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The relationship between Caledonian nappe tectonics and Silurian turbidite deposition in North Greenland

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SUMMARY: The relationship between the northern part of the Caledonian fold belt of East Greenland and the North Greenland fold belt is explored within the context of Silurian sedimentation and tectonics. A model is developed relating the Caledonian nappes of eastern North Greenland to major tectonic and sedimentological features of the Silurian of the remainder of North Greenland. The abrupt change from a thin succession of predominantly slowly deposited muds to a thick succession of rapidly deposited sandstone turbidites at the Ordovician/Silurian boundary, in the deep-water basin N of the carbonate platform in North Greenland, is directly related to uplift and westerly directed nappe emplacement in the eastern Caledonides. It is suggested that uplift to the E of North Greenland, which commenced in the late Ordovician or early Silurian, provided the main source of the Silurian turbidites of North Greenland. This is corroborated by the dominant westerly transport direction of the Silurian turbidites. Nappe emplacement during the latest Llandovery (Silurian), and foundering of the whole of the carbonate platform of eastern North Greenland E of the Victoria Fjord Arch (approximately 60 000 km^2), is marked by the replacement of shallow water carbonates by basin turbidites. These events were directly related to isostatic readjustments as the nappes advanced onto the eastern fringe of the platform.

The North Greenland fold belt extends eastwards along the N coast of Greenland (Dawes 1971, 1976; Dawes & Soper 1973) to the shelf area of the Wandel Sea (Fig. 1), where it appears to intersect the N–S trend of the Caledonides of East Greenland (Haller 1970, 1971). The North Greenland fold belt represents an eastern extension of the Innuitian tectonic province of Arctic Canada (Trettin & Balkwill 1979), which developed E–W trending folds during orogenic movements lasting from the Devonian until the Carboniferous; its southern margin is transitional, not thrust. By contrast, the structure of the northern Caledonides of Kronprins Christian Land (Fig. 1), which represents the northernmost extension of the East Greenland Caledonides, is characterized by westward-directed nappes, with associated folds and reversed faults which appear to result from a short compressive event of Silurian age. The Caledonian Orogeny in East Greenland, including Kronprins Christian Land, also differs from the Norwegian Caledonides on the eastern side of the former Iapetus Ocean. While much of Norway appears to have been situated on an active margin throughout Ordovician and Silurian times, northern East Greenland was situated along a passive margin (Henriksen & Higgins 1976; McKerrow 1982), though an active margin may be indicated S of 74°N by monzonites and granodiorites dated between 510 and 480 Ma (Higgins & Phillips 1979).

In eastern North Greenland (Fig. 1) the Ordovician is represented on the platform by shallow marine carbonates, while in the northern basin (Fig. 1), black cherts, black shales, thin-bedded chertified turbidites and re-sedimented limestone conglomerates are present (Surlyk *et al.* 1980). In the early Silurian, carbonate deposition continued on the platform, but there was an abrupt change in sedimentation in the northern basin, with the appearance of sandstone turbidites. Towards the end of the early Silurian (latest Llandovery, C_6), basin turbidites and mudstones spread for the first time over the carbonate platform to the E of Wulff Land (Fig. 1).

In North Greenland, the platform carbonates and their cover of basin turbidites are essentially undeformed to the W of Danmark Fjord (Fig. 1). To the N, there is a gradual transition into the progressively more strongly folded sediments of the North Greenland fold belt, and only the northern fringe of platform carbonates are involved in the folding. The southern margin of the North Greenland fold belt is not thrust, but transitional (Dawes & Soper 1973, 1979; Soper *et al.* 1980; Higgins *et al.* 1981); the folds verge northwards and intensify away from the carbonate platform, and major nappes are absent. To the E of Danmark Fjord in Kronprins Christian Land, the platform carbonates, together with the later basin turbidite cover, are cut by steep reverse faults and low angle thrusts (imbricate region on Fig. 1; Peel 1980; Hurst & McKerrow 1981*a, b*). E of this imbricate region, the platform carbonates and their basin clastic cover pass below the nappes of the Caledonian thrust belt (Fig. 1).

