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

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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

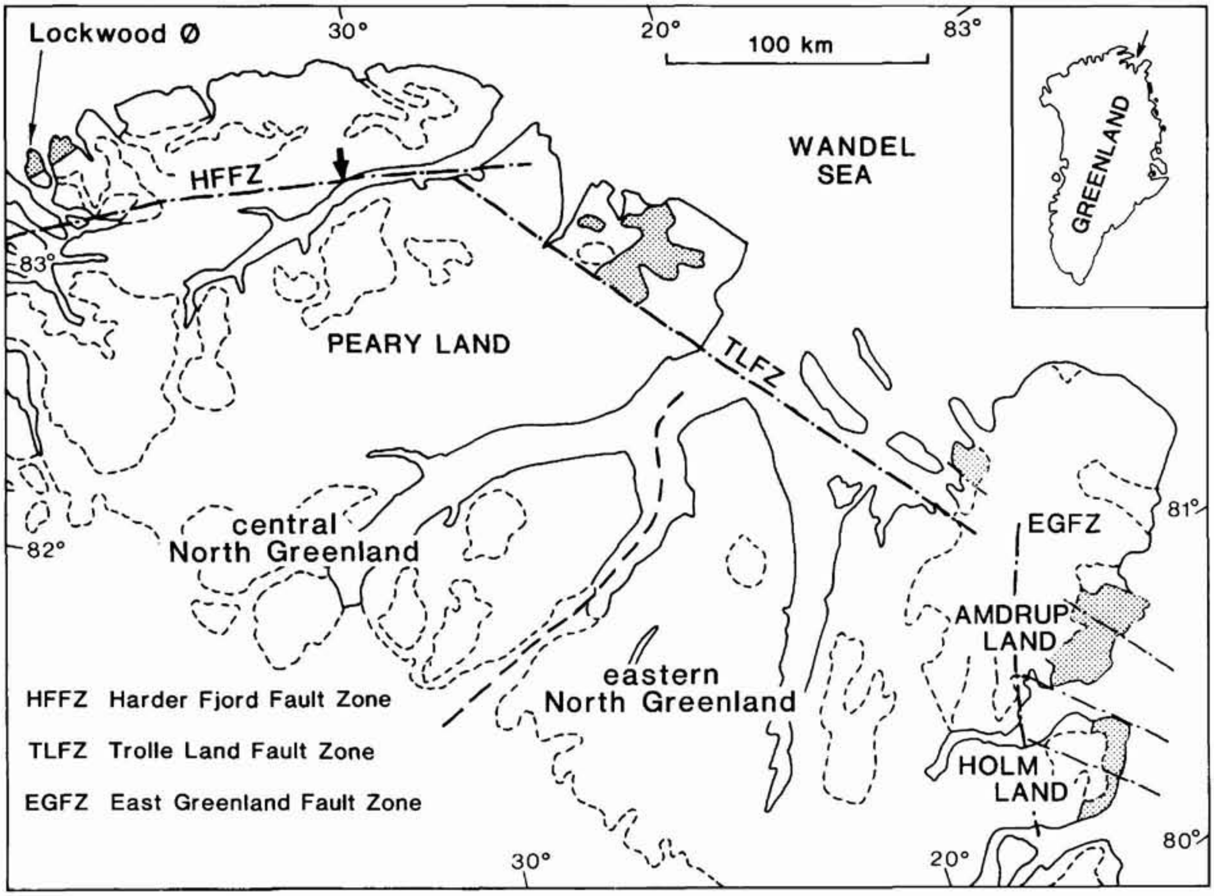

Fig. 1. Distribution of Upper Palaeozoic sediments (shaded) and major structural elements in central and eastern North Greenland. Arrow indicates a small outcrop of the Kap Kraka Formation.

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).

