen Formations and probably parts of the Adams Bjerg Formation (Hurst, 1980a), led to the development of a scarp between the platform and the slope, resulting in a greater ramp-to-

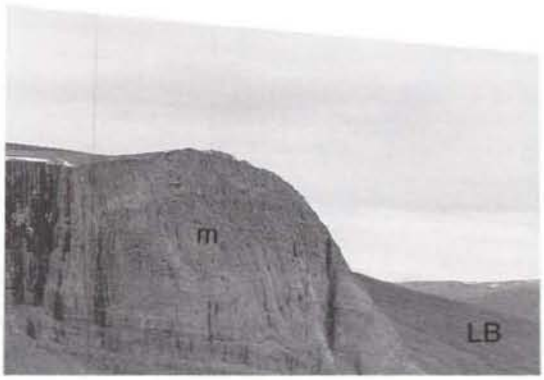


Fig. 46. Shelf-edge mounds (m) of the Djævlekløften Formation (DK) of stage 6S. To the north (right), limestone conglomerates derived from the mounds interdigitate with dark basinal shales (Lafayette Bugt Formation, LB). The Djævlekløften Formation overlies shelf sediments of stage $5S_1$ (Petermann Halvø Formation (PH), Store Canyon (SC) and Kap Ammen (KA) Members of the Aleqatsiaq Fjord Formation). Eastern cliffs of southern Nares Land, southern Nordenskiöld Fjord. Cliff height *c.* 650 m.

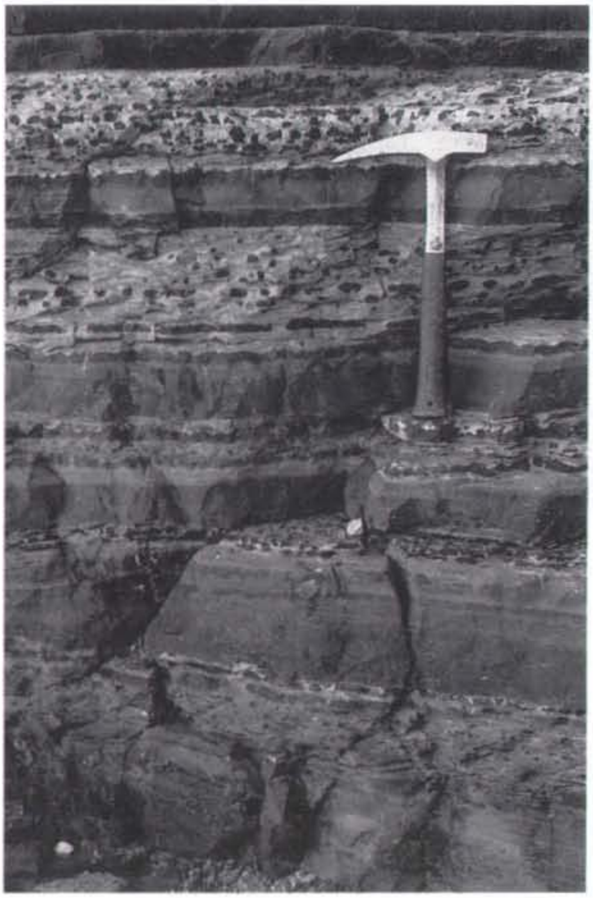


Fig. 47. Dark, finely laminated intermound lime mudstone of the Djævlekløften Formation (stage 6S) with black chert in nodules and layers. Hammer is 35 cm long. Central Warming Land.

slope differentiation (Figs 2, 4; Hurst, 1980a; Hurst & Surlyk, 1983a).

As a consequence of continuing sea-level rises during the late Middle to latest Llandovery, the south-western part of Washington Land was drowned during the earliest Late Llandovery, and inundated by the black shales of the Lafayette Bugt Formation. Contemporaneously, new mounds were initiated on the slope further to the east at Kap Independence (Fig. 51), while the impressive carbonate ramp-margin reef belt continued its development (Hurst, 1980a; Hurst & Surlyk, 1983a).

6T: Longitudinal turbidite trough

The most dramatic depositional change in the deep-water trough took place in the early Late Llandovery when a major longitudinal, sand-rich, turbidite system was developed following the late Early Cambrian – earliest Silurian starved basin phase (Figs 2, 3, 5, stage 6T). An early phase of fine-grained dilute turbidity current deposition was initiated close to the Ordovician-Silurian boundary in the eastern part of the trough. Significant turbidite deposition, however, started abruptly in Late Llandovery time and a sand-rich elongate submarine fan system rapidly developed (Hurst & Surlyk, 1982; Surlyk, 1982; Surlyk & Hurst, 1984). Turbidite deposition continued throughout the Silurian, and the resulting succession is placed in the Peary Land Group. The formations of the Peary Land Group, dominated by sandstone turbidites, mudstones or conglomerates (Hurst & Surlyk, 1982; Larsen & Escher, 1985, 1987; Surlyk & Ineson 1987a, b), are interpreted here as stages 6T–7T in the evolution of the basin.

The initiation of stage 6T is represented by the very thick sequence of sandstone turbidites of the Merqujôq Formation (>500–2800 m), which appears to be largely Late Llandovery in age (Higgins & Soper, 1985; Hurst & Surlyk, 1982; Larsen & Escher, 1985). These turbidites are widely distributed in North Greenland between Frederick E. Hyde Fjord in the east and northern Nyeboe Land in the west (Figs 9, 52). In some areas there is a gradual increase in grain size at the top of the starved slope sequence, passing into the first sandstone turbidites, while in other areas the contact with the thick sandstone turbidites interdigitates with the starved slope facies (Higgins & Soper, 1985; Hurst & Surlyk, 1982; Surlyk *et al.*, in prep.). Turbidite deposition commenced abruptly in central Johannes V. Jensen Land in the Llandovery with the incoming of extremely thick (up to 30 m) sandstone turbidite beds, distinguished as the Sydgletscher Formation (Fig. 53) (Hurst & Surlyk, 1982).

The main part of the Merqujôq Formation represents deposition in the outer-fan and trough floor environment in a highly elongate east-west submarine fan system. Palaeocurrents are uniform towards the west-south-west, parallel to the Navarana Fjord escarpment which formed the margin of the carbonate platform. Turbidite deposition took place right up to the escarpment, and the steep profile of the scarp slope may have been maintained by erosion by longitudinal turbidity currents. The top part of the formation is characterised by complex channelling interpreted as representing a braided mid-fan environment (Fig. 54). The largest observed channels have widths of several hundred metres and depths of about 50 m. Turbidite sedimentation was punctuated by several episodes of carbonate conglomerate deposition; beds range from 0.5 to 50 m in thickness and, in type, from well-sorted pebble beds to totally disorganised boulder beds with individual clasts often reaching a diameter of several metres (Figs 55, 56). In

Fig. 48. Dark intermound sediments and mounds (m) of the Djævlekløften Formation (DK) belonging to stage 6S. Sediments of stage $5S_1$ are represented by the Newman Bugt (NB), Kap Ammen (KA) and Store Canyon (SC) Members of the Aleqatsiaq Fjord Formation (AF), and the overlying Petermann Halvø Formation (PH). Looking east in Store Canyon, southern Nyeboe Land. Height of mountain about 550 m.

contrast to the longitudinally derived turbidites, the conglomerates were derived from the southern platform area and from the platform margin escarpment, as reflected in the concave erosional surface which truncates the top of the scarp at Navarana Fjord (Surlyk & Ineson, 1987a, b).

Stage 7: Final drowning of the platform

The last phase in the evolution of the Silurian carbonate ramp and rimmed shelf was a consequence of continued shelf foundering and associated sea-level rise (Figs 3, 5, stage 7). The trough expanded southwards as a result of eustatic sea-level rise, the loading effect of the thick turbidite sequence to the north and downflexing caused by encroaching Caledonian nappe sheets in

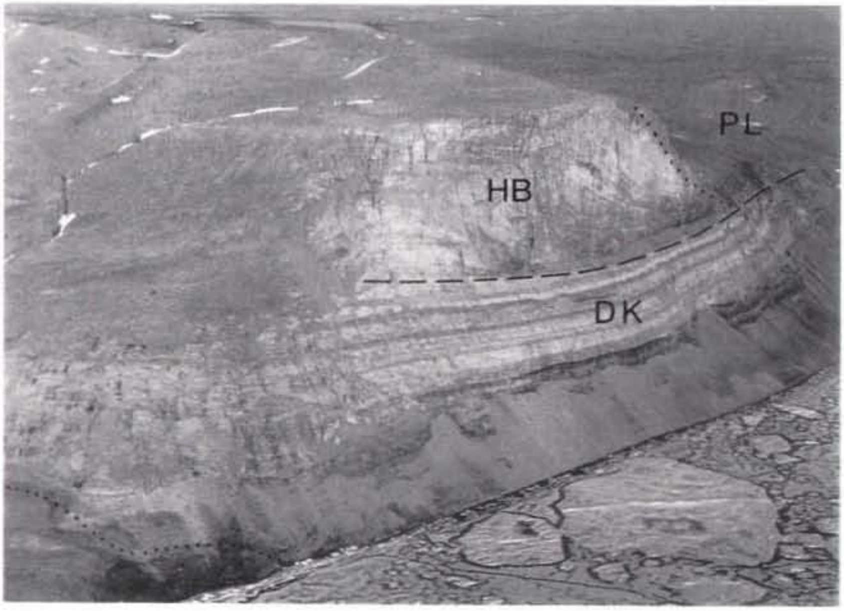


Fig. 49. Biostromal deposits of stage 6S (Djævlekløften Formation, DK) overlain by mound-complexes (Hauge Bjerge Formation, HB, stage 7S) and siliciclastic sediments of the Peary Land Group (PL, stage 7T). Kap Tyson, western Hall Land. Height of cliff is 740 m.

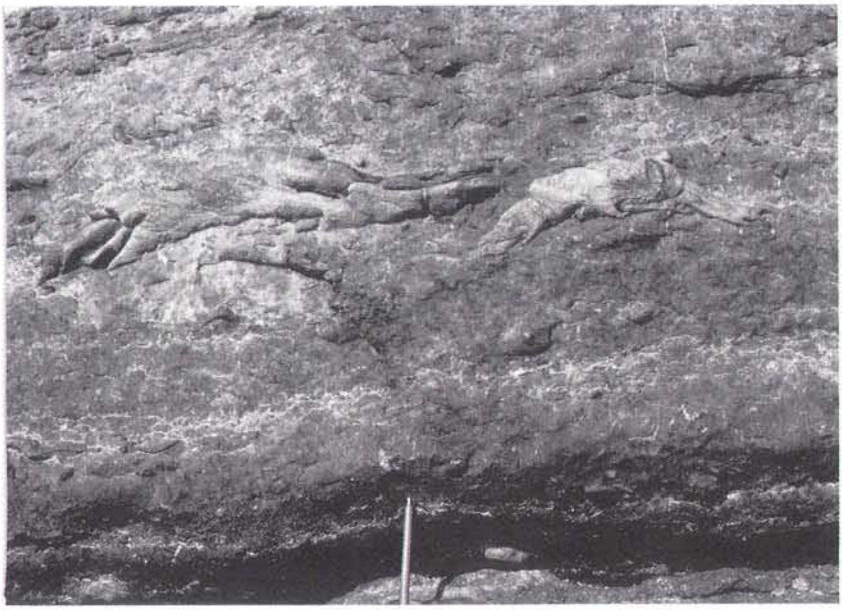


Fig. 50. Biostromal limestone of the Djævlekløften Formation (stage 6S) with abundant *in situ* stromatoporoids and corals. Pencil 15 cm long. Offley Island.

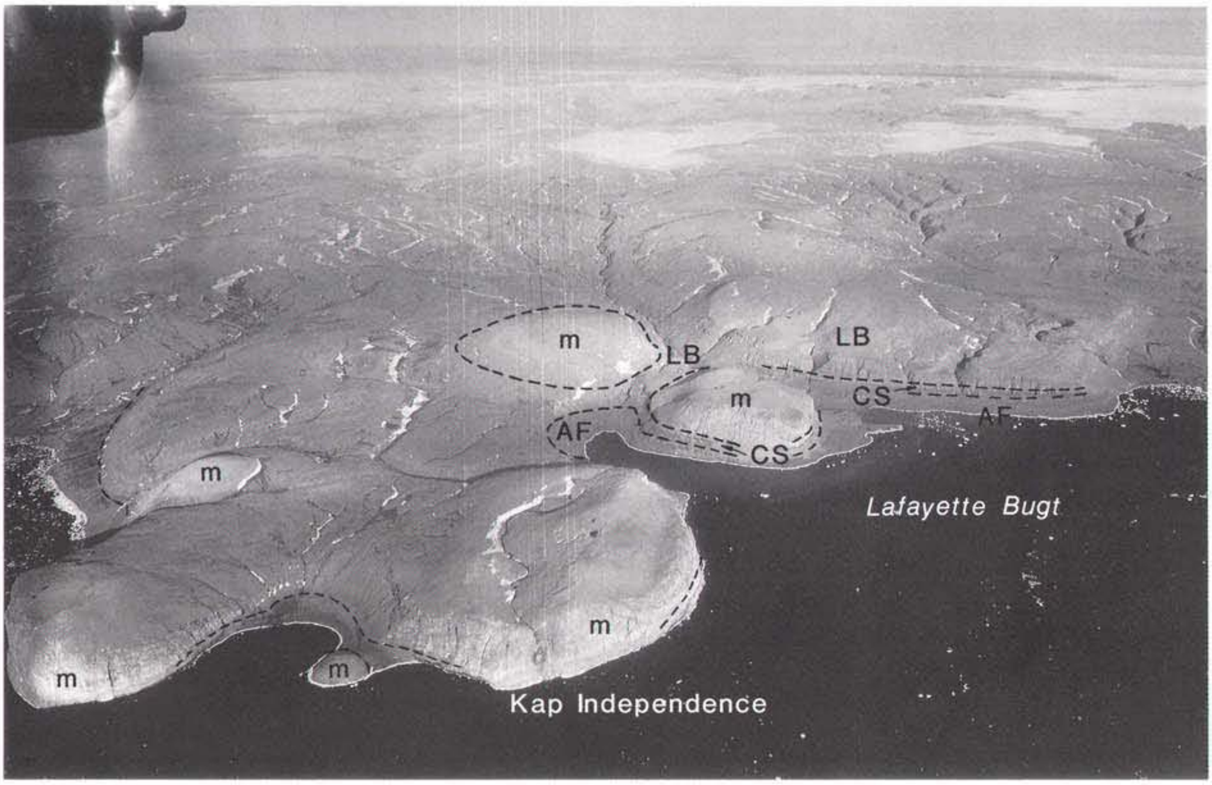


Fig. 51. Carbonate mounds (m) of the Kap Independence Member (Pentamerus Bjerge Formation) embedded in slope deposits of the Cape Schuchert (CS) and Lafayette Bugt (LB) Formations (stage 6S). AF: Aleqatsiaq Fjord Formation. Westernmost Washington Land. Aerial photograph 545 K1-SØ no. 2259. Copyright Kort- og Matrikelstyrelsen, Denmark; reproduced with permission A.87/200.

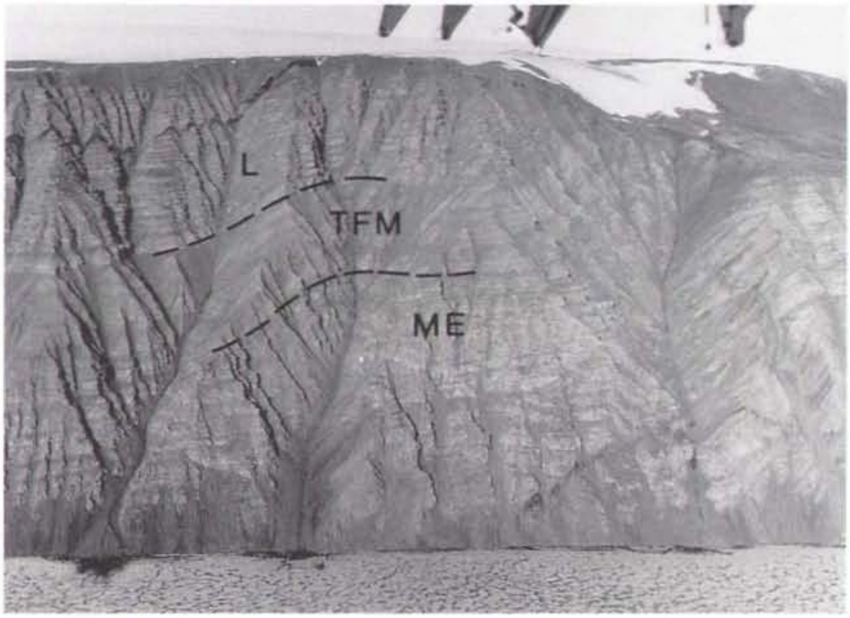


Fig. 52. Sandstone turbidites of the Merqujôq Formation (ME, stage 6T), overlain by a thin mudstone unit, the Thors Fjord Member of the Wulff Land Formation (TFM) and sandstone turbidites of the Lauge Koch Land Formation (L, stage 7T). Cross-cutting black bands are late Cretaceous dykes. West side inner J. P. Koch Fjord, cliffs 900 m high.

the eastern areas. Eventually the shelf was drowned completely during the latest Llandovery and carbonate sedimentation was only locally maintained around major mound complexes. The shelf was inundated by hemipelagic mudstones and siltstone turbidites of the Thors Fjord Member (Wulff Land Formation), Profilfjeldet Member (Lauge Koch Land Formation), and Lafayette Bugt Formation (Figs 2–5).

7S: Late Llandovery – Early Ludlow reef belt

During the final phase of drowning of the platform, carbonate sedimentation was only locally maintained, leading to the formation of isolated mounds. These sediments are referred to the Samuelsen Høj Formation between Kronprins Christian Land and Peary Land, the Hauge Bjerge Formation in the area between western Wulff Land and eastern Washington Land, and to the Pentamerus Bjerge, Kap Godfred Hansen, Kap Morton and Kap Maynard Formations in Washington Land (Hurst, 1980a, 1984; Sønderholm *et al.*, 1987; Sønderholm & Harland, in prep.; Figs 2, 4). Carbonates of this late stage are not represented between western Peary Land and western Wulff Land, probably due to Recent erosion.

Fig. 53. Structureless medium-grained sandstone turbidite of the Sydgletscher Formation, about 40 m thick marking the initiation of the Peary Land Group. Base of stage 6T. Johannes V. Jensen Land. The white band in the middle of the bed is a calcite-filled fracture.

Fig. 54. Turbidite filled mid-fan channels in the top part of the Merqujôq Formation (stage 6T), Thor Fjord. Person encircled for scale.

The approximately 300 m high pinnacle reefs of the Samuelsen Høj Formation (Fig. 57) occur on top of the Odins Fjord Formation where they form a 50 km long east-west linear belt in eastern Peary Land. Mound complexes are also widespread in Valdemar Glückstadt Land and in Kronprins Christian Land (Figs 1, 4, 5) where they are larger than the mounds in Peary Land. In Kronprins Christian Land mounds appear to occur stratigraphically lower (Late Llandovery, C5) in the succession than in Peary Land (Late Llandovery, C6), since there is lateral interdigitation of the lower part of the mound complexes with the level-bedded sediments of the Odins Fjord Formation (stage 6S). Mound formation probably terminated during the Late Llandovery (C6); sparse graptolite evidence suggests that this termination occurred slightly earlier in the east than in the west (Hurst, 1984; Hurst & Surlyk, 1982; Peel *et al.*, 1981).