It is not possible to trace the relationship between the Caledonian and North Greenland fold belts within the orogen, as the two fold belts meet in the Wandel Sea. However, this paper attempts to relate the two fold belts within the context of Silurian sedimentation and tectonics. Carbonate platform and basin turbidite sediments provide a record linking the development of the two fold belts.

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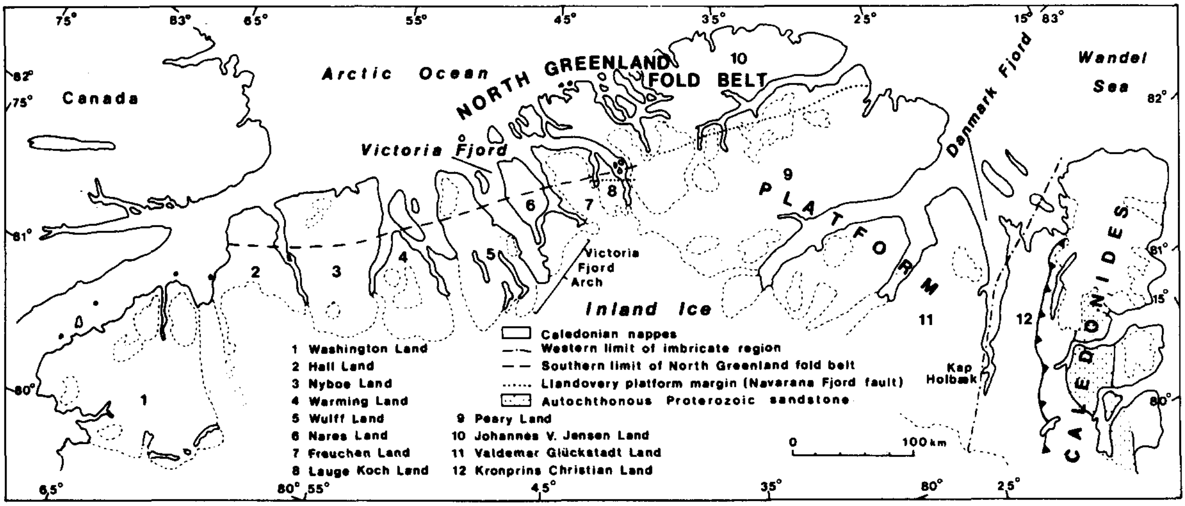

FIG. 1. Geographical location map of North Greenland showing the major geological features discussed in the text. E of the Victoria Fjord Arch is referred to as eastern North Greenland. The western limit of the imbricate region is probably equivalent to the western limit and extent of the Caledonian nappes. The present-day outcrop of the Caledonian nappes includes the Vandredalen, Sæfaxi Elv and Finderup Land nappes (see Fig. 3; Hurst & McKerrow 1981*a*). In Peary Land the southern limit of the North Greenland fold belt runs parallel, but just to the N of the carbonate platform margin. Note that the well defined Llandovery carbonate platform margin stops at the Victoria Fjord Arch. The latest Llandovery platform subsidence occurred E of Victoria Fjord Arch and S of the Llandovery platform margin (Navarana Fjord Fault). The southern and eastern boundaries are not known. N of the Llandovery carbonate platform margin is the pre-middle Silurian deep-water basin. The Proterozoic sandstones (and quartzites) of Kronprins Christian Land form the Prinsesse Caroline–Mathilde Alper and are part of the Independence Fjord Group of Collinson (1980) (see Fig. 3).

The Silurian turbidites of North Greenland

In the deep-water basin to the N of the North Greenland carbonate platform (Fig. 1) less than 1 km of 'starved basin' sediments accumulated during the Ordovician, in contrast to 2–4 km of Silurian turbidites (Hurst & Surlyk 1980; Surlyk *et al.* 1980). In this basin, the development of the Silurian turbidites commenced at different times in different areas, but is close to the Ordovician–Silurian boundary. During the Llandovery, turbidites were restricted to the northerly basin, whilst to the S on the platform, shallow marine carbonates continued until latest Llandovery (C_6) times, before being succeeded by turbidites.