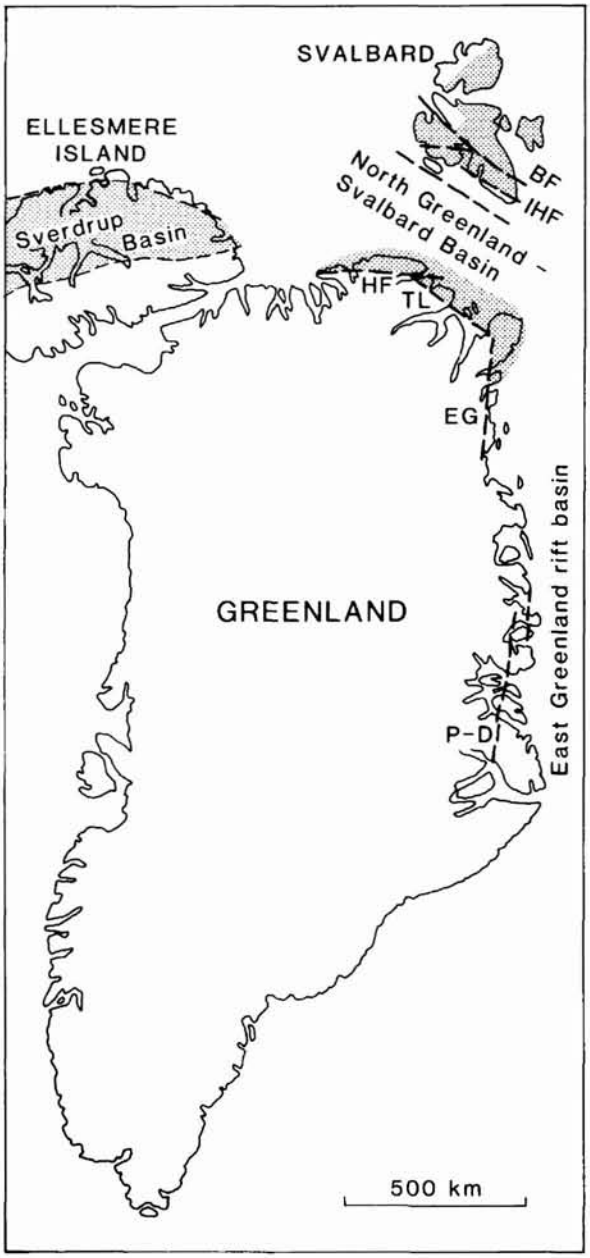

Fig. 2. General pre-drift configuration of Greenland, Svalbard and Ellesmere Island. The stippled area indicates the known extent of the Upper Palaeozoic basins. BF, Billefjorden Fault; IHF, Inner Hornsund Fault; HF, Harder Fjord Fault Zone; TL, Trolle Land Fault Zone; EG, East Greenland Fault Zone; 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.