In western North Greenland mound complex or associated flank sediments form sequences approximately 200–1000 m thick (Dawes, 1987; Hurst, 1980a; Sønderholm *et al.*, 1987; Sønderholm & Harland, in prep.). Carbonate sedimentation was only maintained around the major mounds of the previous phase of deposition (Figs 58, 59), and it was a period of partial destruction of the mounds and mass transport by debris flows (Fig. 60). These sediments form a linear belt extending from northern Washington Land, through central Hall Land, Nyeboe Land and Warming Land to western Wulff Land which indicates the position of the former shelf edge (Hurst, 1980b; Sønderholm *et al.*, 1987; Sønderholm & Harland, 1989b; see Figs 1, 5). Due to present-day erosion it is not known how long carbonate deposition persisted. Hurst (1980a) and Dawes & Peel (1984) considered that it extended at least into the Early Ludlow, but thin beds of resedimented carbonates within the Chester Bjerg Formation are of Pridoli age.

7T: Trough expansion

The complex foundering of the shelf described above was associated with a southwards expansion of the trough during the Late Llandovery (Hurst & Surlyk, 1982; Hurst *et al.*, 1983; Larsen & Escher, 1985; Surlyk, 1982; Surlyk & Hurst, 1984; Sønderholm *et al.*, 1987). The foundering of more than 30 000 km^2 of carbonate shelf was probably caused by the combined effects of eustatic sea-level rise, loading of the eastern shelf by Caledonian nappes, loading of the trough by several kilometres of mainly Upper Llandovery turbidites and associated downflexing of the outer shelf, and by the influx over the platform of terrigenous muds from the Caledonian mountains. The northern shelf margin was inundated by clastic sediments in the Late Llandovery, whereas the southern part first started to receive terrigenous clastics at the Llandovery-Wenlock boundary, indicating that shelf foundering was in part accomplished by flexuring. In western North Greenland the inundation of the outer platform was probably initiated in the early Late Llandovery, while it commenced

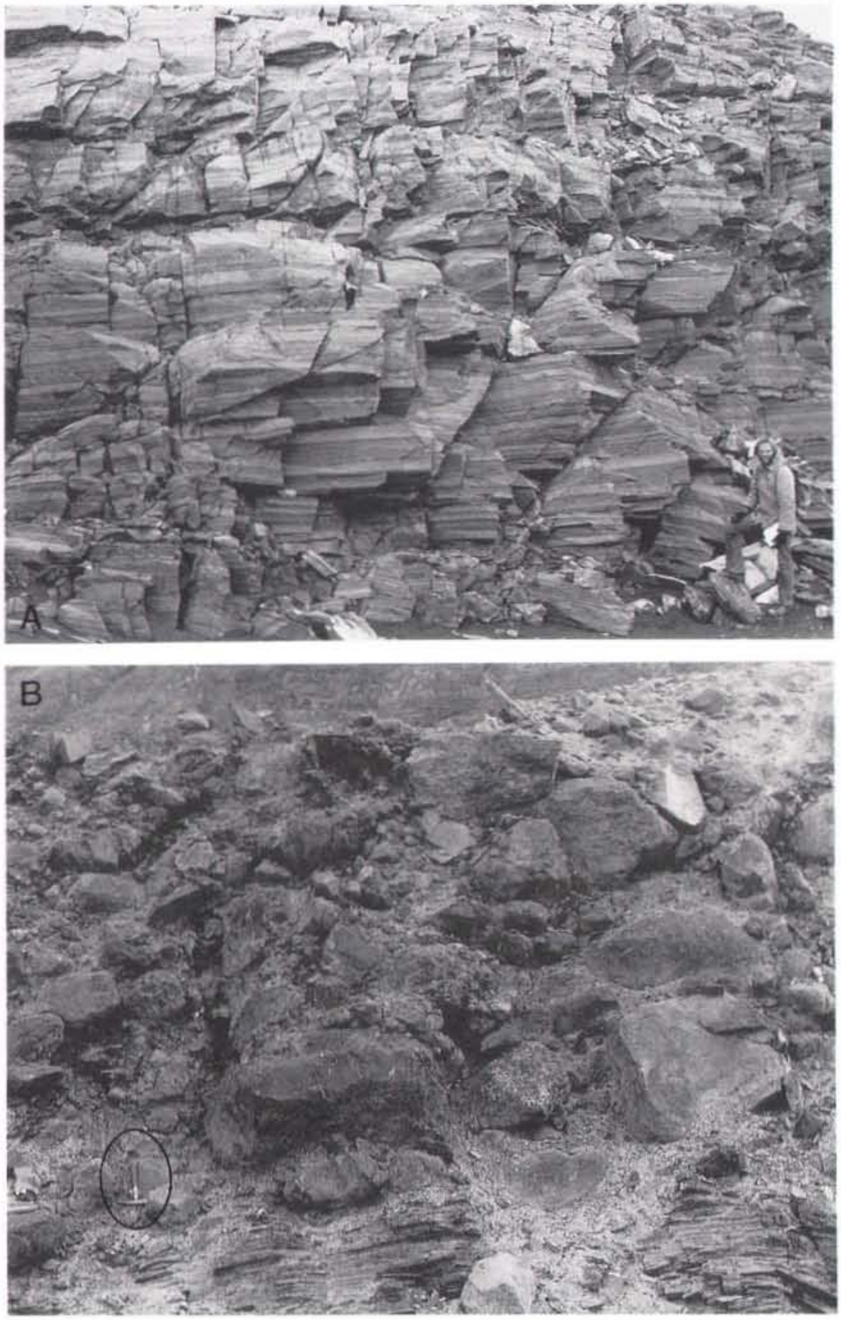


Fig. 55. Thick sequence of muddy carbonate turbidites (A) overlying carbonate boulder conglomerates of the Citronens Fjord Member shown in B (note hammer for scale). Merqujôq Formation (stage 6T), Citronen Fjord, Peary Land.

somewhat later in the Late Llandovery (C4) in central North Greenland. The extensive submergence resulted in deposition of uniform black mudstones on top of the foundered shelf carbonates and the succession of up to about 100 m of mudstones makes up the Thors Fjord Member of the Wulff Land Formation (Hurst & Surlyk, 1982; Larsen & Escher, 1985; 1987). The depositional regime can be characterised as a slope and rise system passing northward into the deep-water trough.

Following the late Llandovery – Wenlock phase of trough expansion and submarine fan starvation caused by foundering of the carbonate platform, the turbidite depositional systems rapidly built up again as an extensive, westwards prograding submarine fan system.

The turbidite deposits of this phase are mainly placed in the Lauge Koch Land Formation (Fig. 52; Hurst & Surlyk, 1982; Larsen & Escher, 1985, 1987; Surlyk & Hurst, 1984). Easternmost localities in eastern Peary

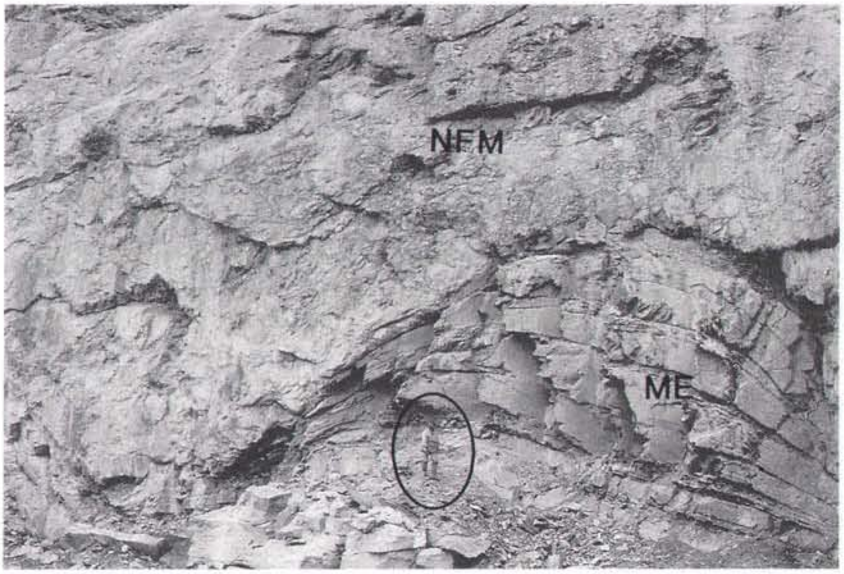


Fig. 56. Carbonate boulder conglomerate of the Navarana Fjord Member (NFM) showing giant-scale loading into sandstone turbidites of the Merqujôq Formation (ME, stage 6T). West coast of Navarana Fjord. Note person for scale.

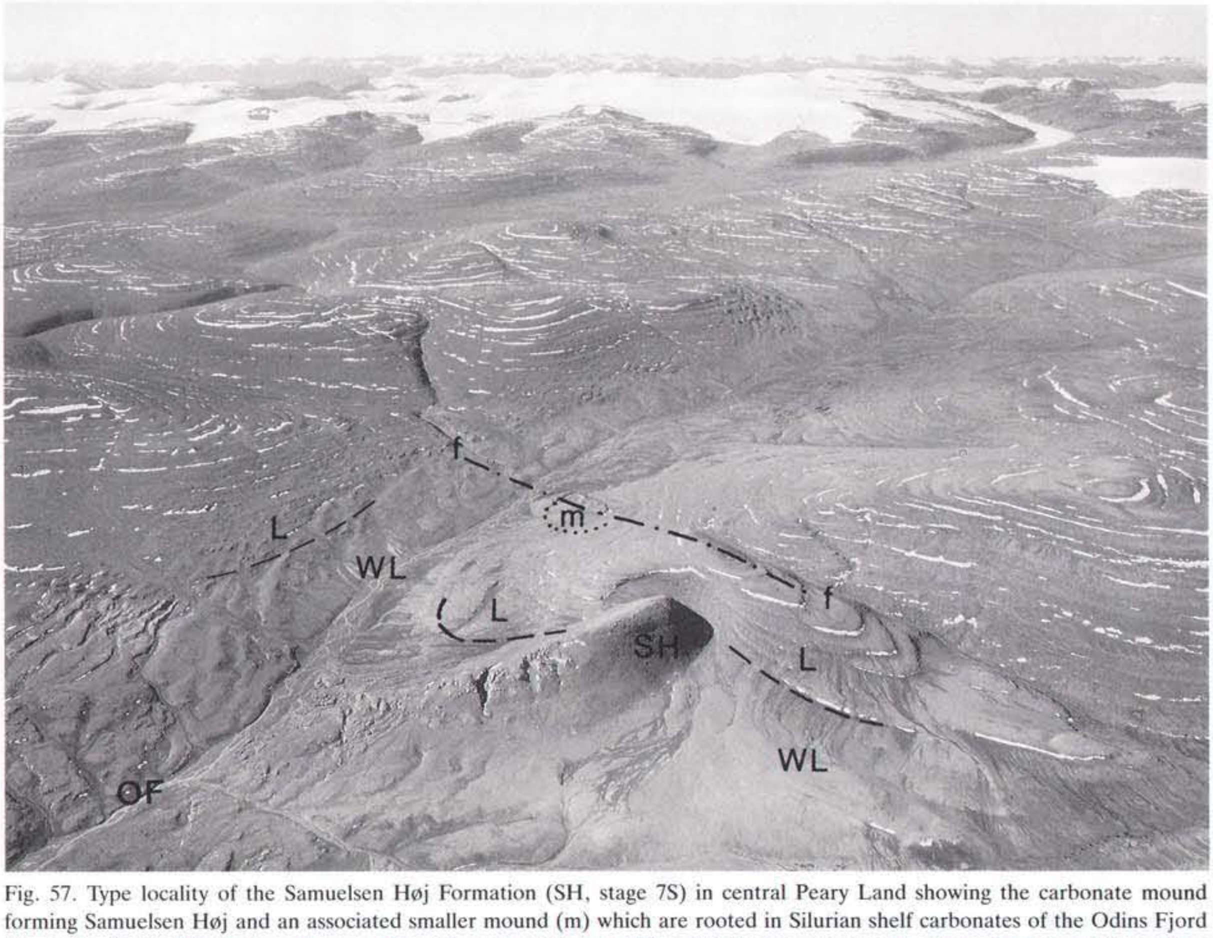


Fig. 57. Type locality of the Samuelsen Høj Formation (SH, stage 7S) in central Peary Land showing the carbonate mound forming Samuelsen Høj and an associated smaller mound (m) which are rooted in Silurian shelf carbonates of the Odins Fjord Formation (OF). Siliciclastic sediments of the Peary Land Group (WL, Wulff Land Formation; L, Lauge Koch Land Formation; stage 7T) envelope the carbonates, with the turbidites of the latter formation forming characteristic terraced hills to the north. Samuelsen Høj is about 2 km long. Aerial photograph 548 C-N, no. 4280A. Copyright Kort- og Matrikelstyrelsen, Denmark; reproduced with permission A.87/200.

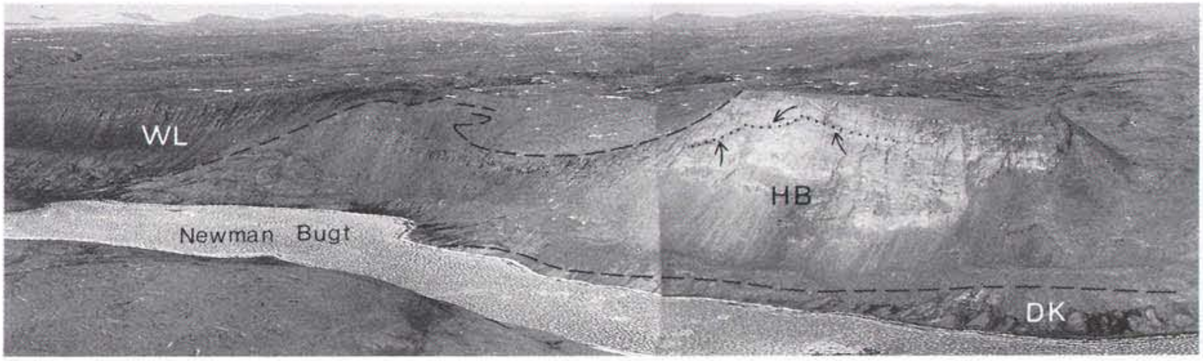


Fig. 58. Shelf edge mounds of stage 7S (HB, Hauge Bjerge Formation) on top of biostromal platform carbonates of the Djævlekløften Formation (DK; stage 6S), surrounded by shales of the Wulff Land Formation (WL) of the Peary Land Group (stage 7T). Arrows indicate possible slump scars. Western Nyeboe Land; cliffs are 550 m high.

Land are characterised by thick, upward-fining cycles about 50–100 m thick composed of thick, locally pebbly, structureless sandstones passing upwards into dark, laminated mudstones (Fig. 61). The cycles can be traced laterally for at least 5 km. They are interpreted as representing a system of stacked, wide inner fan valleys where the upper muddy part reflects channel abandonment and passive filling. Farther westwards the inner fan valleys give way to a system of complex channels characteristic of a braided mid-fan environment. From western Peary Land and westwards to Hall Land, only outer fan, fan fringe and basin plain environments are represented (Fig. 62). West of Victoria Fjord, the sandstone/mudstone ratio, sand grain size and turbidite bed thickness decrease in a downcurrent direction.

The entire depositional setting is interpreted as an elongate submarine fan imperceptibly passing into a basin plain (Hurst & Surlyk, 1982; Surlyk & Hurst, 1984). Pulses in turbidite deposition alternated with periods of fan starvation resulting in alternations of turbidite sandstone and mudstone packages and in changes in the southern extent of the main turbidite body. These variations probably mainly reflect changes in sea-level, with low levels resulting in increased influx of sandy turbidity currents and high levels resulting in fan starvation and mud deposition.

During the middle Wenlock a major phase of conglomeratic deposition was initiated at the eastern, proximal end of the basin (Hurst & Surlyk, 1982; Larsen & Escher, 1985, 1987; Surlyk & Hurst, 1984). The conglomeratic depositional system prograded westwards and reached northern Nyeboe Land in the early Ludlow. The conglomeratic units form the Nordkronen Formation. At the type locality south of Frederick E. Hyde Fjord the formation is incomplete, and only 100 m are preserved; farther west a 600–700 m succession oc-

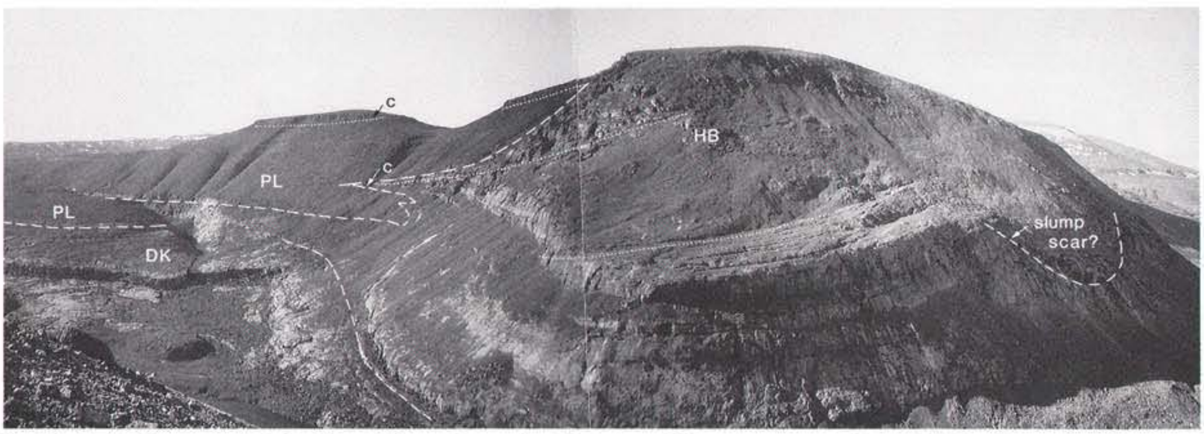


Fig. 59. Shelf edge mound of the Hauge Bjerge Formation (HB; stage 7S) on the eastern side of Hall Land overlying biostromal carbonates of the Djævlekløften Formation (DK). The mound is *c.* 500 m high and the steeply dipping beds indicate a syn-depositional relief of *c.* 300 m. Note the possible slump scar on the northern, basin-ward side of the mound. The mound is surrounded by carbonate conglomerates (c) and shales of the Peary Land Group (PL; stage 7T).

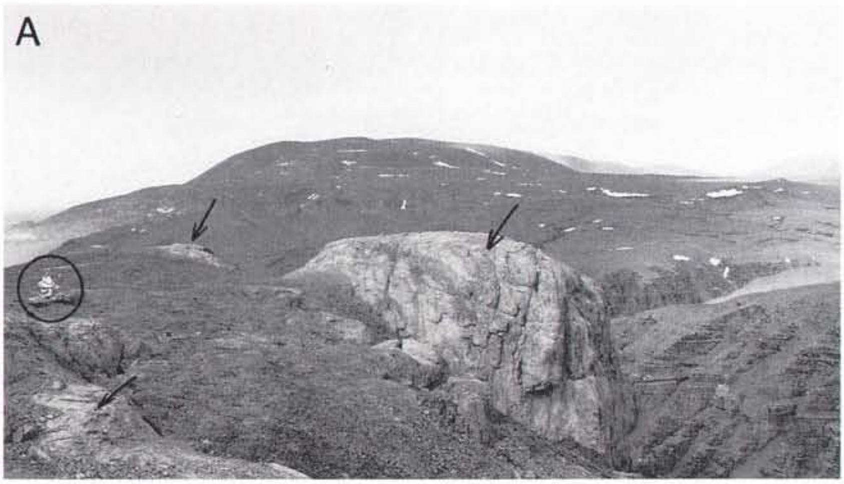


Fig. 60. Huge olistoliths (arrowed) and debris flows (df) derived from the large mound complexes of the Hauge Bjerge Formation (stage 7S) embedded in black shales of the Peary Land Group (stage 7T). Encircled helicopter for scale. A, western Hall Land; B, western Nyeboe Land.

curs on Stephenson Ø, 281 m on Hendrik Ø, and in northern Nyeboe Land a feather edge of the unit measures 32 m.