Silurian turbidites are distributed throughout North Greenland (Fig. 2), and in general the proportion of sand to mud decreases progressively in a westerly direction, as does the total thickness, so that in the extreme W (SW Hall Land and Washington Land; Fig. 1) Silurian clastic sediments consist only of thin hemipelagic black mudstones (Hurst 1980*a*, *b*). During the Llandovery, turbidites in the basin N of the carbonate platform were mostly cyclically arranged fine sandstones and siltstones displaying a variety of typical Bouma sequences (Hurst & Surlyk 1982). Some thick (5–40 m) non-graded, structureless fine sandstone beds, particularly in the lowest part of the Llandovery turbidite sequence, suggest catastrophic sedimentation episodes (Surlyk *et al.* 1980).

Towards the end of the Llandovery, the shallow water carbonates of the platform were suddenly succeeded by 2–3 km of basin turbidites and mudstones over the whole of North Greenland, E of the Victoria Fjord Arch (Fig. 1; Surlyk *et al.* 1980). The deep environments and great thickness of Silurian turbidites on top of the platform carbonates indicate substantial platform carbonate collapse over a large area (Fig. 1). Though the southern boundary of the collapsed area is uncertain, partly due to ice cover and partly due to removal of the Silurian sediments, an area approaching 60 000 km^2 appears to have foundered in the latest Llandovery.

Recent information indicates that collapse of the carbonate platform occurred slightly earlier to the E in Kronprins Christian Land (Fig. 1). The earliest Silurian turbidites contain *Monoclimacis griestoniensis*, *M.* aff. *M. crenulata*, *Monograptus* aff. *M. richardsi*

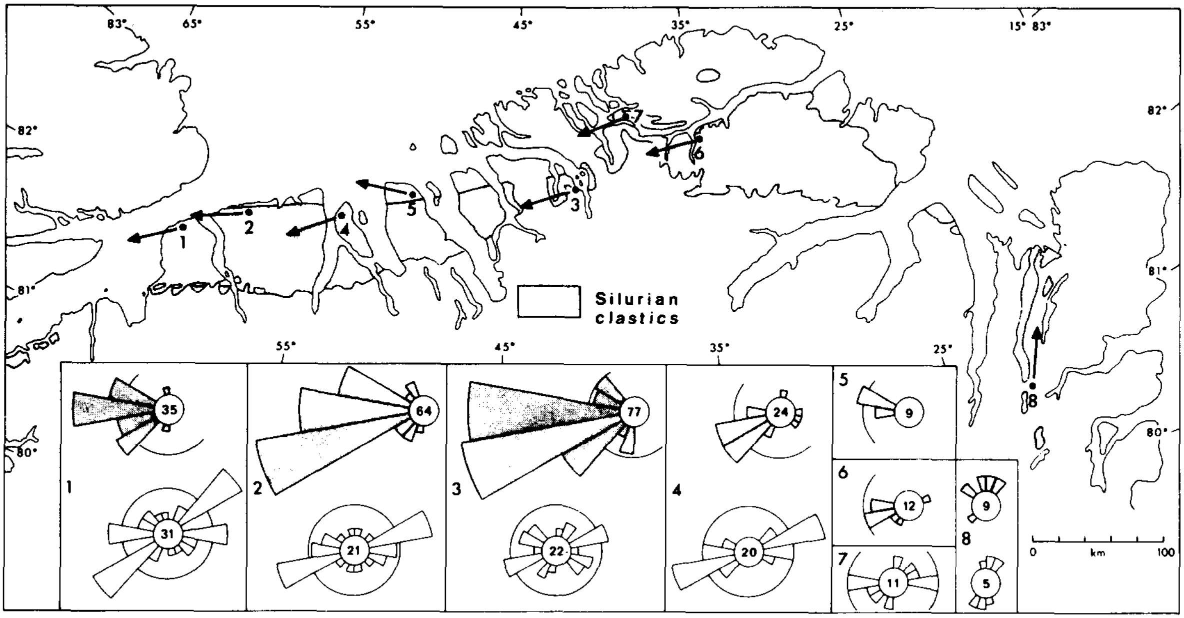

FIG. 2. Distribution of Silurian clastic rocks together with palaeocurrent data in North Greenland. Most of the outcrops are of turbidites, but in SW Hall Land and Washington Land the sediments are solely hemipelagic mudstones. Stippled rose diagrams are directional measurements (e.g. flutes) and open rose diagrams are trend measurements (e.g. grooves) (Hurst & Surlyk 1982). Dots 5 and 8 represent small outcrops of Silurian turbidites.

minor, M. priodon and *M. spiralis,* indicating the upper Llandovery *M. griestoniensis* Zone (M. Bjerreskov, pers. comm. 1981). Further to the W and N, the base of the turbidites on the carbonate platform contains slightly younger graptolites indicating the uppermost Llandovery *M. spiralis* or *C. sakmaricus–C. laqueus* Zones (Hurst & Surlyk 1982).