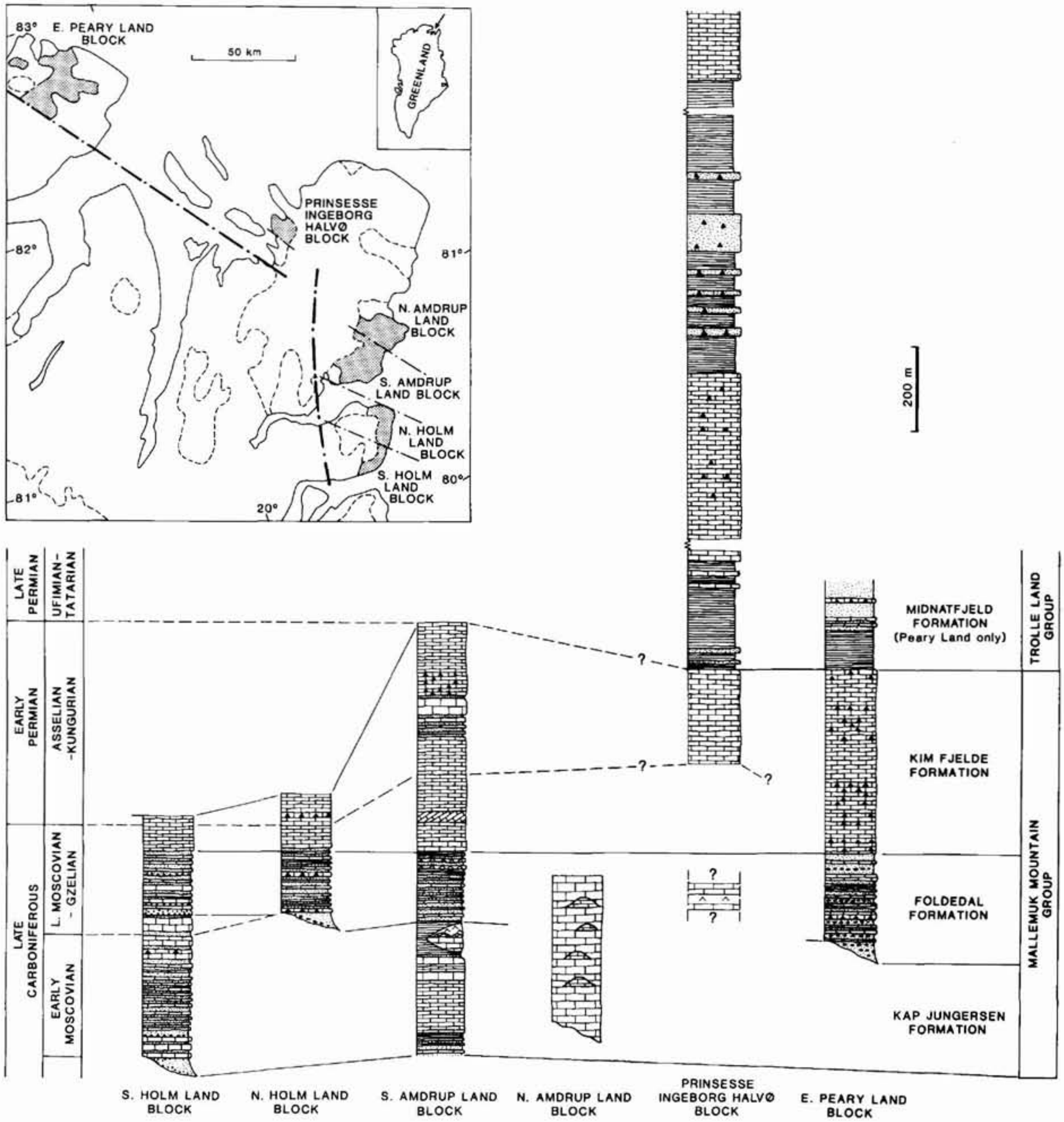

Fig. 3. Lithostratigraphic correlation of the marine Upper Palaeozoic sediments in eastern North Greenland. Solid lines indicate lithostratigraphic units; dotted lines are the proposed biostratigraphic correlation (based on Håkansson & Stemmerik, 1984; Stemmerik & Håkansson, 1989; Nilsson *et al.*, 1991).