The conglomerates differ markedly from all of the earlier deep-water conglomerates described above. The latter are all derived from the upper slope and carbonate shelf to the south; they are mainly chaotic, disorganised types with lime mud matrix, poor clast sorting, and a variety of clast lithologies. In contrast, the conglomerates of the Nordkronen Formation are more organised and are interbedded with sandstone turbidites. They occur in relatively thin, sheet-like beds, with a sandstone matrix identical to the sandy turbidites. The clasts are well sorted and rounded, pebble-sized, green, black and grey chert (Fig. 63). The chert conglomerates were deposited from high density turbidity currents travelling westwards along the trough axis from a source area in the rising Caledonian mountains (Fig. 64) (Surlyk & Hurst, 1984).

The generally well-rounded and sorted appearance of the chert pebbles indicates that the parent rock was lithified at the time of erosion and that considerable transport and sorting had taken place in the coastal zone before redeposition by density currents. Some chert pebbles have yielded radiolarian remains suggestive of an Ordovician age, and the chert pebbles were probably derived from uplifted, thick cherty sequences of mainly Ordovician age (Vølvedal and Amundsen Land Groups

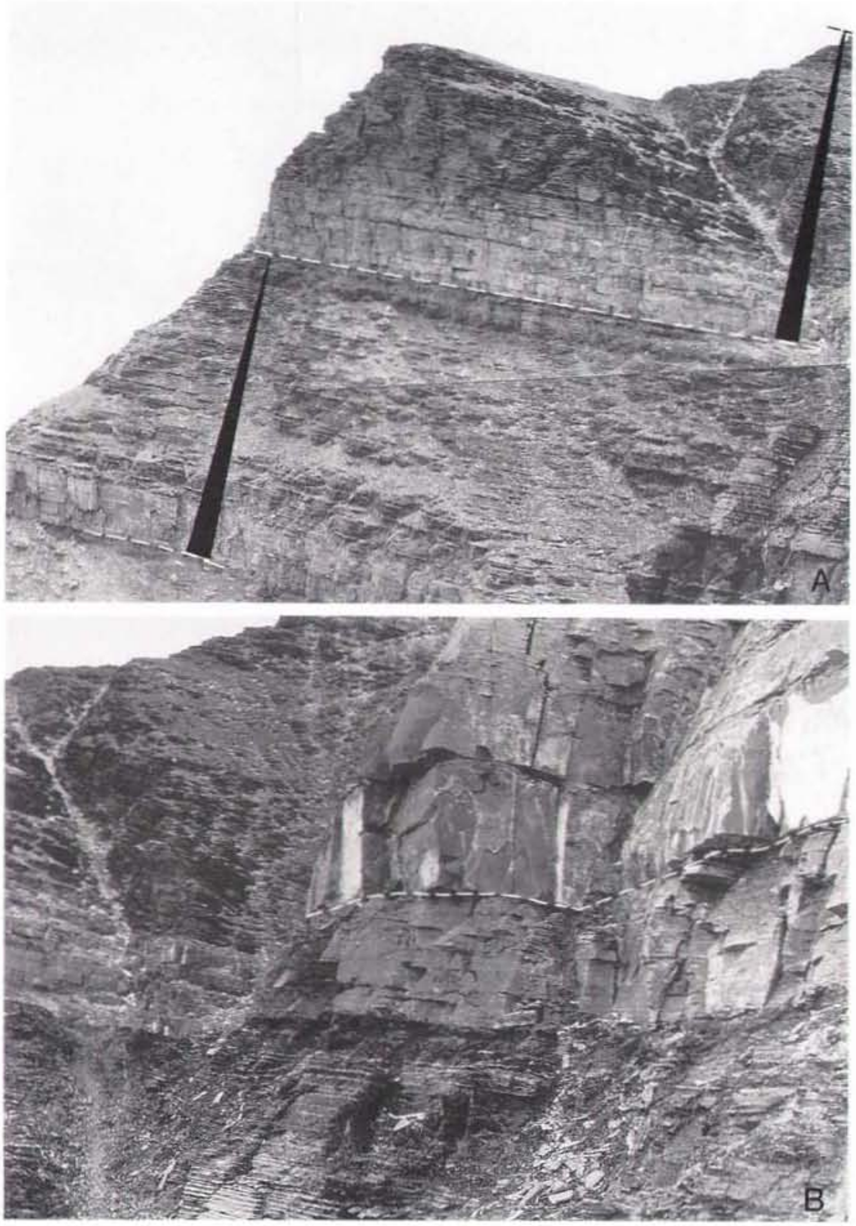


Fig. 61. A. Stacked thinning-upwards and fining-upwards inner fan valley succession of the Lauge Koch Land Formation (stage 7T). B. Detail of the base of the lower thinning-upwards sequence shown in A. Bed above stippled level is *c.* 1 m thick. Eastern Peary Land.

and correlatives); no other known units contain sufficient volumes of cherts.

The last phase of the trough fill is only preserved in the western part of North Greenland, west of Freuchen Land. It is represented by the Nyeboe Land Formation and the Chester Bjerg Formation (Hurst & Surlyk, 1982; Larsen & Escher, 1985, 1987). This part of the sequence totals about 1000 m in thickness and is of latest Silurian age, possibly reaching into the earliest Devonian.

In the transition zone of the Nyeboe Land Formation and the Chester Bjerg Formation, packages of fine sandstone turbidites alternate with packages of silty mudstones, often with starved ripples. This facies association reflects a fan fringe depositional environment characteristic of the transition between outer fan and basin plain deposits. The bulk of the Chester Bjerg Formation comprises laminated light green weathering mudstones or siltstones, deposited from muddy contour currents, very dilute turbidity currents, or nepheloid layers in a distal basin plain.

Fig. 62. Overturned sequence of stacked 20–40 m thick thinning-upwards cycles in the distal fan fringe of the Lauge Koch Land Formation, Peary Land Group (stage 7T), northern Nyeboe Land.

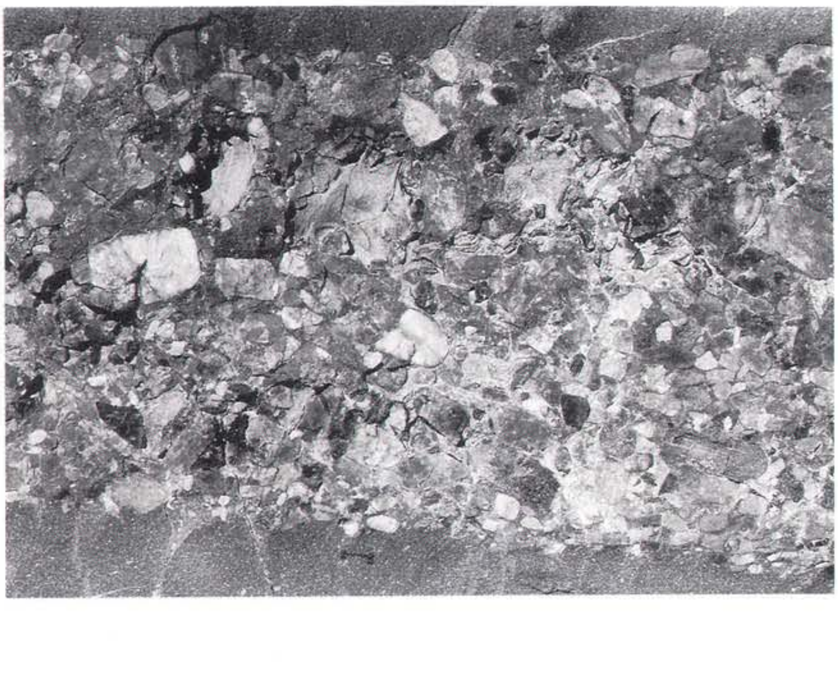


Fig. 63. Chert pebble conglomerate bed (20 cm thick) showing inverse grading. Hendrik Ø Member (stage 7T), Hendrik Ø.

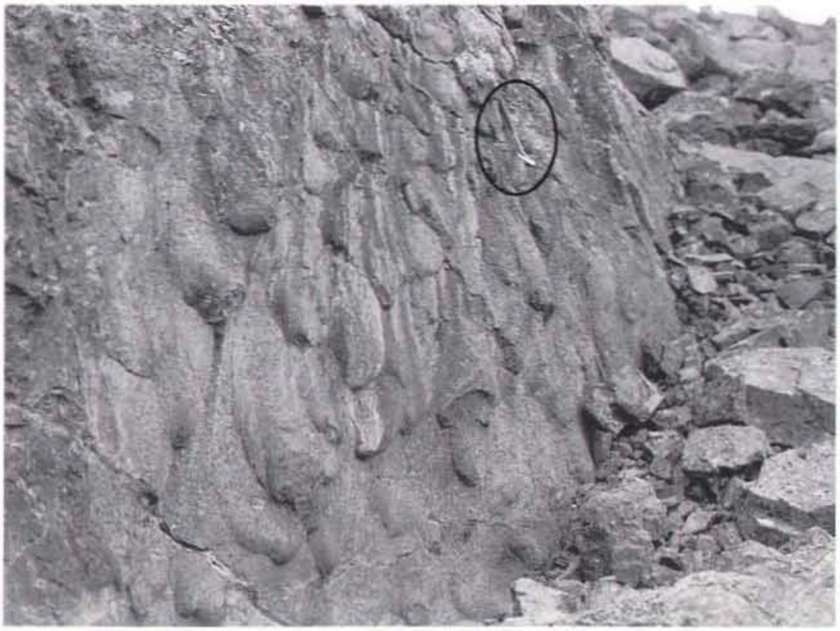


Fig. 64. Large scale flute casts on the sole of vertical chert pebble conglomerate of the Hendrik Ø Member (stage 7T). Current towards the top of picture. Hammer for scale. Stephenson Ø.

Caledonian and Ellesmerian events in North Greenland

The Early Palaeozoic Franklinian Basin in North Greenland seems to have formed by rifting. It may thus be of fully ensialic nature, or an aulacogen, or it may represent continental break-up and formation of a narrow ocean (Surlyk & Hurst, 1984). The nature of the crust beneath the basin is not well known, but it is probably of continental or transitional type in most of its preserved, southern part. Thus, the basin reflects the evolution of a normal, passive continental margin. However, a number of events during basin evolution can be related to the progressive closure of the Iapetus Ocean and the formation of the East Greenland Caledonides (Surlyk & Hurst, 1984).

The earliest and most conjectural event was the uplift of the eastern shelf areas in Cambrian and Early Ordovician time, resulting in a marked hiatus which decreases progressively towards the west away from the Iapetus margin (Figs 2, 4). This phase was followed by the incoming in the Early Silurian of enormous amounts of sandy turbidites forming the submarine fan system of the Peary Land Group. The sedimentation rate increased dramatically and the bulk of the turbidite sequence was deposited during a short time interval in the Late Llandovery. The turbidites had their source area in the rising Caledonian mountain belt to the east; their initiation gives the most precise time record of Iapetus Ocean closure and orogenic uplift in the present northern North Atlantic region. In the Late Llandovery huge areas of carbonate platform foundered, probably due to the combined effect of downflexing of the outer platform caused by loading of the trough with several kilometres of sediments derived from the rising Caledonides, and loading by westwards advancing Caledonian nappes and thrust sheets (Fig. 42).

The next phase was characterised by the incoming in mid-Wenlock time of westward-prograding chert-pebble conglomerates, perhaps originating from upthrust Ordovician chert sequences exposed to erosion in Caledonian thrust sheets.

The Franklinian Basin in North Greenland thus records the evolution of a carbonate-dominated, passive east-west trending continental margin , exposed to the influence of the closure of the Iapetus Ocean and the building of the Caledonian mountains to the east. The Franklinian Basin in North Greenland finally closed in Devonian – Early Carboniferous times, resulting in strong deformation of the northern part of the Franklinian trough sequence during the Ellesmerian Orogeny.

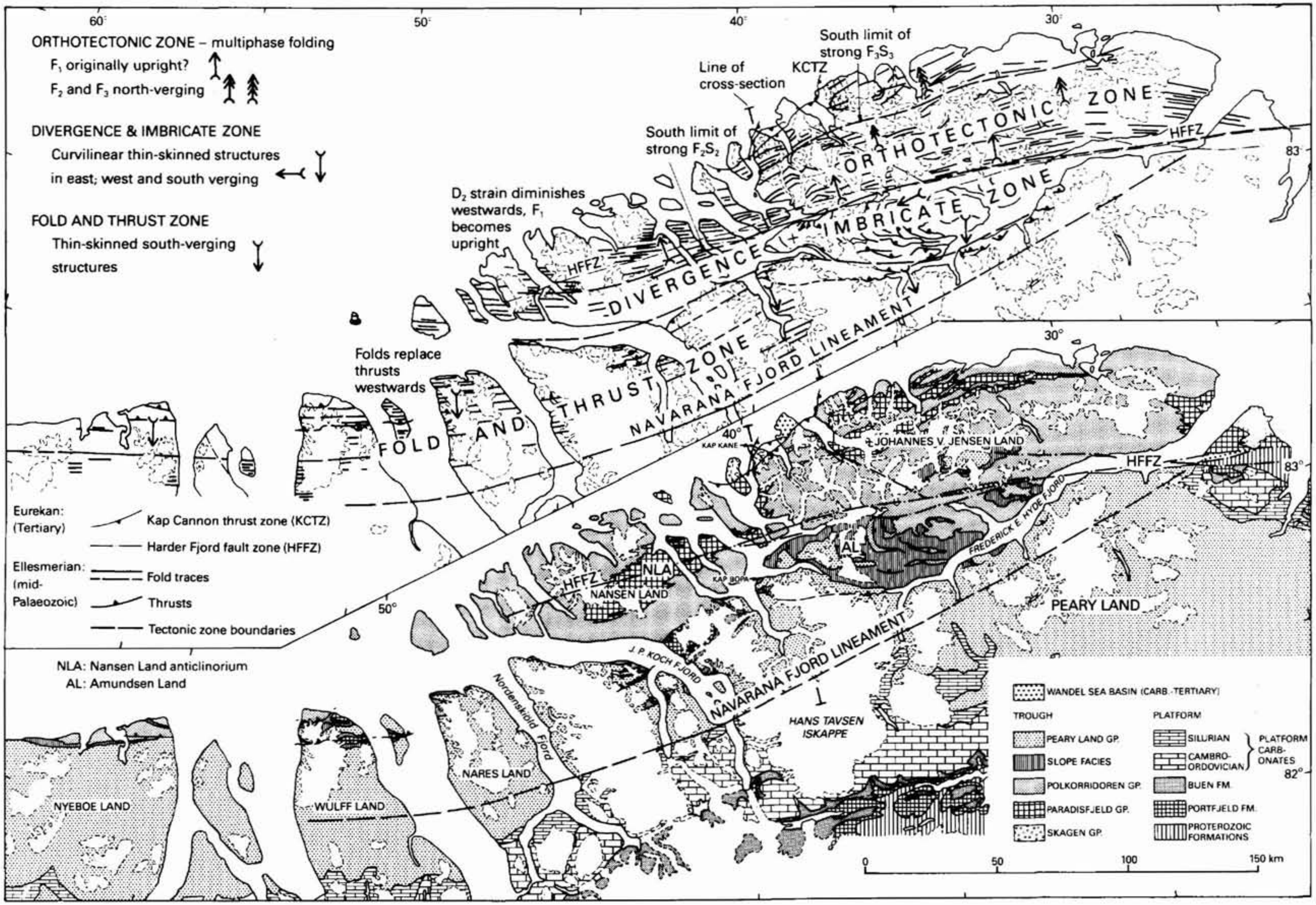


Fig. 65. Upper structural map shows trends of main folds and thrusts in the North Greenland fold belt and the division into three tectonic zones. The lower geological map shows the distribution of main units of the trough and shelf succession. Modified after Soper & Higgins (1987).

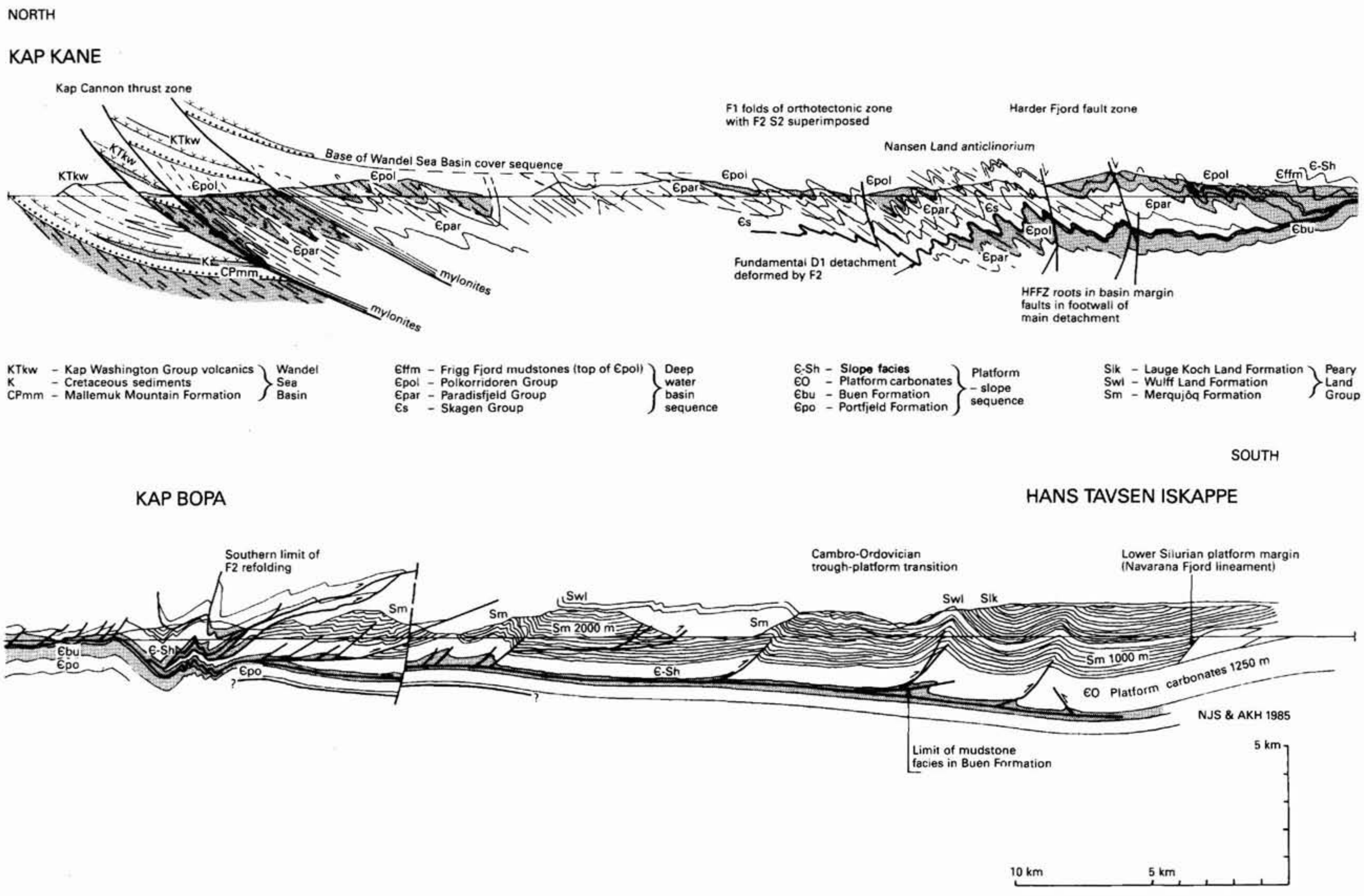


Fig. 66. North-south cross-section of the North Greenland fold belt. See Fig. 65 for the line of section. Most folds and thrusts shown are Ellesmerian (Devonian-Carboniferous) in age, but note that the Kap Cannon thrust zone at the northern end of the section is Tertiary. Modified after Soper & Higgins (1987).