The turbidites which succeed the platform carbonates are mainly fine-grained sandstones similar to the earlier Llandovery turbidites of the northern basin, but the thick structureless, catastrophic flows are absent. However, to the E in Kronprins Christian Land many conglomerates occur within the sequence. They contain rounded clasts of quartzite which are undoubtedly derived from the autochthonous 'Proterozoic Swell' (Hurst & McKerrow 1981*a*) of eastern Kronprins Christian Land (the area of outcrop of Proterozoic sandstone shown in Fig. 1). These conglomerates have a source different from the chert-pebble conglomerates which occur at the top of the Silurian turbidite sequence in Peary Land (Christie & Peel 1977; Surlyk *et al.* 1980).

Over most of North Greenland transport directions in the Silurian turbidites indicate derivation from the E (Fig. 2) but in Kronprins Christian Land the transport direction was from the S. The age of the youngest preserved turbidites increases to the W: middle Wenlock from Kronprins Christian Land to Freuchen Land on the eastern edge of the Victoria Fjord Arch; Ludlow from Wulff Land to eastern Nyeboe Land; and Upper Pridoli from western Nyeboe Land to Hall Land (Fig. 1).

The Caledonian nappes of eastern North Greenland

The Caledonian fold belt in Kronprins Christian Land (Fig. 1) is characterized by westerly-directed thrusting (Fränkl 1954, 1955; Haller 1970, 1971; Hurst & McKerrow 1981*a*, *b*). Prior to the Llandovery there were apparently no Palaeozoic orogenic movements, nor was there any igneous activity. Some compressional folding took place after emplacement of the nappes; folds striking N or NE affect both nappes and the autochthonous region to the E.

Three large nappes in Kronprins Christian Land contain late Proterozoic and early Palaeozoic clastic and carbonate sediments which appear to have been originally deposited in shelf, slope and deep basin environments (Hurst & McKerrow 1981*a*, *b*). Several formations present on the autochthon (foreland in Fig. 3) to the W of the present nappe front (imbricate region in platform carbonates on Fig. 1) are represented (often by deeper water facies) in the nappes (Fig. 3).