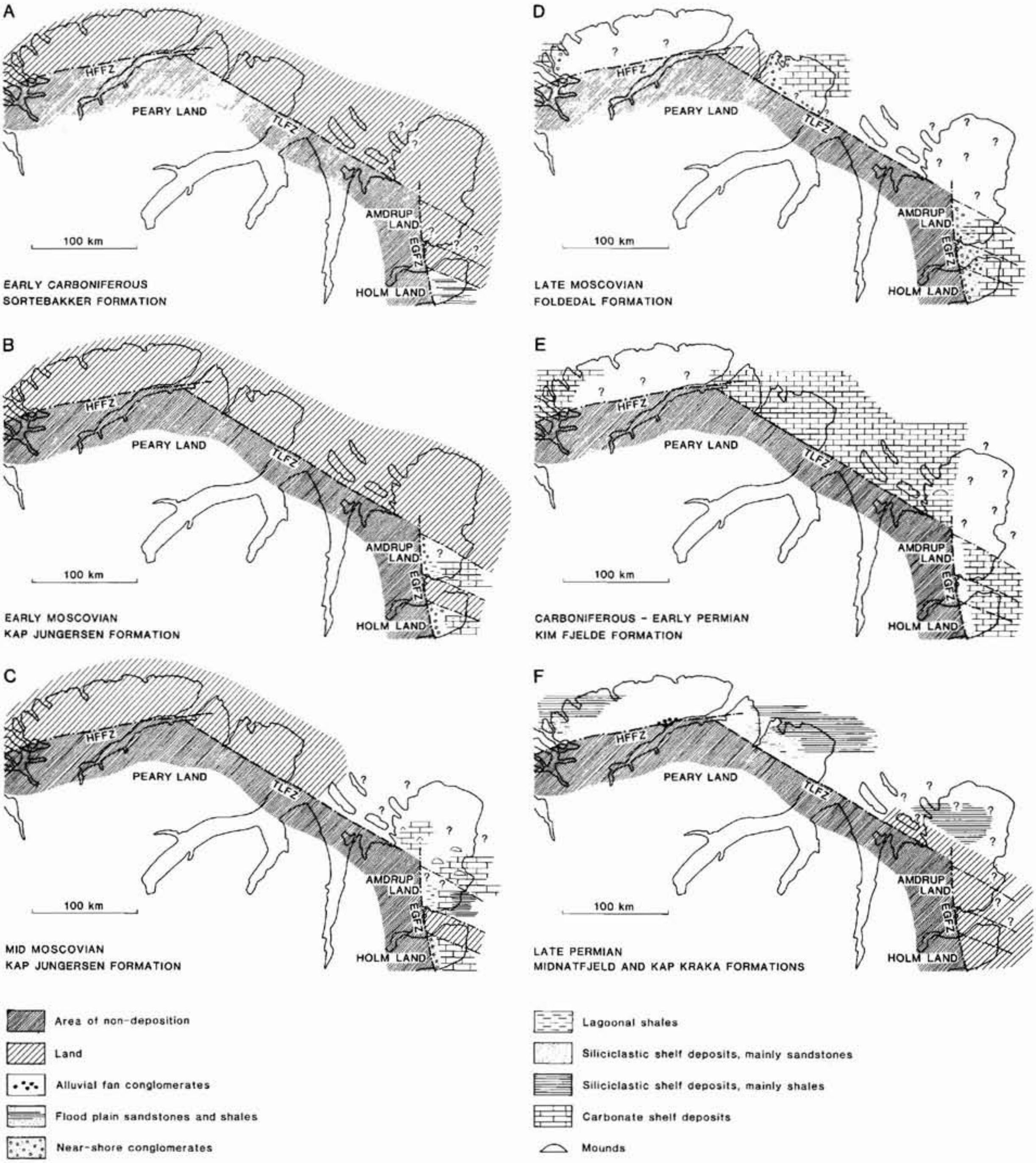

Fig. 4. Palaeogeographic maps and facies patterns during: A, early Carboniferous; B, early Moscovian; C, mid Moscovian; D, late Moscovian; E, latest Carboniferous – Early Permian; F, Late Permian (from Stemmerik & Håkansson, 1989). HFFZ, Harder Fjord Fault Zone; TLFZ, Trolle Land Fault Zone; EGFZ, East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