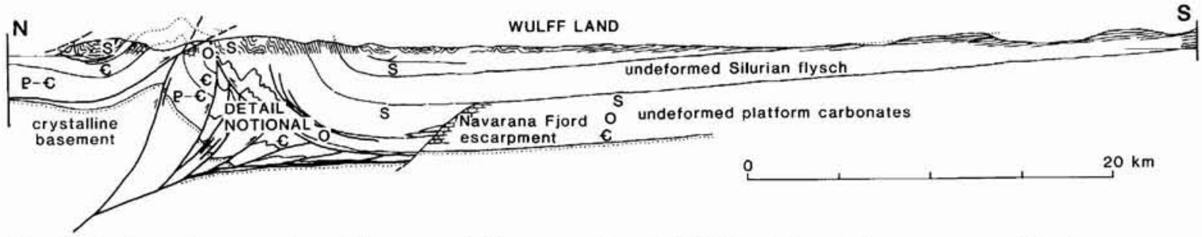


Fig. 67. North-south cross-section of the mountain front monocline in Wulff Land showing interpretation of the deep structure. After Higgins & Soper (1989).

The Ellesmerian Orogeny

The mid-Palaeozoic Ellesmerian Orogeny, which brought sedimentation in the Franklinian Basin to a close, involved compression of the Early Cambrian – latest Silurian trough sequence against the carbonate shelf which flanked it to the south. In the resulting Ellesmerian fold belts of both North Greenland and northern Ellesmere Island fold trends run E-W to NE-SW, broadly parallel to the main facies boundaries within the Franklinian Basin. Little is known of the geotectonic context of the Ellesmerian Orogeny, although it has usually been interpretated in terms of southward underthrusting of ocean floor against and beneath the continental block and Franklinian Basin (Trettin *et al.*, 1972; Dawes & Soper, 1973; Trettin & Balkwill, 1979). However, the early Palaeozoic granitic plutonism and arc-type volcanism of northernmost Ellesmere Island (Pearya) formerly viewed as characteristic of an *in situ* magmatic arc are now viewed as elements of an exotic terrane (Trettin, 1987).

The region of North Greenland affected by Ellesmerian deformation is conventionally known as the North Greenland fold belt. Deformation is most intense in northern Peary Land (Johannes V. Jensen Land) where three phases of coaxial folding are recognised and metamorphic grade reaches low amphibolite facies (Dawes, 1976). Both deformation and metamorphism decrease southwards. Three distinct tectonic zones can be recognised (Fig. 65), spatially related to the geometry of the Franklinian Basin (Soper & Higgins, 1987).

A southern thin-skinned fold and thrust zone coincides with a region which was transitional between the platform and trough for much of the Cambrian. It is approximately bounded to the south by the Navarana Fjord lineament, a pronounced mid-Ordovician to early Silurian platform escarpment the position of which was probably initially controlled by faulting (see previous discussion). Deformation is of classic fold and thrust style with flexural slip folds located above thrust ramps. Folds verge southwards; thrusts dip at gentle to moderate inclinations northwards and have a southwards sense of displacement (Fig. 65). Westwards from the line of section of Fig. 66 the most conspicuous feature of the fold and thrust zone is a major mountain front monocline which attains an amplitude of some 7 km at its greatest development in Wulff Land. Attempts to model the deep structure beneath the monocline by Soper & Higgins (1990) show that it cannot be interpreted as entirely thin-skinned and that crystalline basement must be involved. In their model (Fig. 67) an early Palaeozoic extensional basement ramp is envisaged as having been reactivated during the Ellesmerian Orogeny.

The divergence and imbricate zone (Fig. 65) corresponds to the tract across which the vergence of folds changes from south to north. It also coincides with a pronounced change in the stratigraphic level of rocks exposed at the surface. To the north, in the orthotectonic zone on the site of the trough, Lower Cambrian rocks are exposed. To the south, across the fold and thrust zone and adjacent parts of the undeformed platform, Silurian rocks are exposed except where older rocks are brought to the surface in anticlinal fold cores and thrust sheets. The divergence zone widens eastwards, where it is characterised by imbricate thrusts with curvilinear traces which verge to the west and south (Pedersen, 1986).

The orthotectonic zone is developed on the site of the trough proper, with its thick fill of Lower Cambrian carbonate and siliciclastic turbidites (Paradisfjeld Group and Polkorridoren Group). In the eastern part of the orthotectonic zone structures referable to three coaxial tectonic episodes (F1, F2 & F3) are recognised. F1 folds are dominant in the south, where they are upright. To the north, F2 folds become superimposed on F1; these are consistently overturned northwards and develop a south-dipping axial plane fabric. Near the north coast, where F1 and F2 are isoclinal, F3 folds are superimposed and the metamorphic grade rises to low amphibolite facies. In the western part of the orthotectonic zone in Nansen Land and adjacent islands the dominant structures are spectacular trains of F1 folds, upright or slightly northward verging (Fig. 13); F2 structures are only weakly developed and F3 is absent here. A cross-section through the fold belt (Fig. 66) illustrates the relationships between the zones.

Following a period of erosion and peneplanation, the folded early Palaeozoic sediments of the Ellesmerian fold belts were overlain by Carboniferous to early Tertiary sediments and volcanics. In northern Ellesmere Island these sequences are referred to the Sverdrup Basin, and in North Greenland to the Wandel Sea Basin (Stemmerik & Håkansson, 1991; Håkansson *et al.*, 1991).

Acknowledgements. We would like to thank our many colleagues and friends, fellow participants in the several stages of the North Greenland Project and its associated studies, for freely making available their results and observations. Project leader Niels Henriksen provided the organisational framework which allowed us easy access to North Greenland geology and the time to study it, albeit briefly. Hans P. Trettin (Geological Survey of Canada) is thanked for his guidance in connection with the preparation of an earlier manuscript (Higgins *et al.*, in press), a contribution to the *Decade of North American Geology* programme, which formed the basis for the present paper. Birgitte Larsen is thanked for typing the original manuscript. Jette Halskov, Bodil Sikker Hansen and Bente Thomas are thanked for artwork, and Jakob Lautrup for photographic illustrations.

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The North Greenland Project: camp life.

Carboniferous and Permian history of the Wandel Sea Basin, North Greenland

Lars Stemmerik and Eckart Håkansson

Upper Palaeozoic sediments in North Greenland were deposited in basins formed as the result of rifting between Norway, Greenland and Svalbard. The succession comprises Upper Carboniferous fluviatile sediments, Upper Carboniferous mixed shallow marine siliciclastic sediments and carbonates, Lower Permian shallow water carbonates, and Upper Permian carbonates, cherts and shales. Major depositional sequences encompass the following intervals: early Moscovian, mid Moscovian – Gzelian, Asselian-Kungurian, and Ufimian-Kazanian.

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Upper Palaeozoic sedimentary rocks in eastern areas of North Greenland (Fig. 1) were discovered by J. P. Koch and A. Wegener during the Danmarks Expedition of 1906–08. However, the remoteness of the area has severely restricted exploration and, until recently, knowledge of the Upper Palaeozoic succession has been confined largely to palaeontological and biostratigraphic accounts of the very limited material collected by J. P. Koch and A. Wegener in 1907, by E. Nielsen in 1938, by J. C. Troelsen in 1948 and by W. E. Davies in 1961 (Nathorst, 1911; Grönwall, 1916; Frebold, 1950; Dunbar, 1962; Dunbar *et al.*, 1962; Ross & Dunbar, 1962; Ross & Ross, 1962; Peel *et al.*, 1974; Bendix-Almgreen, 1975; Dawes, 1976; Petryk, 1977).

Upper Palaeozoic sediments throughout central and eastern North Greenland were investigated in some detail during 1978 and 1980, as a part of the North Greenland Project of the Geological Survey of Greenland (Håkansson, 1979; Håkansson *et al.*, 1981; see Henriksen & Higgins, 1991). This work was followed recently by a more detailed study of the Upper Palaeozoic deposits on Prinsesse Ingeborg Halvø (Håkansson *et al.*, 1989). The outcome of this recent work was not included in the lithostratigraphic frame-work established by Stemmerik & Håkansson (1989).

The overall correlation of the Carboniferous and Permian deposits of Svalbard, the Sverdrup Basin of Arctic Canada and the Wandel Sea Basin of North Greenland is well established (Håkansson & Stemmerik, 1984; Stemmerik & Worsley, 1989; Davies & Nassichuk, in press). However, looking in more detail, the most striking depositional similarities are found between the successions on Svalbard and in the Sverdrup Basin (Davies & Nassichuk, in press). This may reflect the fact that the limited exposures in Greenland include only the more shallow water parts of the shelf sequence.

Geological setting and structural framework

Upper Palaeozoic sedimentation post-dates the Caledonian orogenesis in eastern North Greenland and the Ellesmerian orogenesis in central North Greenland (Håkansson *et al.*, 1981; Higgins *et al.*, 1985; Hurst *et al.*, 1985). Sedimentation reflects structural development in two different tectonic settings somewhat artificially united as the Wandel Sea Basin (Håkansson & Stemmerik, 1989). It is suggested that deposition of Upper Palaeozoic sediments in Holm Land and Amdrup Land (Fig. 1) occurred in a basin developed as the result of rifting between Greenland and Norway (Fig. 2). Sediments exposed in eastern Peary Land and on Lockwood Ø (Fig. 1) appear to have accumulated in a basin formed as the result of rifting between central North Greenland and Svalbard (Fig. 2). These two basins formed part of an extensive mosaic of interconnected basins covering the Barents Shelf region and the marginal areas of North Greenland during the Late Palaeozoic (Stemmerik & Worsley, 1989).

Sedimentation was fairly uniform in the Wandel Sea Basin during Late Carboniferous and Early Permian times (Fig. 3). In the Holm Land area sedimentation started in the latest Devonian or earliest Carboniferous

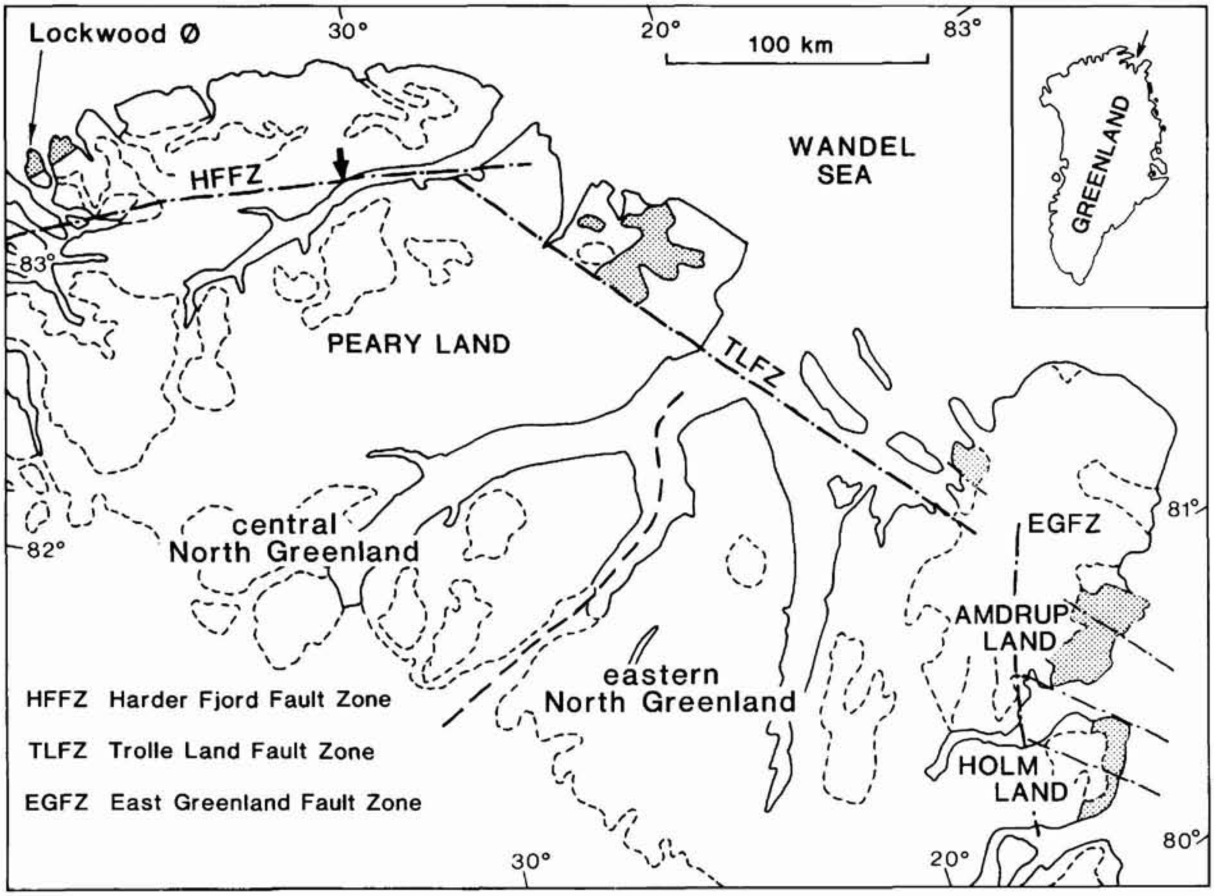

Fig. 1. Distribution of Upper Palaeozoic sediments (shaded) and major structural elements in central and eastern North Greenland. Arrow indicates a small outcrop of the Kap Kraka Formation.

and fluviatile sediments comparable to those in central East Greenland were deposited. The sediments were faulted and eroded, prior to the Late Carboniferous transgression, in a tectonic phase not recorded elsewhere in the area. Sedimentation continued north of the Trolle Land Fault Zone into the Late Permian in what appears to be a tectonically active basin. Similar conditions occur also in several of the basins in the Svalbard – Barents Sea region (e.g. Stemmerik & Worsley, 1989).

Upper Palaeozoic sediments in Holm Land and Amdrup Land rest directly on Precambrian basement, whereas the sediments in eastern Peary Land overlie a variety of strata deformed during the Ellesmerian Orogeny (Håkansson, 1979; Håkansson *et al.*, 1981).

Holm Land – Amdrup Land basin

Upper Palaeozoic sediments in Holm Land and Amdrup Land were deposited during the initial stages of the rifting between Greenland and Norway. Rifting was initiated during latest Devonian or earliest Carboniferous time and is synchronous with, and related to, rifting events in Svalbard, the Barents Sea and central East Greenland (Stemmerik & Worsley, 1989).

The main structural feature in Holm Land and Amdrup Land is the N-S trending East Greenland Fault Zone, considered to be the northern extension of the post-Devonian Main Fault Zone (Vischer, 1943) of central East Greenland (Fig. 2). Sedimentation was probably restricted to the subsiding areas east of this fault zone (Fig. 4). A series of NW-SE trending faults controlled the differential sedimentary history of a number of small fault blocks on this subsiding platform (Figs 1, 3).

A major tectonic event during mid-Carboniferous times disturbed the Lower Carboniferous sediments along N-S trending faults prior to the Late Carboniferous (early Moscovian) transgression (Håkansson *et al.*, 1981; Håkansson & Pedersen, 1982).

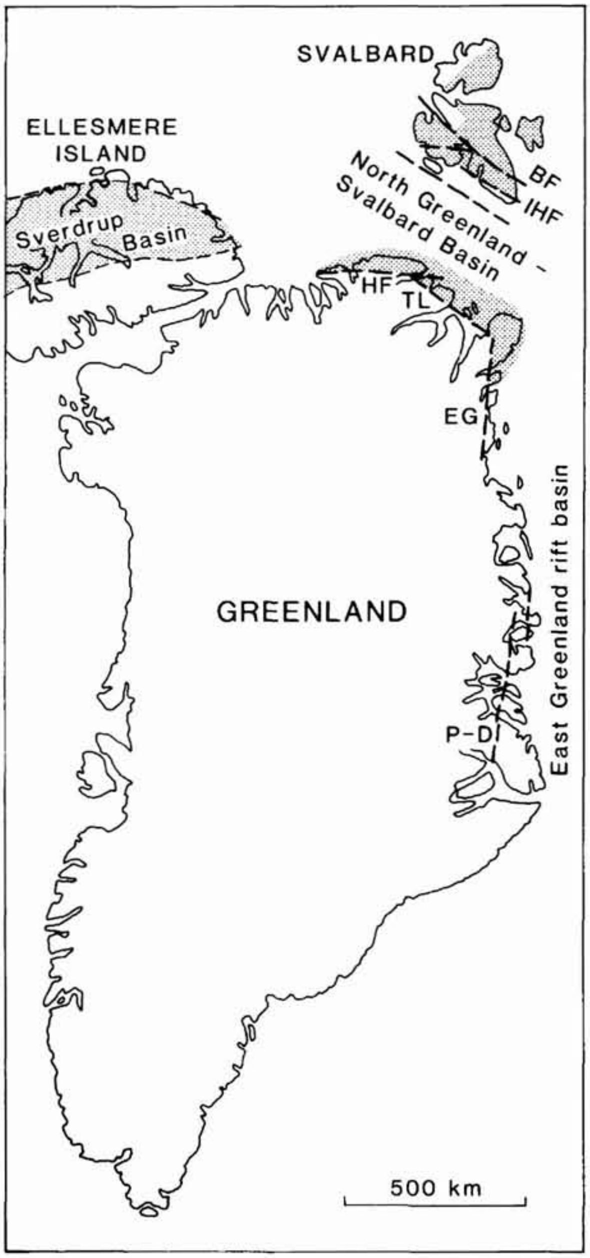

Fig. 2. General pre-drift configuration of Greenland, Svalbard and Ellesmere Island. The stippled area indicates the known extent of the Upper Palaeozoic basins. BF, Billefjorden Fault; IHF, Inner Hornsund Fault; HF, Harder Fjord Fault Zone; TL, Trolle Land Fault Zone; EG, East Greenland Fault Zone; P-D, post-Devonian Main Fault (based on Steel & Worsley, 1984; Davies & Nassichuk, in press; and various GGU maps).

Peary Land – Prinsesse Ingeborg Halvø basin

Upper Carboniferous – Upper Permian sediments in Peary Land and Prinsesse Ingeborg Halvø are limited by the roughly E-W trending Harder Fjord Fault Zone and the NW-SE trending Trolle Land Fault Zone (Fig. 2). Favouring a pre-drift position of Svalbard north-east of Greenland (Fig. 2), these fault zones are roughly parallel to the fault-system which Steel & Worsley (1984) consider to have controlled the Late Palaeozoic sedimentation in Svalbard. Thus, we suggest that during the Late Palaeozoic North Greenland constituted a fault-bound basin which was closely related to the basins found in Svalbard (Fig. 2).

The onset of sedimentation in this area during the Late Carboniferous may be structurally controlled. The following period was characterised by gentle subsidence of the basin and not until mid-Permian times is there evidence of renewed movements along the Harder Fjord and Trolle Land Fault Zones (Håkansson & Pedersen, 1982; Nilsson *et al.,* 1991). The Permian-Triassic boundary is marked by a low angle unconformity throughout the Arctic (Håkansson & Stemmerik, 1984; Steel & Worsley, 1984).

Stratigraphy and lithofacies

A stratigraphic scheme for the Lower Carboniferous to Upper Permian sediments in the Wandel Sea Basin has recently been proposed by Stemmerik & Håkansson (1989). Correlation between the main outcrop areas, Holm Land – Amdrup Land and eastern Peary Land, is fairly well established for the Upper Carboniferous to lowermost Permian part of the succession (Fig. 3). However, the Permian part of the succession is not well dated and, accordingly, correlation is poor. These correlation problems have been substantiated further by the discovery of a thick Permian siliciclastic succession restricted to Prinsesse Ingeborg Halvø (Håkansson *et al.*, 1989).

The succession in the Holm Land – Amdrup Land area has been investigated in greatest detail (Håkansson *et al.,* 1981; Håkansson & Stemmerik, 1984; Stemmerik, 1989a, b; Stemmerik & Håkansson, 1989). Here outcrops can be followed for considerable distances along strike but, unfortunately, they only extend for a few kilometres E-W perpendicular to strike. As a result only a very limited cross-section is actually exposed.