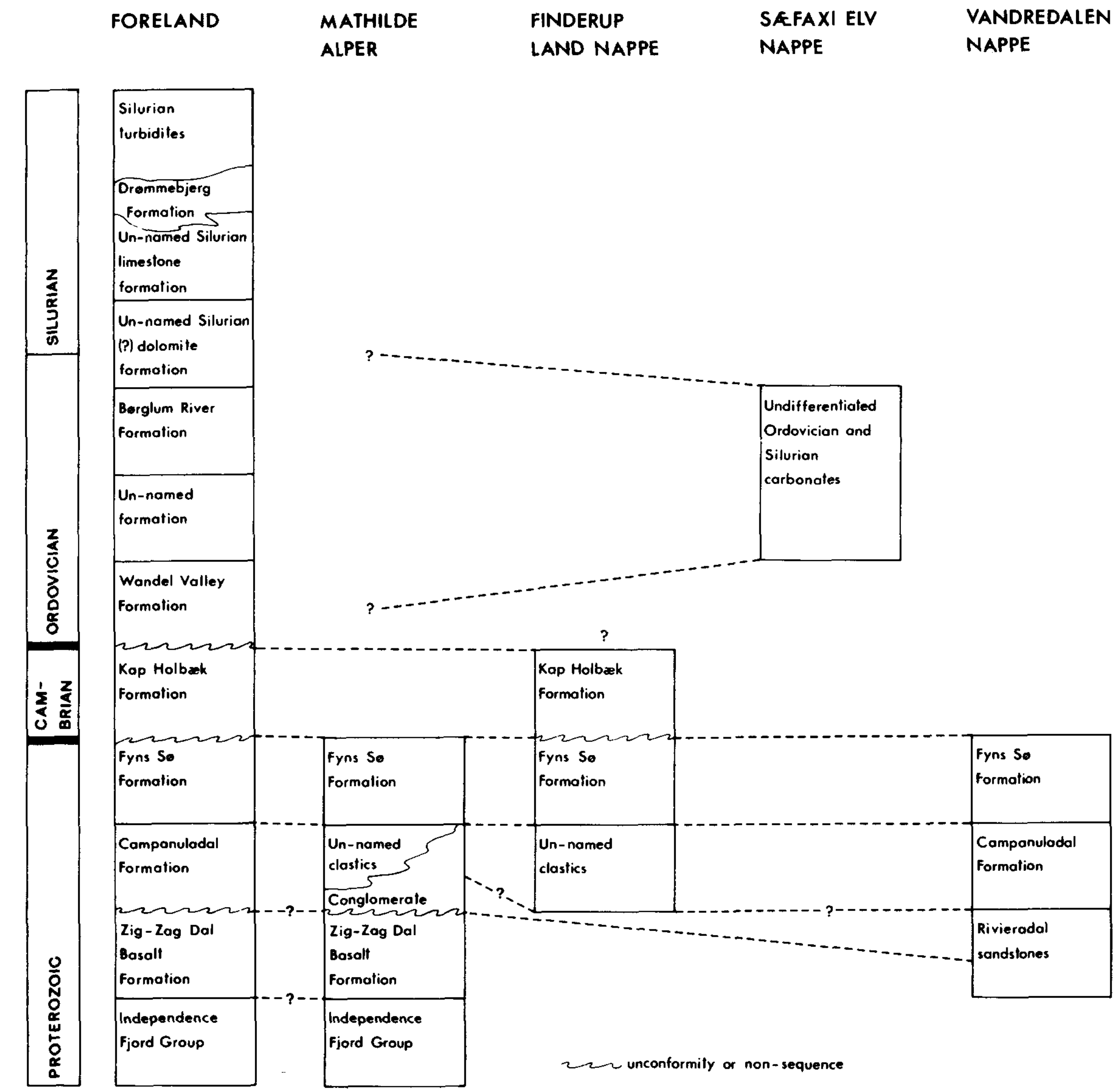

FIG. 3. Simplified schematic stratigraphies and correlation of autochthonous and allochthonous sediments in Kronprins Christian Land. The foreland is a convenient term which includes both carbonate platform sediments and its cover of basin turbidites, and the stratigraphy pertains only to Kronprins Christian Land and immediately W of Danmark Fjord. Mathilde Alper = Prinsesse Caroline–Mathilde Alper (see Fig. 1). Based on own information and Clemmensen (1979), Collinson (1980), Hurst & McKerrow (1981*a*, *b*), Jepsen *et al.* (1980) and Peel (1980).

In particular, because the Fyns Sø Formation is present on the platform (foreland) to the W, on two of the three large nappes and on the eastern autochthon of Proterozoic sandstones in the Prinsesse Caroline–Mathilde Alper (Fig. 3), the nappes are interpreted as having travelled from E of the present-day outcrops of the Fyns Sø Formation. This would involve transport distances of at least 100 km (Hurst & McKerrow 1981*a*, *b*).

There are grounds for supposing that the true displacement was considerably greater. A thin-skinned interpretation of the imbricated region would suggest that it developed as a duplex structure between a fundamental floor thrust, which now surfaces at Kap

Holbæk on the western side of Danmark Fjord (Fig. 1), and a roof thrust, which underlies the exotic nappes. The country between the present-day western margin of the nappes and Danmark Fjord consists of platform carbonate rocks with a thin cover of basin turbidites, cut by numerous reverse faults and minor thrusts (Peel 1980). This imbricate region (Fig. 1) suggests that the roof thrust once extended as far W as Danmark Fjord. This would suggest a minimum displacement of 150 km for the large nappes, though much greater distances are quite possible.