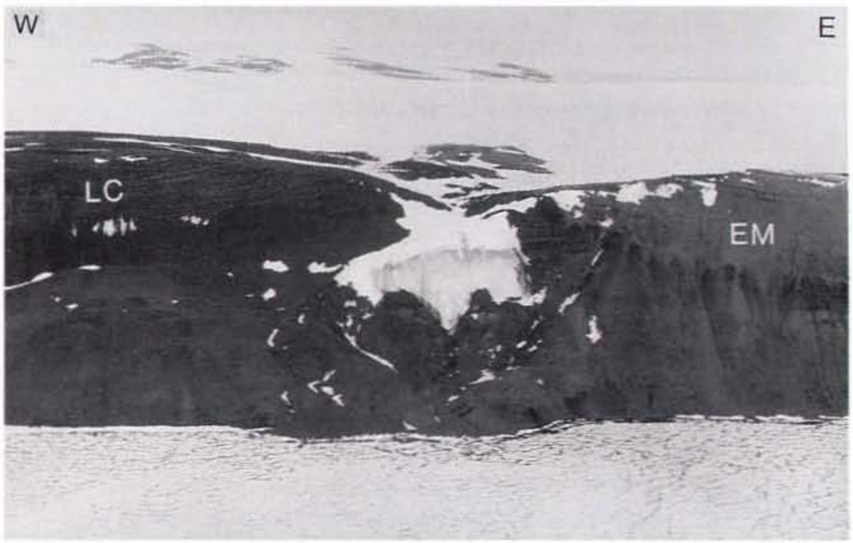

Fig. 5. Lower Carboniferous (LC) fining upward cycles of flood-plain origin unconformably overlain by marine lower Moscovian sediments (EM). Cliff height approximately 350 m, southern Holm Land.