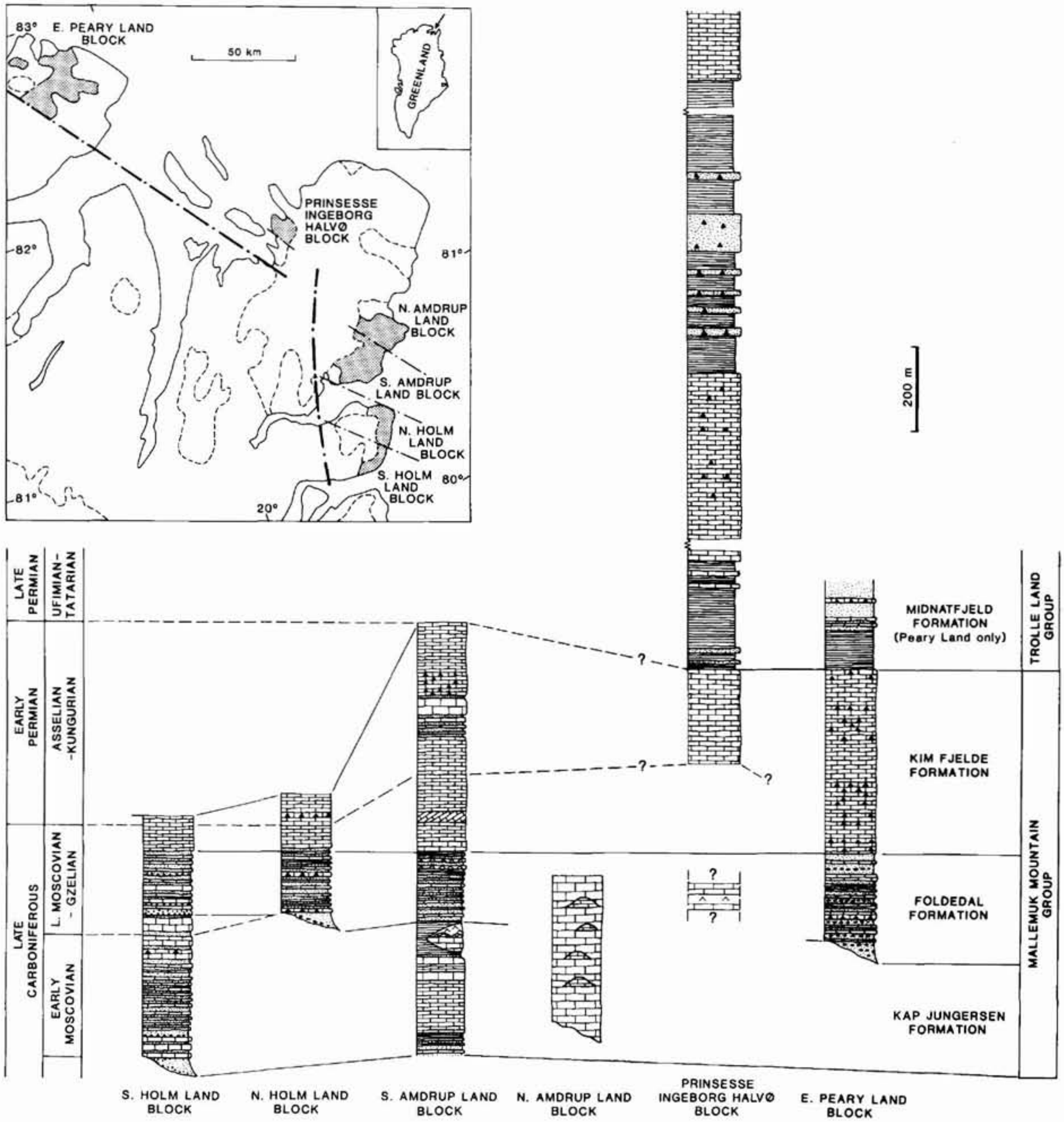

Fig. 3. Lithostratigraphic correlation of the marine Upper Palaeozoic sediments in eastern North Greenland. Solid lines indicate lithostratigraphic units; dotted lines are the proposed biostratigraphic correlation (based on Håkansson & Stemmerik, 1984; Stemmerik & Håkansson, 1989; Nilsson *et al.*, 1991).

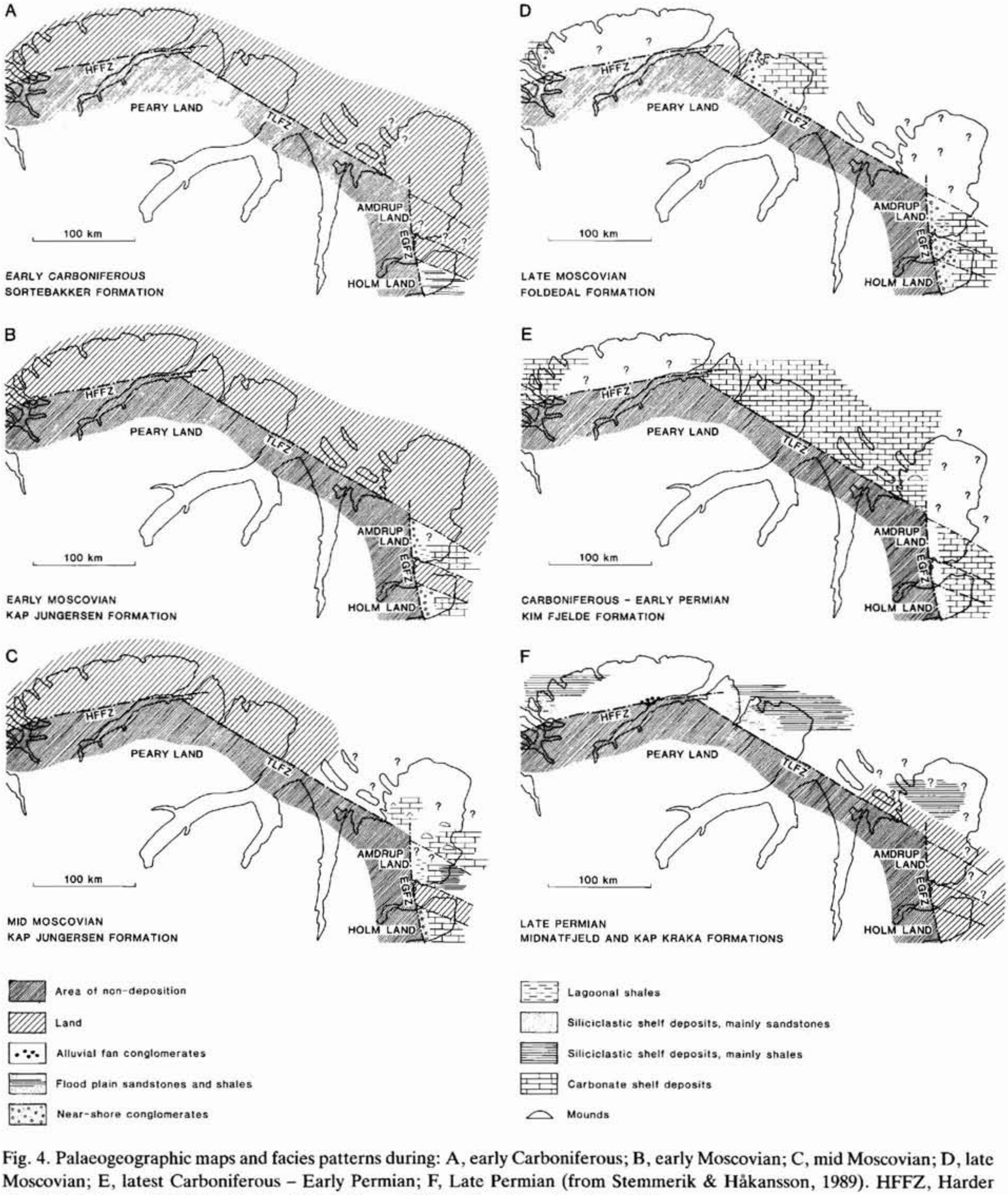

Fig. 4. Palaeogeographic maps and facies patterns during: A, early Carboniferous; B, early Moscovian; C, mid Moscovian; D, late Moscovian; E, latest Carboniferous – Early Permian; F, Late Permian (from Stemmerik & Håkansson, 1989). HFFZ, Harder Fjord Fault Zone; TLFZ, Trolle Land Fault Zone; EGFZ, East Greenland Fault Zone.

Basin evolution

Early Carboniferous (Visean?) fluviatile sedimentation

Prior to the early Moscovian transgression a thick succession of fluviatile sediments (Sortebakker Formation) accumulated on the southern Holm Land block (Fig. 4A). This more than 600 m thick succession consists of stacked, fining-upward cycles of flood-plain origin (Håkansson & Stemmerik, 1984). A low angle unconformity divides the sediments into a lower shaly unit with mainly thin cycles, and an upper sandy unit with thick cycles (Fig. 5).

The sandy unit includes more than 40 cycles which may be traced laterally for several kilometres (Fig. 5). Each cycle has an erosional lower surface overlain by 3–7 m thick sandstones showing a variety of stream generated structures indicating easterly palaeocurrents. The fine-grained part of each cycle is composed of carbonaceous shale and occasional thin coal beds containing a sparse macroflora of early Carboniferous age (Nathorst, 1911).

Late Carboniferous cyclic shelf sedimentation

The early Moscovian – Gzelian Kap Jungersen and Foldedal Formations consist of shelf sediments deposited in two major fining-upward megacycles 170–400 m thick (Fig. 3). Early Moscovian shelf sedimentation was confined to the southern Holm Land and the Amdrup Land blocks (Figs 4B, C). In contrast late Moscovian – Gzelian shelf sedimentation was far more widespread covering Holm Land, southern Amdrup Land, most of Peary Land and possibly also Prinsesse Ingeborg Halvø (Fig. 4D).

Early Moscovian transgression and shelf sedimentation

The base of the early Moscovian transgressive succession is exposed along the south coast of Holm Land. Prior to the transgression, the Lower Carboniferous sediments were disturbed along N-S trending faults and subsequently eroded (Fig. 5; Håkansson *et al.*, 1981).

During the initial stages of the transgression conglomerates and coarse-grained sandstones accumulated in high energy, coastal environments towards the west (Fig. 4B). As the sea-level rose, the conglomerates gradually migrated further westwards forming a wedge-shaped body. Seawards, towards the east, thick deposits of shelf sediments accumulated (Fig. 4B). In southern Holm Land the early stages of shelf sedimentation were dominated by sheet-like bodies of alternating cross-bedded, immature sandstone and biogenic limestone, predominantly wackestone. The limestones yield a normal marine fauna dominated by brachiopods, bryozoans, corals and fusulinids. Occasionally, chaetetids form small patch-reefs, but otherwise reef development is not indicated (Stemmerik, 1989b). In contrast the sandstones only contain a limited fauna of mainly gastropods.

The regular occurrence of normal marine fossils in the sandstones indicates that also this phase of the cycles was marine. The large areal extent of individual beds (Fig. 6) and the almost complete lack of siliciclastic material in the limestones suggest that the cyclicity was caused by very rapid changes in depositional conditions

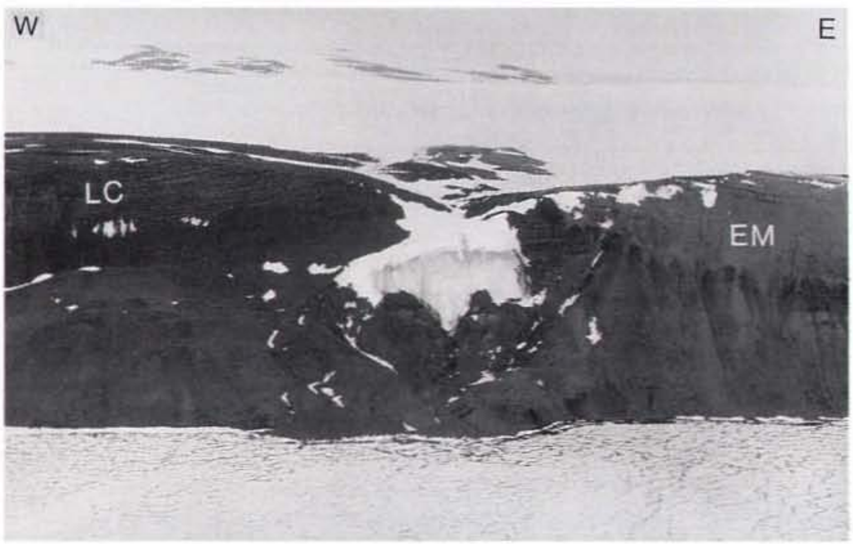

Fig. 5. Lower Carboniferous (LC) fining upward cycles of flood-plain origin unconformably overlain by marine lower Moscovian sediments (EM). Cliff height approximately 350 m, southern Holm Land.

Fig. 6. Interbedded biogenic limestones and sandstones of the Kap Jungersen Formation (lower Moscovian). Exposed section approximately 100 m, southern Holm Land.

over wide areas of the shelf rather than by facies progradation. Gradually, sandstone intervals became less frequent and the upper part of the Kap Jungersen Formation is composed almost exclusively of bedded biogenic limestone (Fig. 4C).

In southern Amdrup Land the succession exhibits a more complex facies pattern (Figs 4B, C). The initial transgressive deposits are not exposed; the oldest sediments are cyclically-interbedded sandstones, shales and biogenic limestones of lagoonal origin. Above follows a thick succession of shelf limestone which is highly fossiliferous in the lower part. Typically, these limestones are overlain by shales but, locally, limestone deposition continued and developed into a 1–2 km wide, N-S trending carbonate platform (Fig. 7). Initially, mainly hypersaline, chert-rich dolomite accumulated producing a platform with up to 50 m of relief (Fig. 7). Afterwards small bryozoan-crinoid mounds grew on top of the platform at the same time as shale deposition took place in the surrounding topographic lows (Stemmerik, 1989a). Several episodes of sea-level drawdown are suggested to account for the regular occurrence of gypsum beds in the shales and the early vadose diagenetic alteration of the lower part of the mounds. Finally, the entire southern Amdrup Land area became a site of gypsum deposition.

The thick succession of poorly dated, Moscovian bryozoan-dominated mounds and associated carbonates in northern Amdrup Land is believed to be the northwards continuation of this mid-Moscovian platform. There is no evidence of evaporite deposition in northern Amdrup Land, but diagenetic studies of the mounds suggest that they have been subjected to subaerial exposure (Stemmerik, in press).

Late Moscovian – Gzelian shelf sedimentation

During late Moscovian times the sea transgressed over northern Holm Land and most of the eastern Peary Land blocks (Fig. 4D). The transgression was apparently closely related to tectonic activity along the East Greenland, Trolle Land and Harder Fjord Fault Zones (Håkansson & Stemmerik, 1984) and thick wedges of conglomerates were deposited in the newly transgressed areas (Fig. 4D). The input of siliciclastic material was gradually reduced and cyclic sandstone and biogenic

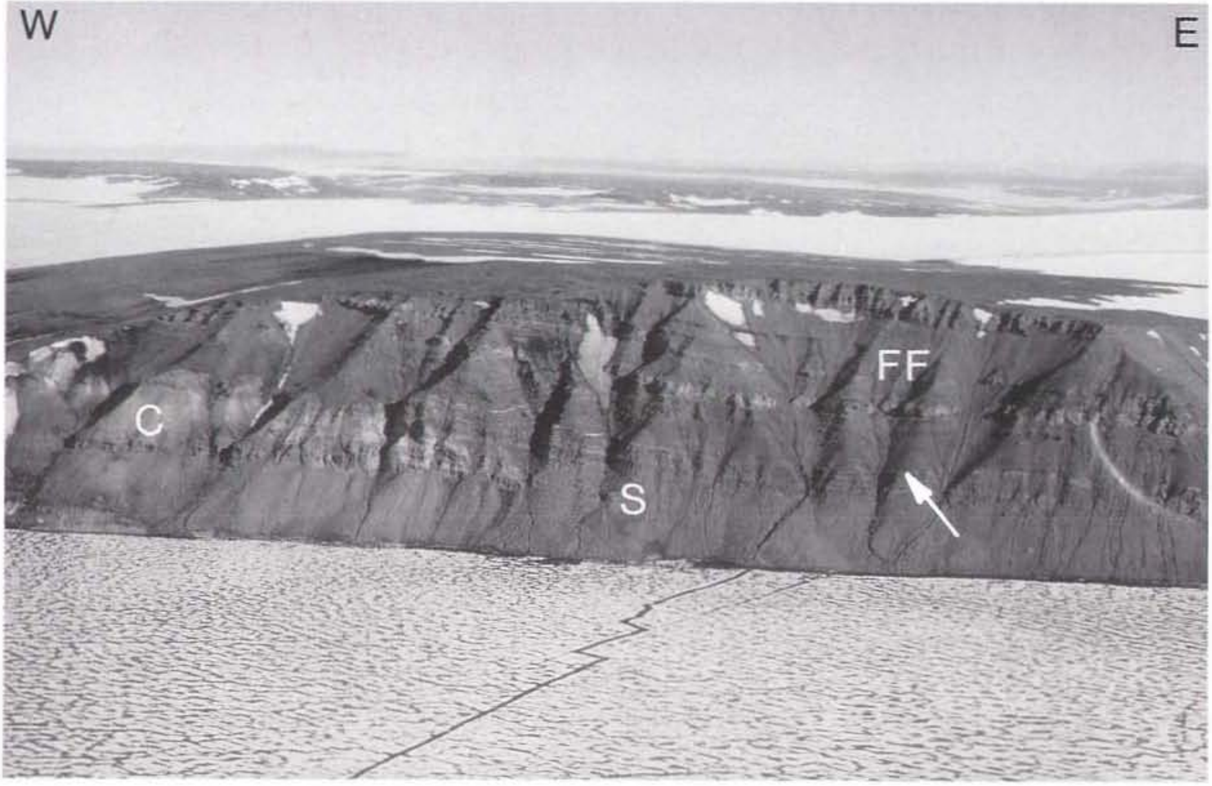

Fig. 7. The early Moscovian – Gzelian succession in southern Amdrup Land. Note the isolated carbonate platform (C) surrounded by shales (S) also belonging to the Kap Jungersen Formation (lower Moscovian). The transition to the overlying Foldedal Formation (FF) (upper Moscovian – Gzelian) is placed at a thick sandstone above the uppermost gypsum layer (arrow). Cliff height approximately 350 m.

limestone were deposited in Holm Land and most of eastern Peary Land (Figs 4D, 8). However, depositional environments in southern Amdrup Land continued to differ from the regional pattern also during the late Moscovian, and deposition of interbedded sandstone, shale and biogenic limestone in quieter, lagoonal environments was re-established. Repeated emergence of the upper part of the succession is indicated both by layers of chicken-wire anhydrite and by abundant levels of shrinkage cracks in the fine-grained siliciclastic sediments.

Late Carboniferous – Early Permian (Kungurian) transgression and carbonate shelf sedimentation

The Moscovian-Gzelian mixed siliciclastic and carbonate deposits were succeeded in the latest Carboniferous by widespread, rather uniform deposition of shallow water carbonates (Fig. 9). This change was most likely related to a eustatic rise in sea-level.

Well-bedded biogenic limestones are widespread throughout Holm Land, southern Amdrup Land and Peary Land (Fig. 4E). Well preserved macrofossils are rare in these deposits which are mainly composed of fine-grained fragments of brachiopods, bryozoans and crinoids in a micritic matrix. Shallow, more agitated conditions prevailed on the Prinsesse Ingeborg Halvø block where highly fossiliferous wackestones and packstones accumulated.

Sediments from the latest part of the Early Permian (Kungurian) have been recognised only from Peary Land, Prinsesse Ingeborg Halvø and southern Amdrup Land. In Amdrup Land an overall shallowing took place during the Early Permian, and the Kungurian? part of the succession is dominated by highly diverse *in situ* accumulations of brachiopods and bryozoans in a micritic matrix (Madsen & Håkansson, 1989). In Peary Land and on Prinsesse Ingeborg Halvø, on the other hand, the depositional environment apparently became gradually deeper during the Early Permian.

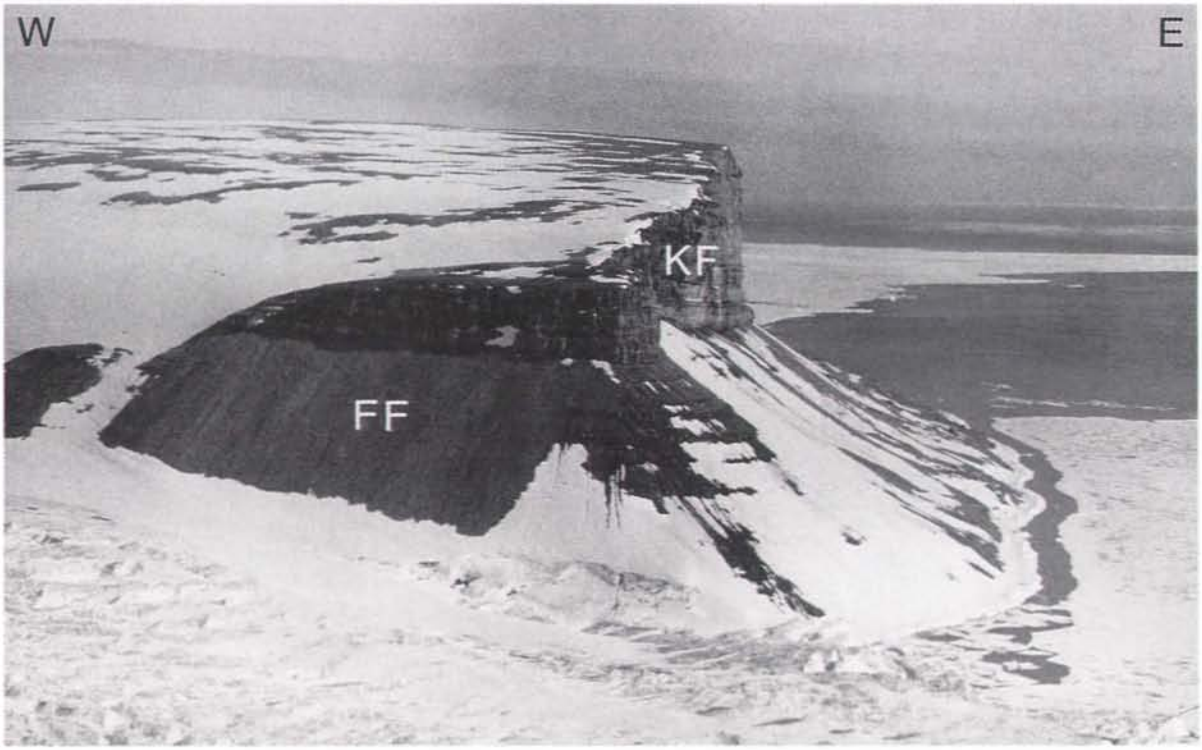

Fig. 8. Interbedded biogenic limestones and sandstones of the Foldedal Formation (FF) (upper Moscovian – Gzelian) overlain by bedded biogenic limestones of the Kim Fjelde Formation (KF). Cliff height approximately 350 m, eastern Holm Land.

Fig. 9. Bedded biogenic limestones of the Kim Fjelde Formation. Exposed section approximately 50 m, southern Amdrup Land.

Late Permian siliciclastic shelf sedimentation

The widespread mid-Permian tectonic event, recognised from central East Greenland, Bjørnøya and Spitzbergen (Worsley & Edwards, 1976; Steel & Worsley, 1984; Surlyk *et al.*, 1986), is recorded in Peary Land and on Prinsesse Ingeborg Halvø by renewed influx of siliciclastic material.

The Early Permian deep carbonate shelf now became dominated by shale and chert deposition (Fig. 4F). Gradually, during the Late Permian, an overall regression changed the sedimentation pattern in Peary Land and sandstones prograded across the shelf. As a result the latest part of the succession in Peary Land is dominated by shallow marine sandstones with a few interbeds of biogenic limestone. On Prinsesse Ingeborg Halvø two shallowing upward sequences are recorded; each sequence, 1000–1200 m thick, comprises a lower basinal shale overlain by shallow water carbonate deposits (Håkansson *et al.*, 1989; Fig. 3).

Further evidence of mid-Permian tectonic activity is recorded along the Harder Fjord Fault Zone where thick wedges of Upper Permian conglomerates, sandstones and carbonaceous shales were deposited locally in fault-bound freshwater basins (Håkansson & Pedersen, 1982; Wagner *et al.*, 1982).

Sequence correlation

The Upper Palaeozoic succession in North Greenland can be divided into a number of transgressive-regressive sequences believed to reflect second-order sea-level fluctuations. Major boundaries (sea-level lowstands) are recorded in the mid-Moscovian, latest Gzelian (Carboniferous-Permian boundary), Kungurian-Ufimian boundary and near the Kazanian-Tatarian boundary (Stemmerik & Worsley, 1989). An additional Late Permian transgressive-regressive sequence is recorded on Prinsesse Ingeborg Halvø, but the more precise age of this sequence is yet unknown (Fig. 3).

The North Greenland depositional sequences show good overall correlation to the sequences in Svalbard (Stemmerik & Worsley, 1989). Correlation to the depositional sequences, recorded by Beauchamp *et al.*, (1989) in the Sverdrup Basin, is less well established. Co-occurring sea-level lowstands appear to occur near the Carboniferous-Permian boundary, at the Kungurian-Ufimian boundary and possibly near the Kazanian-Tatarian boundary.

Acknowledgements. We wish to thank V. Hermansen, N. Turner, J. Lautrup and B. S. Hansen for technical assistance.

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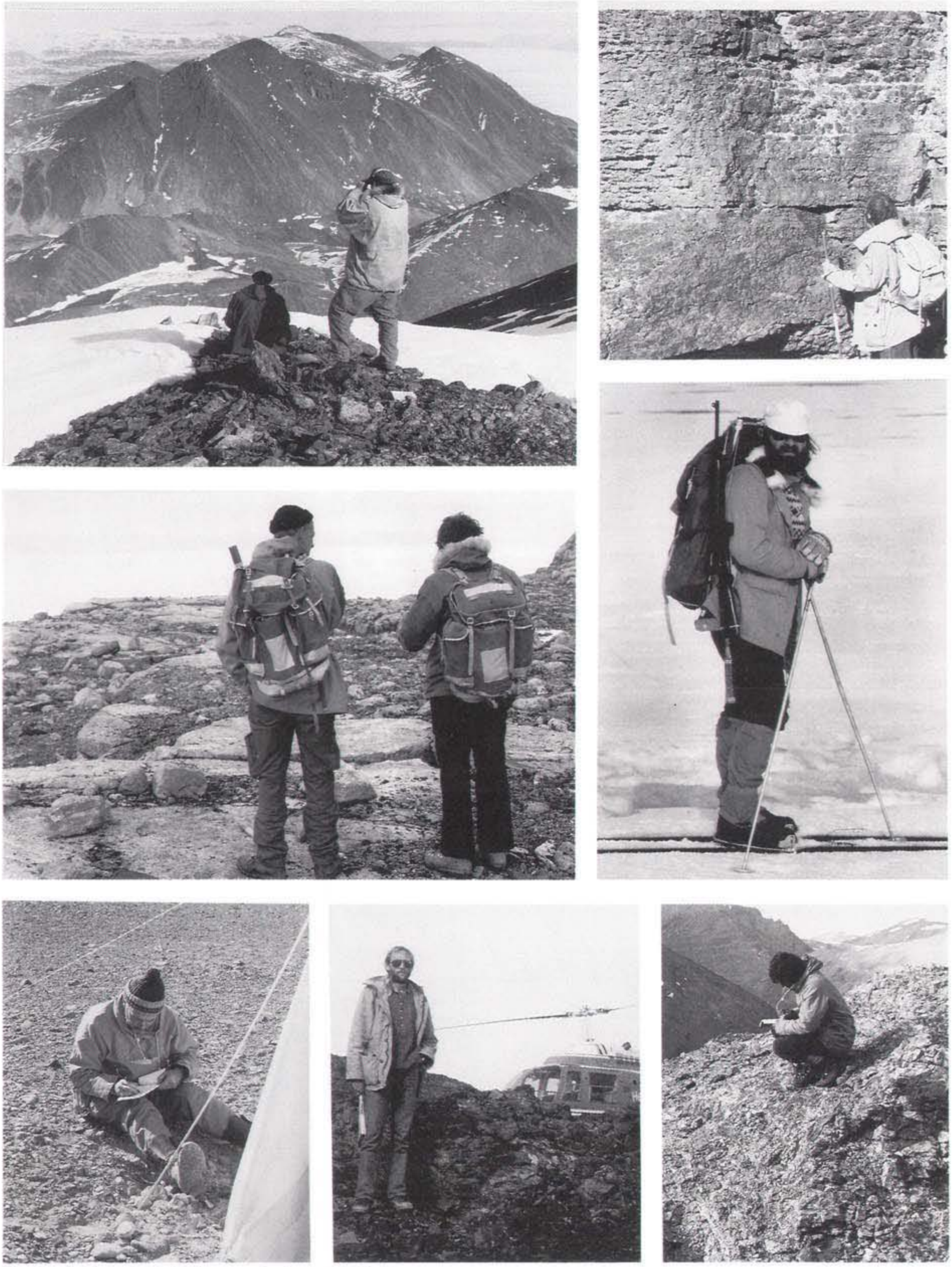

The North Greenland Project: geologists in the field.

Mesozoic and Cenozoic history of the Wandel Sea Basin area, North Greenland

Eckart Håkansson, Claus Heinberg and Lars Stemmerik

Mesozoic deposition in North Greenland is characterised largely by increasing complexity in the configuration of sub-basins developed in response to the major tectonic events in the Wandel Hav Strike-Slip Mobile Belt.

While erosional remnants of Lower and Middle Triassic marine deposits are now confined to a very restricted area, Upper Jurassic – Lower Cretaceous marine to terrestrial deposition took place in two distinct sub-basins resulting from Jurassic left-lateral displacement in the Ingeborg Event. Variable marine and terrestrial Upper Cretaceous strata are restricted to local pull-apart basins formed in the right-lateral mid-Cretaceous Kilen Event; deposition in these basins was everywhere terminated in the continuously right-lateral transpressional movements of the Kronprins Christian Land Orogeny. Compression ceased around the Cretaceous-Tertiary boundary, and a post-orogenic terrestrial sequence of probable Paleocene age is disturbed only by extensional structures.

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The history of exploration of Mesozoic and Cenozoic rocks in North Greenland is brief, even for this remote part of the world. The first post-Palaeozoic fossils were collected from the dark (Cretaceous) sandstones at Nakkehoved on the north coast of Kronprins Christian Land by Eigil Nielsen of the Danish Northeast Greenland Expedition in 1939 (Nielsen, 1941). Ten years later J. C. Troelsen of the Danish Peary Land Expedition (1947–50) added strata of definite Triassic age to the very short list of post-Palaeozoic occurrences, based on localities in eastern Peary Land where younger plant-bearing (Cretaceous) strata were also found (Troelsen, 1950; Kummel, 1953). Reports of Lower Tertiary and Middle Jurassic strata, which were largely unsubstantiated or subsequently shown to be erroneous, were included by Dawes (1976) in the first synthesis of the entire Wandel Sea Basin history. However, knowledge concerning the distribution and history of the post-Palaeozoic strata did not attain a level sufficient to allow more precise speculation about the Mesozoic and Cenozoic development in this crucial corner of the North American continental plate until large scale investigations were initiated during the North Greenland Project of the Geological Survey of Greenland (1978–80); later work has also been supported by the Carlsberg Foundation, Copenhagen.

Geological setting and structural framework

In its original concept the Wandel Sea Basin included the entire Carboniferous to Tertiary succession of eastern and central North Greenland (Dawes & Soper, 1973). However, Håkansson & Stemmerik (1989) recently concluded that the original name should only be maintained at an informal level. The latter authors outlined two major phases in the post-Devonian basin development, with Mesozoic strata confined entirely to the later, strike-slip dominated phase (Håkansson & Pedersen, 1982; Håkansson & Stemmerik, 1989).

The Late Palaeozoic phase in the evolution of the Wandel Sea Basin is described elsewhere in this volume by Stemmerik & Håkansson (1991). Following mid-Permian collapse of an extensive Late Palaeozoic carbonate platform, North Greenland was subjected to a series of strike-slip movements along, or associated with, the major fault zones bordering the stable craton to the north and the north-east (Håkansson & Pedersen, 1982). In the central part of the Wandel Sea Basin area

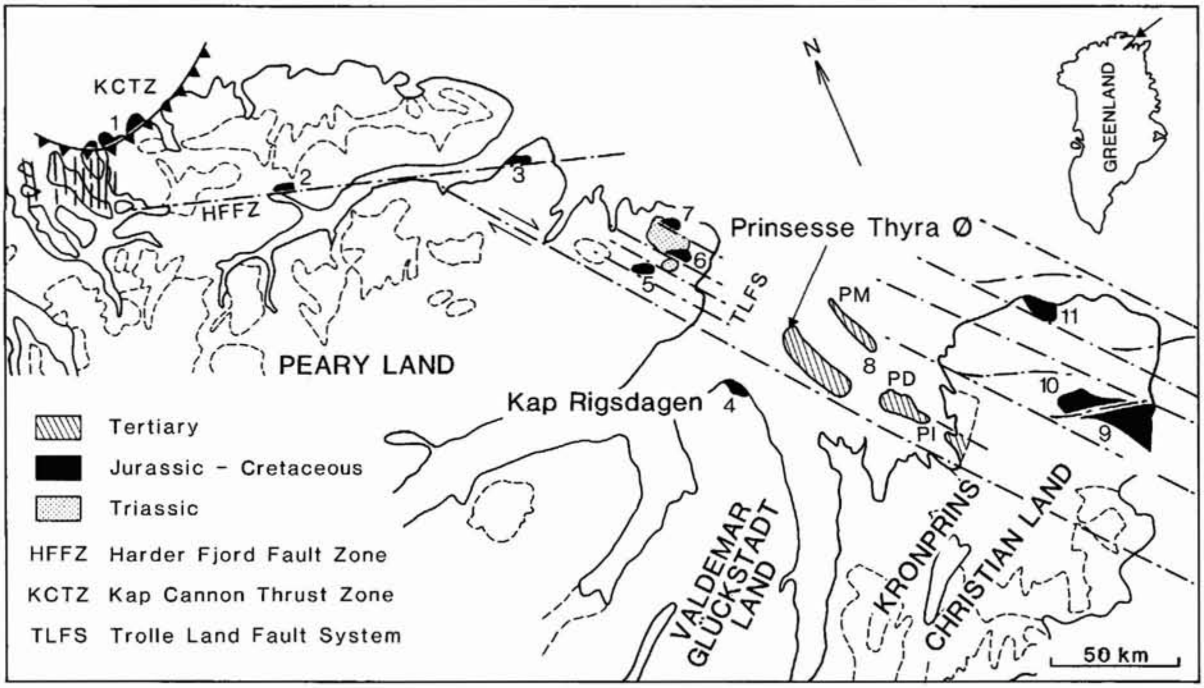


Fig. 1. Map of the main structural lineaments and sediment distribution of the Mesozoic and Cenozoic in the Wandel Sea Basin area. 1, Kap Washington basin; 2, Frigg Fjord basin; 3, Depotbugt basin; 4, Lower Cretaceous at Kap Rigsdagen; 5, 6, Upper Jurassic – Lower Cretaceous; 7, Triassic strata and Herlufsholm Strand basin; 8, Upper Paleocene; 9, Upper Jurassic – Lower Cretaceous; 10, Kilen basin; 11, Nakkehoved basin. Note the dyke swarm in association with the Kap Washington basin. PM, Prinsesse Margrethe Ø; PD, Prinsesse Dagmar Ø; PI, Prinsesse Ingeborg Halvø.

a system of largely parallel faults dissected the former platform in a NW-SE trending system (Fig. 1), which may extend across the present shelf and relate directly to the developing Spitzbergen Fracture Zone (cf. Håkansson & Stemmerik, 1989, Fig. 2). In the on-shore part of central and eastern North Greenland this development found its climax in the Wandel Hav Strike-Slip Mobile Belt (Håkansson & Pedersen, 1982), possibly as an immediate precursor of actual continent separation when Europe and Greenland finally started to drift apart early in the Tertiary (Birkelund & Håkansson, 1983).

The Ingeborg Event

Throughout the Mesozoic Era central and eastern North Greenland were affected repeatedly by strike-slip dominated fault movements in the NW-SE trending Trolle Land Fault System (Fig. 1). An early series of movements which may be concentrated to the early part of the Jurassic has been termed the Ingeborg Event (Pedersen, 1988). In this phase of the history of the Wandel Hav Strike-Slip Mobile Belt, the sense of movement was most likely left-lateral. In eastern Peary Land in particular, differential block movements during this period resulted in an erosional level varying by more than 1 km between neighbouring fault blocks. In terms of basin development the Ingeborg Event had its most profound effect in a further subdivision of the Greenland part of the North Greenland – Svalbard basin. Hence, marine conditions were established in two largely independent areas of deposition (one sub-basin in eastern Peary Land and one in north-eastern Kronprins Christian Land) following the Late Jurassic transgression (Håkansson & Stemmerik, 1989).

The Kilen Event and the Kronprins Christian Land Orogeny

Late Cretaceous geology in North Greenland was controlled by a complex series of events which together characterise the culmination of right-lateral displacement in the Wandel Hav Strike-Slip Mobile Belt (Håkansson & Pedersen, 1982). To a large extent the structural elements are inherited from previous strike-slip phases and thus include broad scale rejuvenation of both the Trolle Land Fault System and the Harder Fjord

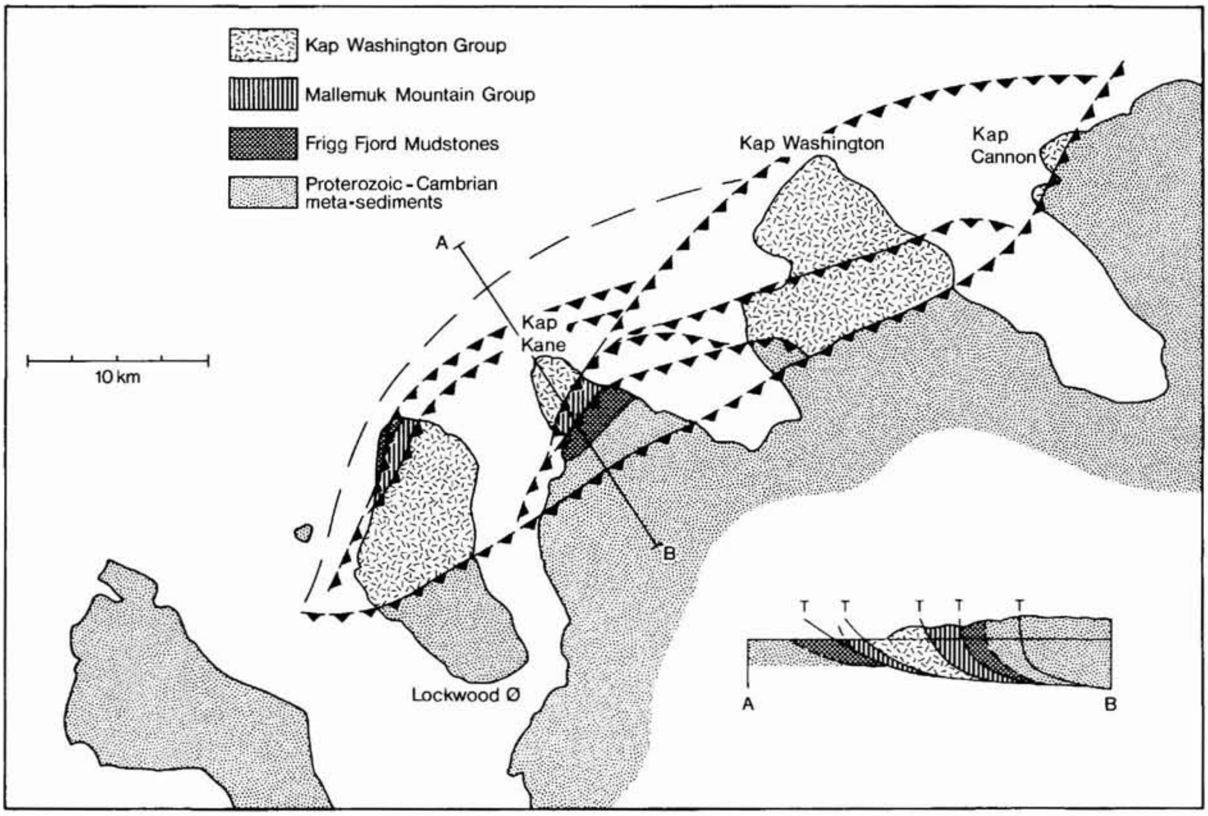


Fig. 2. The Kap Cannon Thrust zone and the Kap Washington basin, north-west Peary Land (after Håkansson & Pedersen, 1982).