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

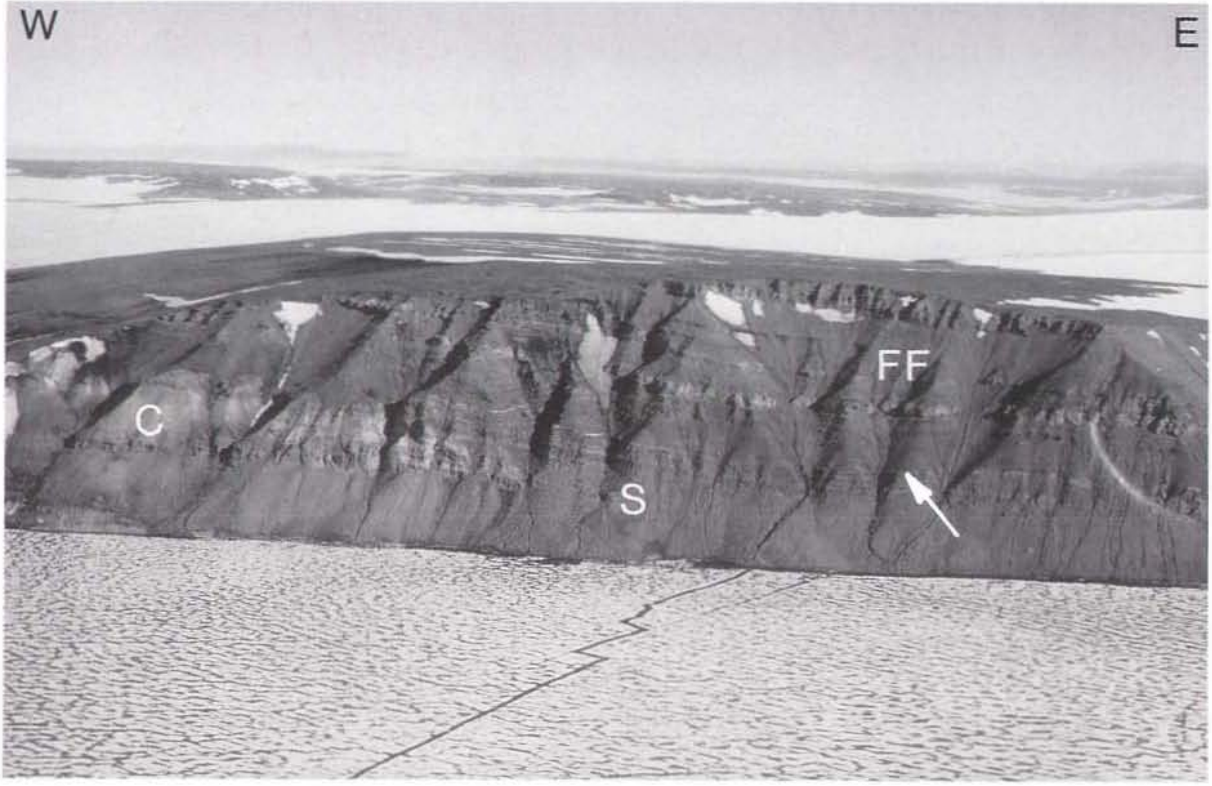

Fig. 7. The early Moscovian – Gzelian succession in southern Amdrup Land. Note the isolated carbonate platform (C) surrounded by shales (S) also belonging to the Kap Jungersen Formation (lower Moscovian). The transition to the overlying Foldedal Formation (FF) (upper Moscovian – Gzelian) is placed at 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.

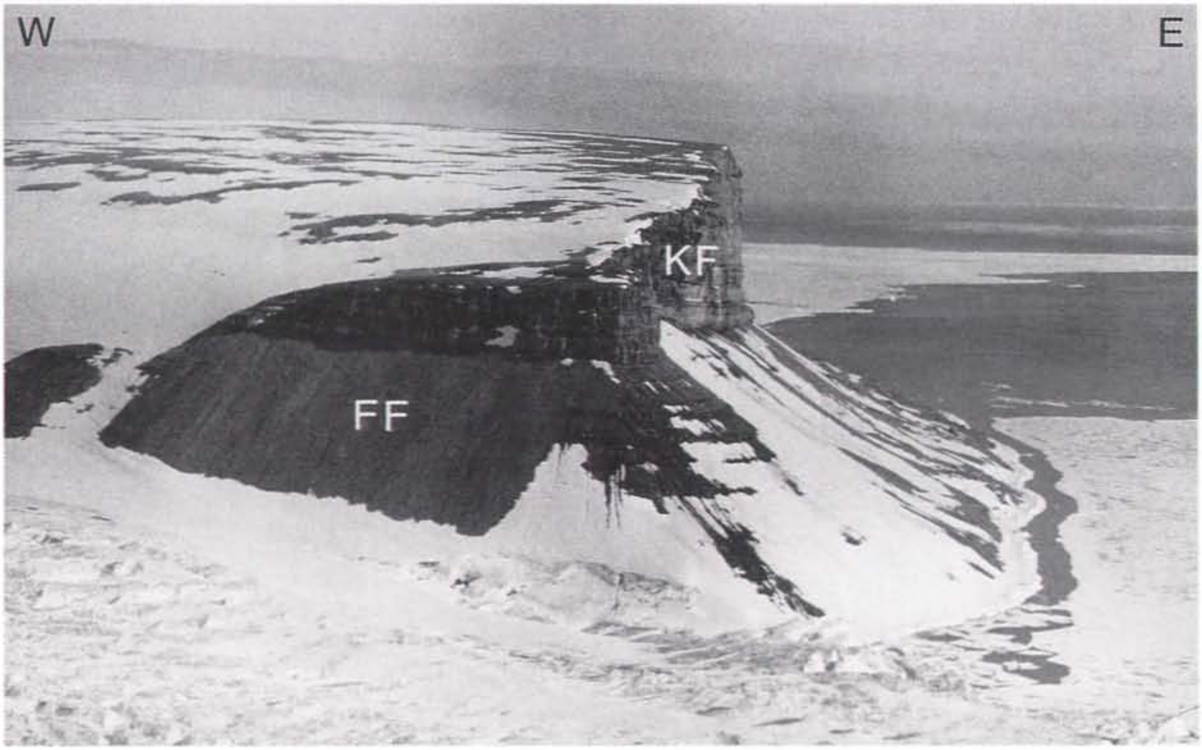

Fig. 8. Interbedded biogenic limestones and sandstones of the Foldedal Formation (FF) (upper Moscovian – Gzelian) overlain by bedded biogenic limestones of the Kim Fjelde Formation (KF). Cliff height approximately 350 m, eastern Holm Land.

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.