Fault Zone (Fig. 1). The intensity and style of deformation, however, change markedly in these later events.

The dominant extensional feature is the development of at least six local pull-apart basins across central and eastern North Greenland, with infill ranging from extrusive volcanics in the extreme western part of the mobile belt to continental clastic and fully marine clastic sediments in the remaining areas. This extensional phase has been termed the Kilen Event by Pedersen (1988). Regardless of depositional differences, all basins are characterised by a very limited areal extent, high rates of accumulation, rapid infill, and immature clastic constituents. In north-western Peary Land extensional forces are further expressed in the formation of a dense N-S striking dyke swarm (Fig. 1; Håkansson & Pedersen, 1982; Birkelund & Håkansson, 1983; Håkansson & Stemmerik, 1984).

Compressional elements are similarly recorded all along the mobile belt and have been referred to the Kronprins Christian Land Orogeny by Pedersen (1988). The dominant style of deformation varies, however, in accordance with the direction of the pre-existing structural elements. Thus, in the Trolle Land Fault System, deformation consisted of reverse movements along the rejuvenated system of steep, NW-SE trending faults defining the zone, with associated E-W oriented domal folding and thrusting being conspicuous in several areas (Håkansson & Pedersen, 1982; Pedersen, 1988; Håkansson *et al.*, in press). Local, low grade shear-related metamorphism in Kronprins Christian Land is probably related to this orogeny (Håkansson *et al.*, 1981b, 1989). Compression in the E-W trending Harder Fjord Fault Zone, on the other hand, is expressed almost exclusively in terms of reverse faulting and thrusting, with little folding and no appreciable strike-slip elements. In the Kap Cannon Thrust Zone, on the north coast of Peary Land, compression is expressed as a series of lobate, listric thrusts indicating an overall sense of displacement towards the north-west. The thrust pattern seems to indicate repeated episodes of deformation in addition to the initial pull-apart basin formation (Fig. 2; Håkansson & Pedersen, 1982).

The final compressional phase everywhere post-dates the extension responsible for the formation of the pull-apart basins. However, no convincing structural evidence for post-Cretaceous compression has yet been found anywhere in eastern North Greenland (Håkansson, 1988).

Continental separation

Following the major compressional events terminating activity within the Wandel Hav Strike-Slip Mobile Belt, the eastern part of North Greenland has apparently been subjected to only tensional events which can be more or less directly associated with the final separation of the American and European continents. Dating of most of these events, however, has so far not been possible due to the almost complete lack of deposits younger than Palaeocene.

Depositional history

The interaction of the three main structural events of the Wandel Hav Strike-Slip Mobile Belt accounts for the apparent paradox that Mesozoic and Cenozoic rocks are not only distributed in a patchy, mosaic pattern far more complex than the distribution of the underlying Upper Palaeozoic rocks, but also – in much of the area – they are considerably more deformed than the Upper Palaeozoic strata. As a result, the preserved remnants of many units have a very limited areal extent (Fig. 3). Furthermore, the precision attained in dating Mesozoic and Cenozoic strata varies tremendously, with the result that it is difficult to accomplish detailed palaeogeographic reconstructions for most of the post-Palaeozoic period.

A formal lithostratigraphy has been proposed for only part of the sequence (Håkansson, 1979).

Triassic clastic shelf sequences

Due to tectonically controlled, differential erosion subsequent to the Ingeborg Event, Triassic strata of the Wandel Sea Basin are only preserved in a limited area in eastern Peary Land (Figs 1, 3; locality 7), where up to 1000 m of Triassic sediments rest with slight angular unconformity on Upper Permian rocks (Håkansson & Pedersen, 1982). The sequence is almost exclusively clastic and, following a basal, reddish, pebble conglomerate, it comprises two major coarsening upwards sequences, referred to the Parish Bjerg (Fig. 4) and Dunken Formations (Fig. 5). The two formations are largely similar in composition, both being dominated by recessive, dark heteroliths giving way to an upper, more prominent unit largely composed of well sorted, fine grained sand. Comminuted carbonaceous detritus of probable terrigenous origin is common throughout most of the sequence but abundant trace fossils, as well as limited occurrences of body fossils, indicate a fully marine origin for the entire Triassic sequence. Each of the two coarsening upwards cycles reflects a major transgressive-regressive pulse with an initial deeper water phase shallowing abruptly due to coastal progradation.

In spite of the slightly angular relation between the Permian Midnatfjeld Formation and the Parish Bjerg

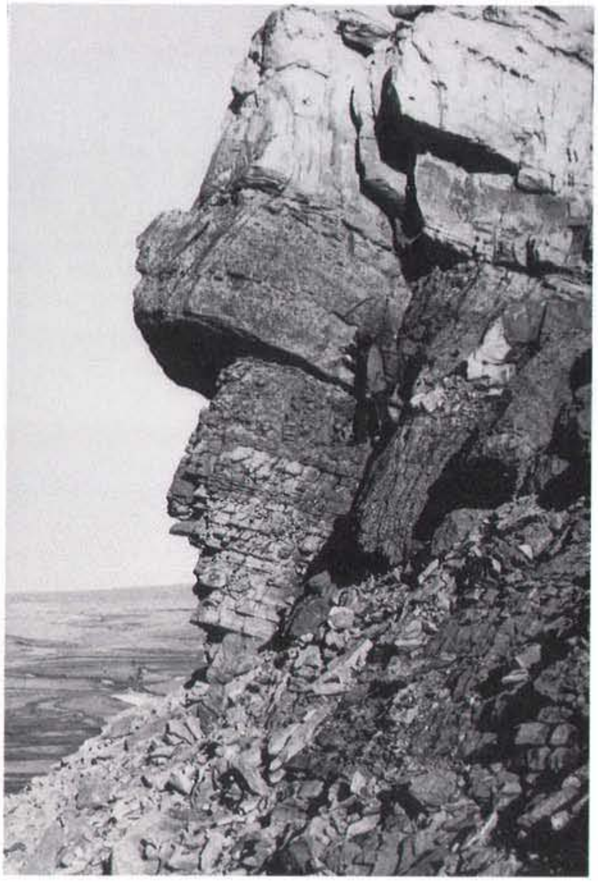
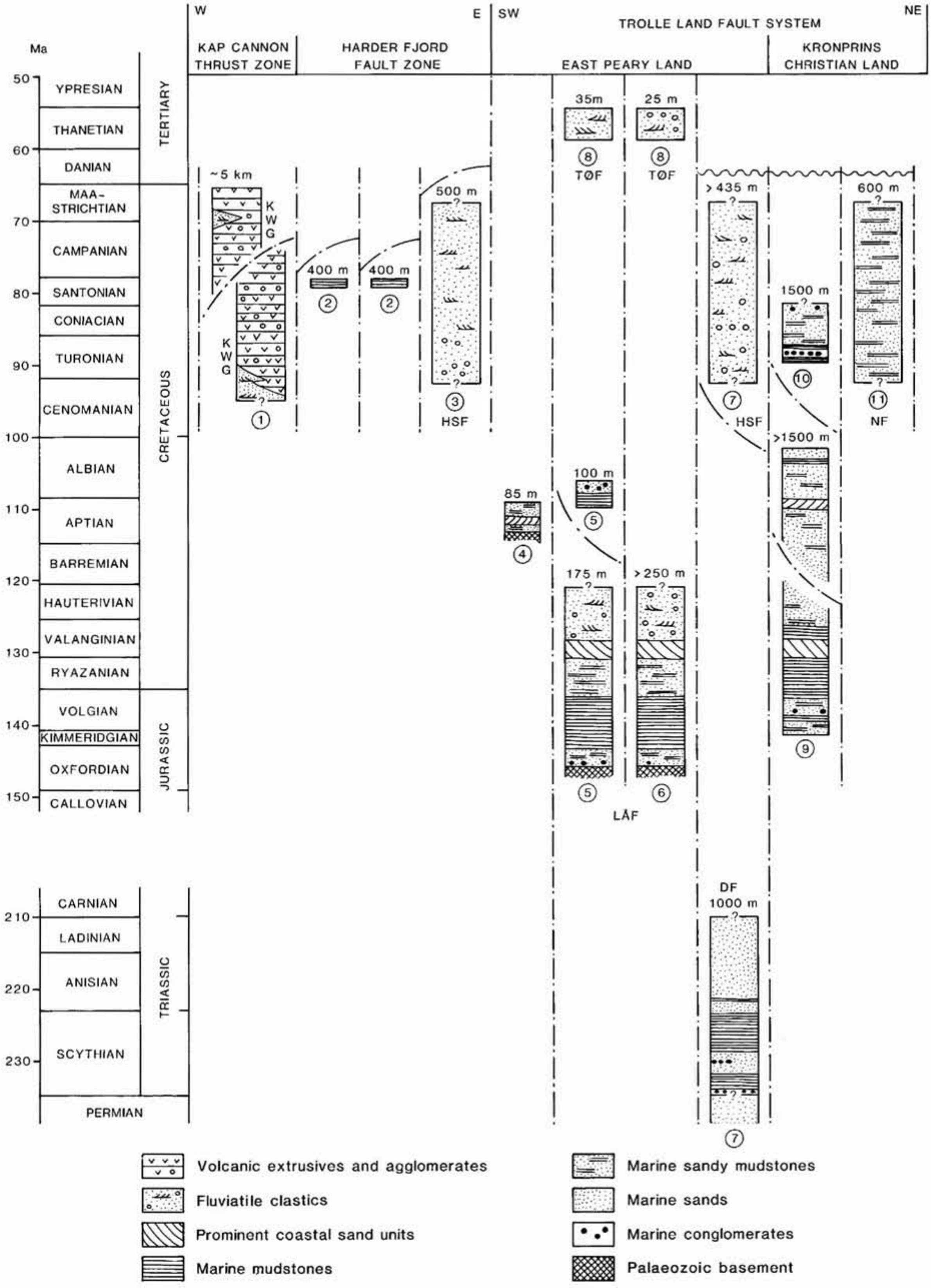


Fig. 4. Parish Bjerg Formation; upper sandy part with wedge of pebble conglomerate next to figure (centre), east Peary Land.

Fig. 3. Stratigraphy, thickness and depositional pattern of the Mesozoic and Cenozoic strata in the Wandel Sea Basin. Encircled numbers refer to localities in Fig. 1. KWG, Kap Washington Group; HSF, Herlufsholm Strand Formation; TØF, Thyra Ø Formation; LÅF, Ladegårdsåen Formation; DF, Dunken Formation; NF, Nakkehoved Formation.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600 m
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NF
>1500 m
100 m
85 m
175 m
>250 m
LÅF
DF
1000 m
Volcanic extrusives and agglomerates
Fluviatile clastics
Prominent coastal sand units
Marine mudstones
Marine sandy mudstones
Marine sands
Marine conglomerates
Palaeozoic basement

Fig. 5. Dunken Formation; the type profile Dunken is characterised by recessive shales in the lower part and prominent sandstone towards the top (height of cliff *c.* 600 m). East Peary Land.

Formation, the Triassic depositional regime can be considered as a continuation of the pattern established in the northern part of the Wandel Sea Basin area in the mid-Permian tectonic event (i.e. in the North Greenland – Svalbard Basin; cf. Håkansson & Stemmerik, 1989; Stemmerik & Håkansson, 1991). The overall sedimentary pattern appears unrelated to the faults of the Trolle Land Fault System which now form the boundary of the Triassic sediments, and deposition during this period undoubtedly took place over a wider subsidence area. However, when compared to the depositional pattern and basin configuration in Svalbard (Steel & Worsley, 1984), it is evident that the North Greenland Triassic constitutes a fully separate entity. Thus, even the very limited occurrence of Triassic strata in North Greenland provides evidence for the continuation of the platform break-up initiated in the Middle Permian.

Only part of the Triassic succession in North Greenland has so far been adequately dated. Palynomorph assemblages from the Parish Bjerg Formation are comparable to European floras of Early Triassic age, while Håkansson (1979), on the basis of the presence of a few euomphalid gastropods, suggested that the Parish Bjerg Formation may span the Permo-Triassic boundary. In the lower half of the Dunken Formation macrofossils indicate the presence of Scythian to Anisian strata (Kummel, 1953; Håkansson & Heinberg, 1977; Håkansson, 1979). The upper part of the Dunken Formation has produced only non-diagnostic ichthyosaur remains. However, in view of the apparent continuity of sedimentation, deposition of the entire formation is considered to have been completed well within the Triassic period (Håkansson & Stemmerik, 1984).

Late Jurassic – Early Cretaceous sedimentation

Strata referable to the later part of the Triassic and most of the Jurassic are missing in North Greenland. Deposition was restored in a major Late Jurassic transgression, evidence of which has been recognised in two distinct sub-basins in eastern Peary Land and Kronprins Christian Land (Fig. 3; localities 5, 6, 9). Apart from differences in depositional evolution, the sub-basins show differences in faunal and microfloral composition (Håkansson *et al.*, 1981a; Birkelund & Håkansson, 1983). However, the overall pattern in the evolution of the depositional environments in both sub-basins shows sufficient similarity to allow an account of the sedimentation to be grouped under stratigraphic rather than regional headings. Thus a Late Jurassic – Early Cretaceous (Valanginian) marine interval is extensively documented in both eastern Peary Land and in Kronprins Christian Land, whereas strata recording a subsequent Aptian-Albian marine interval are now largely absent in eastern Peary Land.

Oxfordian-Valanginian transgressive/regressive pulse. The earliest post-Triassic strata in the Wandel Sea Basin area are recorded from eastern Peary Land where more than 250 m of sandstone, soft sands and shale referred to the Ladegårdsåen Formation unconformably overlie a complex mosaic of Silurian, Carboniferous and Permian sediments (Fig. 3; localities 5, 6; Håkansson, 1979). Following a Middle Oxfordian transgression, marine fine grained sediments accumulated in a generally tranquil environment which apparently prevailed through the Kimmeridgian and Volgian Stages.

Through the Rhyazanian a gradual change towards higher energy, more shallow water environments took place, culminating in an episode of coastal progradation in the Early Valanginian (Håkansson *et al.*, 1981a, 1981b; Håkansson & Stemmerik, 1984). The lower, marine part of the Ladegårdsåen Formation has been dated with some precision in an integrated ammonite-*Buchia*-dinoflagellate study (Håkansson *et al.*, 1981a), whereas the remaining non-marine parts so far have revealed no age indications.

The Kronprins Christian Land sub-basin exposed at Kilen (Fig. 3; locality 9) apparently also experienced a Late Jurassic transgression, but here the base of the approximately 900 m thick sequence is not known; the oldest unit exposed contains an ammonite fauna of Early Kimmeridgian age (Håkansson *et al.*, in press). In the Kimmeridgian-Valanginian part of the sequence, accumulation mostly took place in a muddy, barred, coastal environment and did not attain more open marine, offshore conditions until the Early Valanginian (Håkansson *et al.*, 1981b; Birkelund & Håkansson, 1983). Subsequent to this, coarse, high energy coastal sands were deposited, concluding the first transgressive/regressive pulse. However, in strong contrast to the development in the eastern Peary Land sub-basin, continental strata are absent at Kilen, where an additional transgressive/regressive pulse is documented. In this, a 550 m thick sequence of off-shore shelf mud contains gradually increasing proportions of partly hummocky bedded sand layers (Fig. 6). Unfortunately this interval has not produced any age diagnostic fossils.

Late Early Cretaceous transgression. Deposits from a late Early Cretaceous transgressive episode are almost exclusively preserved at Kilen in Kronprins Christian Land, where at least 650 m of mainly fine grained shelf clastics are present in a fault block distinct from the sequence discussed above (Fig. 3; locality 9; Håkansson *et al.*, in press). As a result of the rather severe Late Cretaceous tectonic disturbance within the Wandel Hav Strike-Slip Mobile Belt actual thicknesses are difficult to ascertain, and relations to both older and younger strata have yet to be established. Preliminary investigations of the sparse fauna and microflora from this part of the sequence have revealed the presence of both Aptian and Albian strata. Most of the sequence accu-

Fig. 6. Lower Cretaceous outcrops in the inner part of Kilen. The lower *c.* 200 m of the undated, post-Valanginian sequence showing the gradual increase of sandstone units in the offshore shelf mudstone is visible. Kronprins Christian Land.

mulated in outer shelf environments with predominantly mud and fine sand facies (Håkansson *et al.*, in press).

Two very limited occurrences may represent the remnants of a parallel transgressive development in the eastern Peary Land sub-basin. At Kap Rigsdagen in Valdemar Glückstadt Land (Fig. 1) an isolated sequence of marginally marine to lagoonal clastic deposits has yielded microfloras indicating an Aptian age for most of the 85 m of strata preserved (Fig. 3; locality 4; Håkansson *et al.*, 1981b). In east Peary Land (Fig. 3; locality 5) a minute fault block exposing approximately 100 m of black mudstone capped by thin sandstones and shell conglomerates may be a somewhat younger open marine equivalent to the sequence at Kap Rigsdagen; the mudstone contains microfloras of Aptian age while ammonites of Early Albian age abound in the top conglomerate (Håkansson *et al.*, 1981b; Rolle, 1981; Birkelund & Håkansson, 1983).

Late Cretaceous pull-apart basin formation

Upper Cretaceous strata are distributed throughout the Wandel Sea Basin area, but their actual areal extent is very limited. Six distinct local pull-apart basins have been recognised along the on-shore part of the Wandel Hav Strike-Slip Mobile Belt (Fig. 3; localities 1–3, 7, 10, 11); suggestions concerning the presence of similar basins off-shore (Birkelund & Håkansson, 1983) remain speculative in the lack of geophysical investigations. Of the six local basins, only the Herlufsholm Strand and Depotbugt basins show a similar depositional development, and so far no basins have been shown to have developed simultaneously. Based on the rather scanty stratigraphic evidence available, Birkelund & Håkansson (1983) pointed out that the infill along the strike-slip belt is progressively younger towards the north-west. The apparently short duration of at least the well dated basins and the considerable thicknesses and immature nature of the sediments in all basins, suggest high rates of accumulation. Sediments in all these Late Cretaceous basins have experienced considerable organic degradation, and only occasionally have organic walled microfossils been preserved.

The westernmost two basins contain the only evidence of magmatic activity recorded in association with Wandel Sea Basin strata. One basin is almost entirely volcanic (Fig. 3; locality 1) and one is cut by post-deformational dykes (Fig. 3; locality 2). This magmatic activity is probably directly related to the N-S oriented dyke swarm in the western part of northern Peary Land (Fig. 1; Håkansson & Pedersen, 1982).

Marine clastic deposits of the Kilen, Nakkehoved and Frigg Fjord basins. At Kilen, in Kronprins Christian Land, an at least 1500 m thick marine clastic sequence accumulated in the early part of the Late Cretaceous, exhibiting an overall shallowing development (Fig. 3; locality 10; Håkansson *et al.*, in press). The initial deposit is a dark, organic-rich somewhat sandy mud with a depth-dependent, overall cyclicity in grain size composition, repeatedly interrupted by the influx of redeposited glauconitic and sideritic, largely bioclastic conglomerates suggesting fairly deep water environments. The proportion of sandy, shallow water sediments increases progressively, reflecting the gradual infill of the basin, but coarse clastic sediments only occur in significant proportions in the uppermost part of the sequence. Occasional macroscopic plant remains are present in the higher parts, but apparently the entire sequence was deposited in a marine environment (Håkansson *et al.*, 1981b).

Following preliminary faunal investigations, including both the ammonites and the inoceramids, it appears that the lower half of the sequence was deposited during Middle Turonian to Early Coniacian times (Håkansson *et al.*, 1981b; Birkelund & Håkansson, 1983; Håkansson *et al.*, in press). However, the upper part has so far not yielded age diagnostic fossils. The relation to an underlying, but undated marine sequence is not fully established.

The Late Cretaceous sequence at Kilen was strongly deformed into a series of domal folds and thrusts during the compressional regime of the Kronprins Christian Land Orogeny which everywhere terminated activity in the Wandel Hav Strike-Slip Mobile Belt (Håkansson & Pedersen, 1982; Håkansson *et al.*, in press).

In the nearby nunataks around Nakkehoved on the north coast of Kronprins Christian Land (Fig. 1), Upper Cretaceous sediments of a quite different nature are exposed (Fig. 3; locality 11). Here the Nakkehoved Formation comprises more than 600 m of monotonous, dark grey, fine-grained arkoses and quartz-sandstones deposited in a tranquil marine environment. The low diversity fauna comprises a variety of bivalves in addition to rare, thin tubular trace-fossils indicating only a general Late Cretaceous age (Håkansson *et al.*, 1981b; Birkelund & Håkansson, 1983). The sediments of the Nakkehoved Formation have been subjected to a short-termed intense increase in heat flow. Neomorphic envelopes around feldspar grains in addition to a complete matrix recrystallisation indicate that the rock-suite locally has been subjected to temperatures well into the low greenschist range (Håkansson *et al.*, 1981b; Håkansson & Pedersen, 1982). However, in spite of this

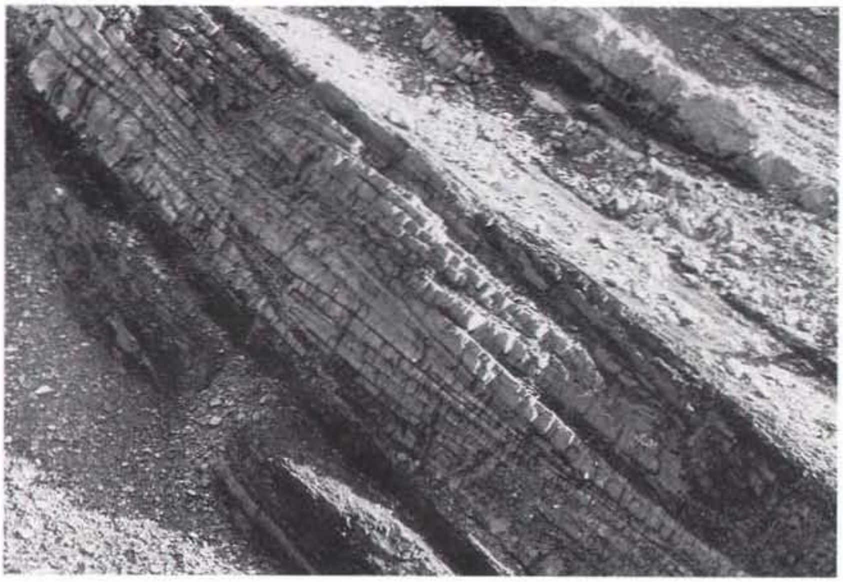

Fig. 7. Channel sands in the lower part of the Herlufsholm Strand Formation in the Depotbugt basin, central Peary Land (Fig. 1, locality 3).

unusual thermal overprint, the sequence of the Nakkehoved Formation is only very gently disturbed.

Around the head of Frigg Fjord (Figs 1, 3; locality 2) some 400 m of dark marine sandy mudstone have been preserved as near vertical wedges in the large-scale tectonic mélange developed in this segment of the Harder Fjord Fault Zone. The sequence contains a well preserved, low diversity inoceramid fauna characteristic of the Late Santonian (Håkansson *et al.*, 1981b).

Fluviatile clastic deposits of the Herlufsholm Strand and Depotbugt basins. Two sequences dominated by fluviatile sandstone and carbonaceous shale are located in close association with the Harder Fjord Fault Zone (Fig. 1; locality 3) and the Trolle Land Fault System (Figs 1, 3; locality 7) in Peary Land. They have both been referred to the Herlufsholm Strand Formation (Håkansson *et al.*, 1981b). Outcrops are bounded by faults or thrusts, and strata in the Herlufsholm Strand basin are moderately folded. Both sequences are dominated by interbedded facies of immature sand and mud with abundant carbonaceous detritus (Fig. 7) and with subordinate conglomerates. Beds of true coal have not been found, but particularly in the Herlufsholm Strand

Fig. 8. Volcanic strata – mainly extrusives – from the lower part of the Kap Washington Group, Lockwood Ø, north-west Peary Land.

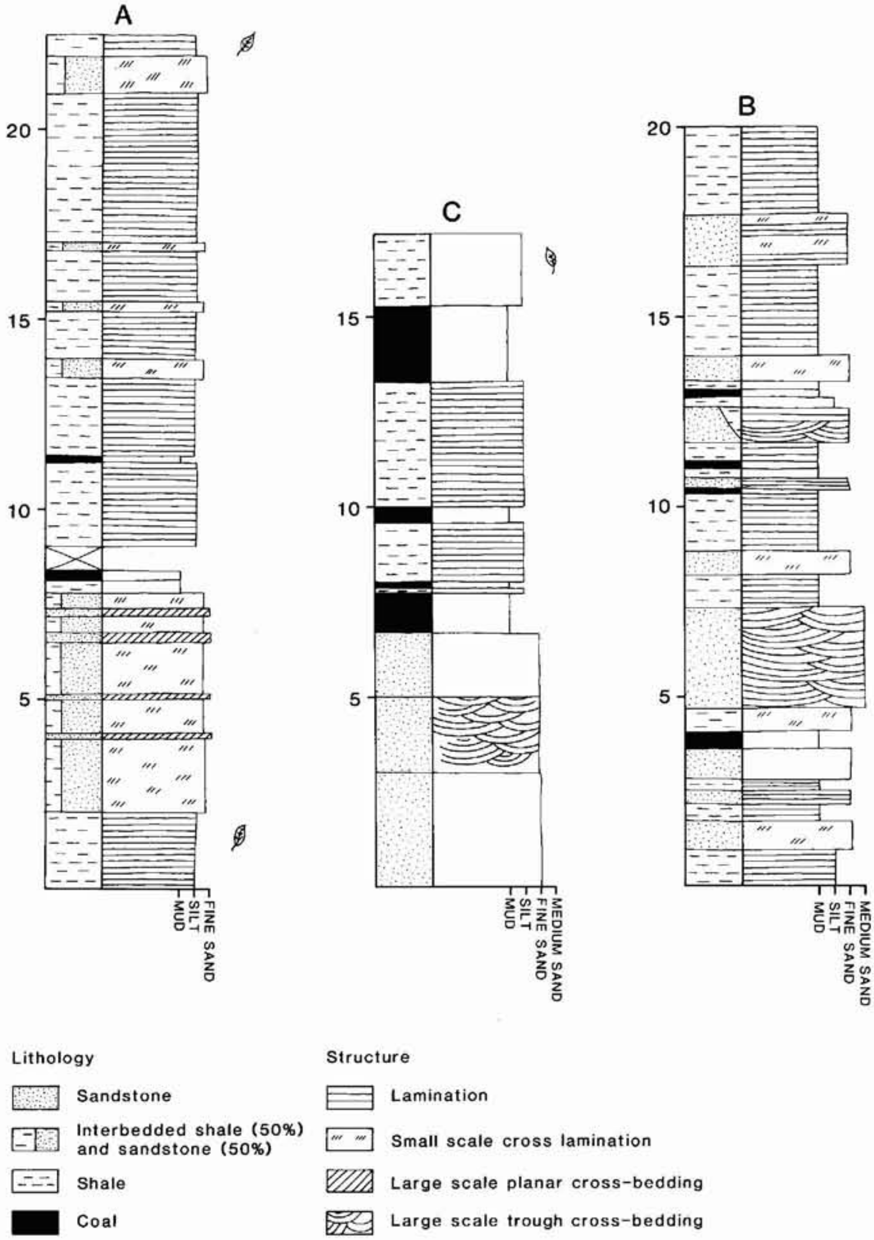

Fig. 9. Sediment logs of the Thyra Ø Formation. A, B, Prinsesse Thyra Ø; C, southern Prinsesse Ingeborg Halvø.

basin, highly carbonaceous shales packed with plant imprints are abundant. Coarse-grained arkosic beds are also conspicuous in this basin. No age diagnostic fossils have been found from either sequence and the age cannot be ascertained beyond the original Late Cretaceous to Early Tertiary estimate given by Troelsen (1950) for the Herlufsholm Strand sequence. However, the deformation and thermal history suggest a probable Late Cretaceous age (Håkansson & Pedersen, 1982; Birkelund & Håkansson, 1983).

Continental volcanics of the Kap Washington basin. The Kap Washington basin (Fig. 3; locality 1; Fig. 8) is the centre of volcanic activity during the development of the Wandel Hav Strike-Slip Mobile Belt and contains at least 5 km of various extrusive volcanic rocks and sediments (Brown & Parsons, 1981); these accumulated in a narrow basin (Fig. 2; Håkansson & Pedersen, 1982). Details of the sediments and the depositional environments are not available. The volcanic suite includes rhyolitic lavas and pyroclastic flows, trachytic and basaltic lavas, as well as various tuffs, agglomerates and breccias, all of a peralkaline provenance (Brown & Parsons, 1981; Soper *et al.*, 1982). The age of the volcanic activity in the Kap Washington basin has been disputed, but it seems that accumulation took place in the Late Cretaceous, most likely during the interval from the Campanian to the Maastrichtian/Danian boundary (see discussion by Batten *et al.*, 1981; Håkansson & Pedersen, 1982; Soper *et al.*, 1982; Birkelund & Håkansson, 1983; Håkansson & Stemmerik, 1984).

Early Tertiary fluviatile sedimentation

Sediments included in the early Tertiary Thyra Ø Formation are restricted to the islands of Prinsesse Thyra Ø, Prinsesse Dagmar Ø, Prinsesse Margrethe Ø, and the southern part of the peninsula Prinsesse Ingeborg Halvø in the central parts of the Wandel Sea Basin area (Fig. 1; Håkansson *et al.*, 1981b). The sediments are unaffected by compressional tectonism related to the Mesozoic strike-slip movements and therefore place an upward age limit on the Wandel Hav Strike-Slip Mobile Belt. It is suggested that they are of (Late?) Palaeocene age based on an abundant, but poorly preserved macroflora (Greenarctic Consortium *in* Dawes, 1976; A. Boyd, E. Håkansson & L. Stemmerik, unpublished information) and a single diagnostic dinoflagellate specimen (Håkansson & Pedersen, 1982).

The Thyra Ø Formation is up to 50 m thick in outcrop but neither the base nor the depositional top are exposed. The sequence is dominated by interbedded fine-grained sand and laminated silt with abundant coal seams particularly on Prinsesse Ingeborg Halvø (Figs 9, 10). Coarser sand and conglomerates are less prominent with the exception of a single isolated outcrop of conglomerate with poorly rounded to subangular blocks on Prinsesse Margrethe Ø farthest to the north-east.

Deposition apparently took place in the distal part of a broad flood plain. Increase in the proportion of laterally widespread coal seams and silt towards the south and west may imply that drainage was in this direction and that the more distally situated areas were dominated by swamps and lakes.

Concluding remarks

Late Palaeozoic to Early Cenozoic sedimentation in North Greenland has been referred to collectively as the Wandel Sea Basin, but it is now apparent that the dynamic history encompassed within this concept involves the development of a succession of superimposed and partly unrelated basins. The complexity of this history relates directly to long-lived activity along a number of fundamental tectonic lineaments which intersected in the Wandel Sea Basin area.

While Late Palaeozoic sedimentation may have taken place largely in a simple tensional regime with differential graben development, as described elsewhere in this volume (Stemmerik & Håkansson, 1991), Mesozoic deposition in North Greenland was controlled by the mounting forces in a strike-slip belt which culminated in actual separation between North America/Greenland and Europe/Svalbard early in the Tertiary. Thus, most of the Mesozoic sedimentation took place in direct response to the dynamic evolution of the intra-cratonic Wandel Hav Strike-Slip Mobile Belt, with the dominantly shallow marine to continental clastic deposits accumulating in at least three generations of gradually smaller basins.

Activity in the mobile belt ceased subsequent to its

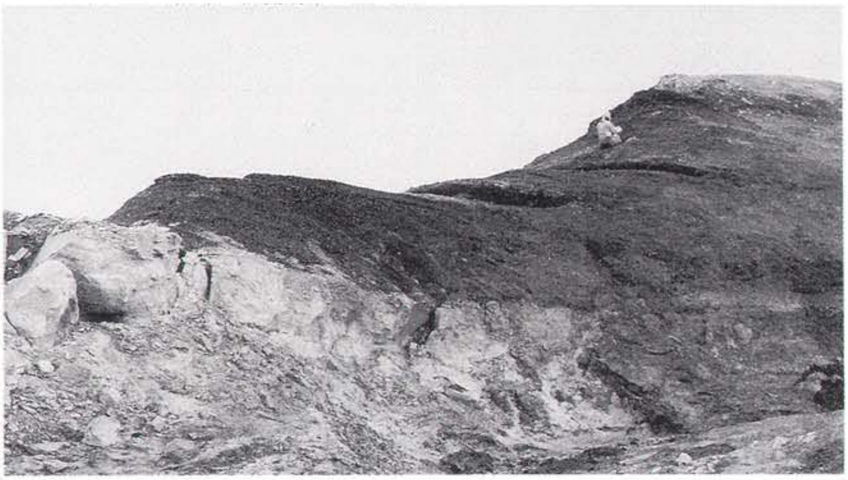

Fig. 10. Medium grained sandstone overlain by interbedded silt and coal (dark stripes), Thyra Ø Formation (Fig. 9C).

compressional climax, close to the Cretaceous-Tertiary boundary, and subsequent Palaeogene sedimentation in North Greenland took place entirely in a passive margin setting with tensional forces dominating.

Acknowledgements. Field work in 1976, 1978 and 1980 was made possible by the Geological Survey of Greenland while expeditions in 1985 and 1988 were financially supported by grants to E. H. from the Carlsberg Foundation. Jakob Lautrup, Jette Halskov, Bente Thomas, Nina Turner and Else Møller-Hansen are thanked for technical assistance in the preparation of the manuscript.

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GEOLOGICAL MAP OF
NORTH GREENLAND
ELLESMERE ISLAND
HALL BASIN
KANE BASIN
Kennedy Channel
Robeson Channel
Humboldt Gletscher
INGLEFIELD LAND
WASHINGTON LAND
DAUGAARD-JENSEN LAND
HALL LAND
NYEBOE LAND
WARMING LAND
WULFF LAND
NARES LAND
FREUCHEN LAND
Lauge Koch Land
N.P. Johansen Land
Permin Land
Hendrik Ø
Petermann Gletscher
Ryder Gletscher
Victoria Fjord
Nordenskiöld Fjord
C.H. Ostenfeld Gletscher
Sherard Osborn Fjord
Sankt George Fjord
Newman Bugt
Polaris Bugt
Hauge Bjerge
Kap Tyson
Kap Ammen
Chester Bjerg
Kap Brevoort
Repulse Havn
Castle Ø
Stephenson Ø
Morris Bugt
Gonioceras Bugt
Cass Fjord
Lafayette Bugt
Franklin Ø
Hans Ø
Alert
INLAND ICE
J.P. Koch Fjord
NANSEN LAND
Sverdrup Ø
John Murray Ø
Beaumont Ø
JOHANNES V. JENSEN LAND
Kap Morris Jesup
Kap Washington
Paradisfjeld
Amundsen Land
Frederick E. Hyde Fjord
Nordkronen
Hans Tavsen Iskappe
P E A R Y L A N D
WANDEL HAV
Skagen
Depotbugt
Kap Eiler Rasmussen
INDEPENDENCE FJORD
HEILPRIN LAND
VILDTLAND
J.C. CHRISTENSEN LAND
Hagen Fjord
Hagen Bræ
Academy Gletscher
MYLIUS-ERICHSEN LAND
VALDEMAR GLÜCKSTADT LAND
Kap Rigsdagen
Kap Kronborg
Danmark Fjord
Kap Holbæk
Prinsesse Thyra Ø
Prinsesse Margrethe Ø
Prinsesse Dagmar Ø
Station Nord
Prinsesse Ingeborg Halvø
Nakkehoved
Nordostrundingen
Kilen
KRONPRINS CHRISTIAN LAND
AMDRUP LAND
Ingolf Fjord
Eskimonæs
HOLM LAND
Mallemukfjeld
Hekla Sund
Centrum Sø
HOVGAARD Ø
Nioghalvfjerdsfjorden
LAMBERT LAND
PROTEROZOIC BASINS
Upper Proterozoic Hagen Fjord Gr.
Upper Proterozoic Rivieradal sandstones
M Upper Proterozoic Moræneso Fm.
Middle Proterozoic Zig-Zag Dal Basalt Fm.
Middle Proterozoic Independence Fjord Gr., Midsommersø Dolerite Fm.
FRANKLINIAN BASIN
SHELF SUCCESSION
Lower Silurian Major build-up complexes
Lower Silurian Washington Land Gr.
Middle Ordovician – Lower Silurian Morris Bugt Gr.
Lower – Middle Ordovician Ryder Gletscher Gr.
Lower Cambrian – lowermost Ordovician Brønlund Fjord Gr., Tavsens Iskappe Gr., Ryder Gletscher Gr.
Lower Cambrian Buen Fm., Humboldt Fm.
Lower Cambrian Skagen Gr., Portfjeld Fm.
SLOPE & TROUGH SUCCESSION
Lower – Upper Silurian
Lower Silurian Cape Schuchert Fm., Lafayette Bugt Fm., Wulff Land Fm.
Lower Silurian Sydgletscher Fm., Merqujôq Fm.
Upper Ordovician – Lower Silurian Harefjeld Fm.
Lower Cambrian – Lower Silurian Amundsen Land Gr., Brønlund Fjord Gr., Tavsens Iskappe Gr., Vølvedal Gr.
Lower Cambrian Polkorridoren Gr.
Lower Cambrian Paradisfjeld Gr.
WANDEL SEA BASIN
Lower Tertiary Thyra Ø Fm.
Upper Cretaceous – Lower Tertiary Kap Washington Gr.
Upper Cretaceous – Lower Tertiary Basic dykes
Upper Jurassic – Upper Cretaceous Herlufsholm Strand Fm., Nakkehoved Fm., Ladegårdsåen Fm.
Triassic Dunken Fm., Parish Bjerg Fm.
Carboniferous – Upper Permian Mallemuk Mountain Gr., Midnatfjeld Fm., Sortebakker Fm.
Precambrian Crystalline basement
Quaternary cover
Major fault
Fault
Major thrust
Thrust
0 20 40 60 80 100 km
Kronprins Christian Land – J. P. Koch Fjord mapped 1978-80
J. P. Koch Fjord – Petermann Gletscher mapped 1984-85
Washington Land after map by H. F. Jepsen et al 1983
and Hall Land partly after P. R. Dawes 1987
Compiled by H.-J. Bengaard and N. Henriksen, 1986
Minor changes by M. Sønderholm and
L. Stemmerik, 1990
Drawn by G. Hougaard, 1986, 1990