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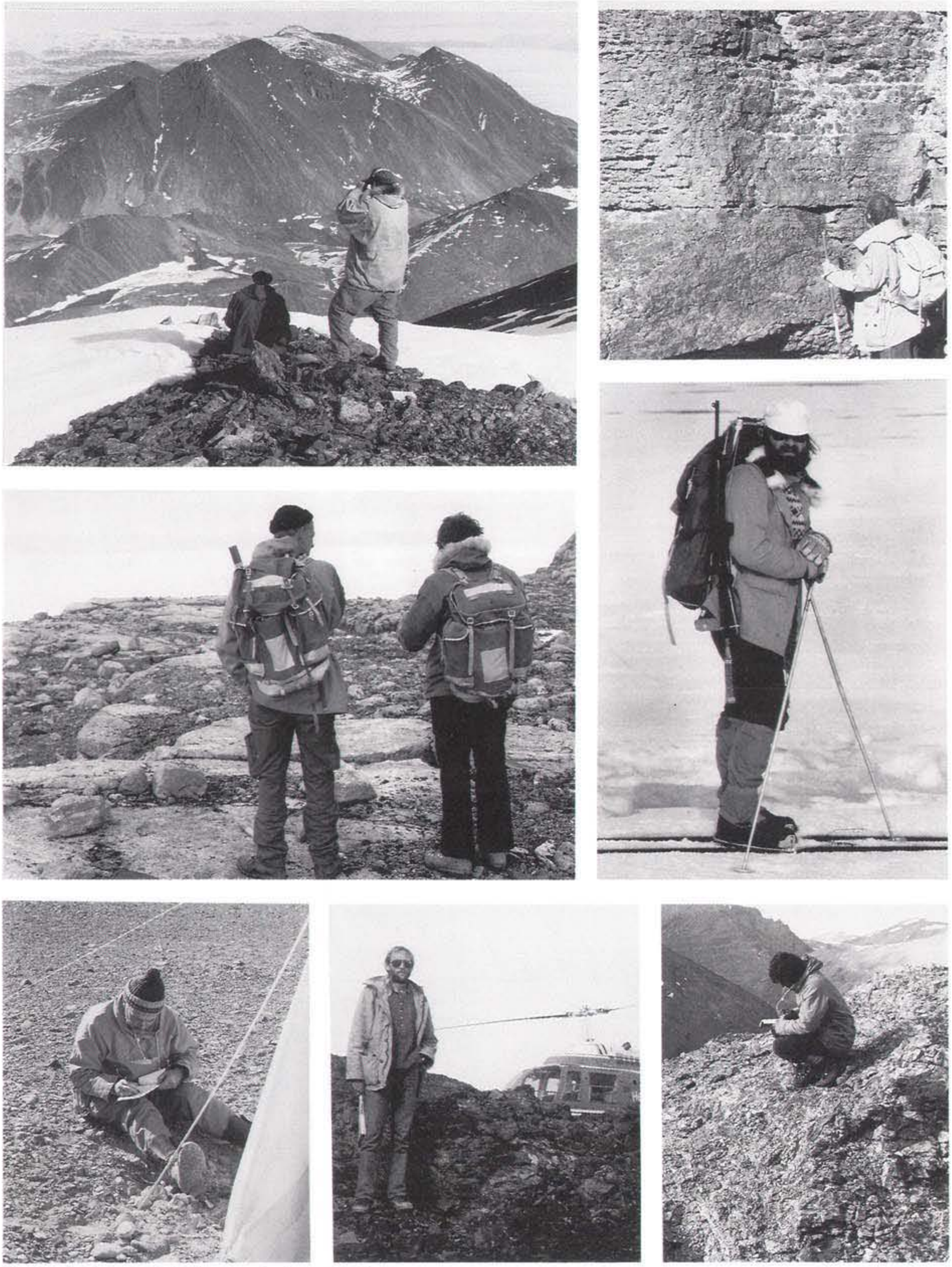

The North Greenland Project: geologists in the field.