The sedimentary sequences within the three large nappes are non-metamorphic and not greatly deformed, but discontinuous exposures and small-scale folding make it difficult to assess the thicknesses accurately. Estimated thicknesses are as follows: Vandredalen Nappe 2.5 km (minimum), probably at least 3.5 km; Finderup Land Nappe 500 m (minimum), probably at least 800 m; Sæfaxi Elv Nappe 300 m (minimum), probably 550 m.

The uppermost nappe (Vandredalen) includes a thick sequence of turbidites below latest Proterozoic shelf sediments (Fig. 3). These Rivieradal sandstones (Fränkl 1954, 1955; Fig. 3) become gradually coarser towards the top, and much of the lower part of the sequence consists of mudstones or thin-bedded silt turbidites. Because of internal deformation, the structural thickness of the Vandredalen Nappe may have been much greater than the sedimentary thickness. We adopt a value of 5 km for the thickness of the total nappe pile at the time of thrusting, although this may be an underestimate.

Synthesis

Silurian sedimentation patterns in North Greenland are characterized by regional scale features which are presumably associated with geotectonic events of comparable scale. Several tectonic and sedimentological features of the Silurian beds of North Greenland require explanation:

1. The abrupt change in sediment type in the deep-water basin to the N of the carbonate platform at the Ordovician–Silurian boundary.
2. The dominant westerly transport direction of the Silurian turbidites.
3. The relationship between the Silurian turbidites and the Caledonian nappes of eastern North Greenland.
4. The late Llandovery foundering of the carbonate platform which affected the whole of North Greenland E of the Victoria Fjord Arch (Fig. 1).

We propose that these events were related in two ways:

1. Erosion of the advancing pile of Caledonian nappes provided much of the source of clastic detritus for the Silurian turbidites (Fig. 4), and
2. Depression of the crust ahead of the nappes led to foundering of the carbonate platform and expansion of basinal turbidite deposition in the latest Llandovery (Fig. 4).

The first indication of erosion in the rising Caledonide mountains to the E of North Greenland is the presence of a thick Llandovery turbidite sequence which was deposited in the basin to the N of the carbonate platform (Fig. 1). The very slow sedimentation rates during the Ordovician are in marked contrast to the rapid deposition of the thick Llandovery sediments which poured into the basin from the E (Surlyk *et al.* 1980). It is important to realize, however, that during the greater part of Llandovery time, the carbonate platform was unaffected by this change and carbonates continued to be deposited until the latest Llandovery (Christie & Peel 1977; Hurst 1979). We suggest that the erosion necessary to produce the Llandovery turbidites was related to uplift and the displacement of the first major nappe at the time of continental collision in the northern Iapetus Ocean.

The Silurian turbidites differ in composition from the earlier Cambro-Ordovician siliciclastic fill of the North Greenland Llandovery basin in that they contain a significant component of matrix carbonate. This change in composition may be associated with the exposure to erosion of late Proterozoic (Fyns Sø and Campanuladal formations) and undifferentiated Ordovician and Silurian carbonates in the developing Caledonian nappes (cf. Hurst & McKerrow 1981*a*). Our model (Fig. 4) also accounts for those features which point to an eastward source for the Llandovery turbidite fill of the North Greenland basin: its consistently westward-directed palaeocurrents and its decreasing thickness and increasing mud content to the W.

The second component of our model, depression of the crust ahead of the advancing Caledonian nappes (Fig. 4), is proposed to account for the spectacular but previously unexplained foundering of the carbonate platform (about 60,000 km^2 involved) in latest Llandovery time (Surlyk *et al.* 1980) over the whole of North Greenland to the E of the Victoria Fjord Arch (Figs 1 and 4). The carbonate platform was depressed sufficiently to accommodate over 2 km of turbidites above the shallow water carbonates. By application of the standard isostacy equations (England & Richardson 1977) it can be shown that the emplacement of a pile of thrust sheets 5 km thick over a surface previously at equilibrium at sea level would induce a depression of about 4 km and thus a topographic elevation of 1 km; the corresponding depression for a 4 km pile would be 3.2 km. This depression would propagate ahead of the advancing nappes, forming a longitudinal trough ahead of the thrust front, and the response time would be instantaneous in geological terms. The total width of the flexure is likely to have been several times the thickness of the upper elastic portion of the lithosphere and thus probably of

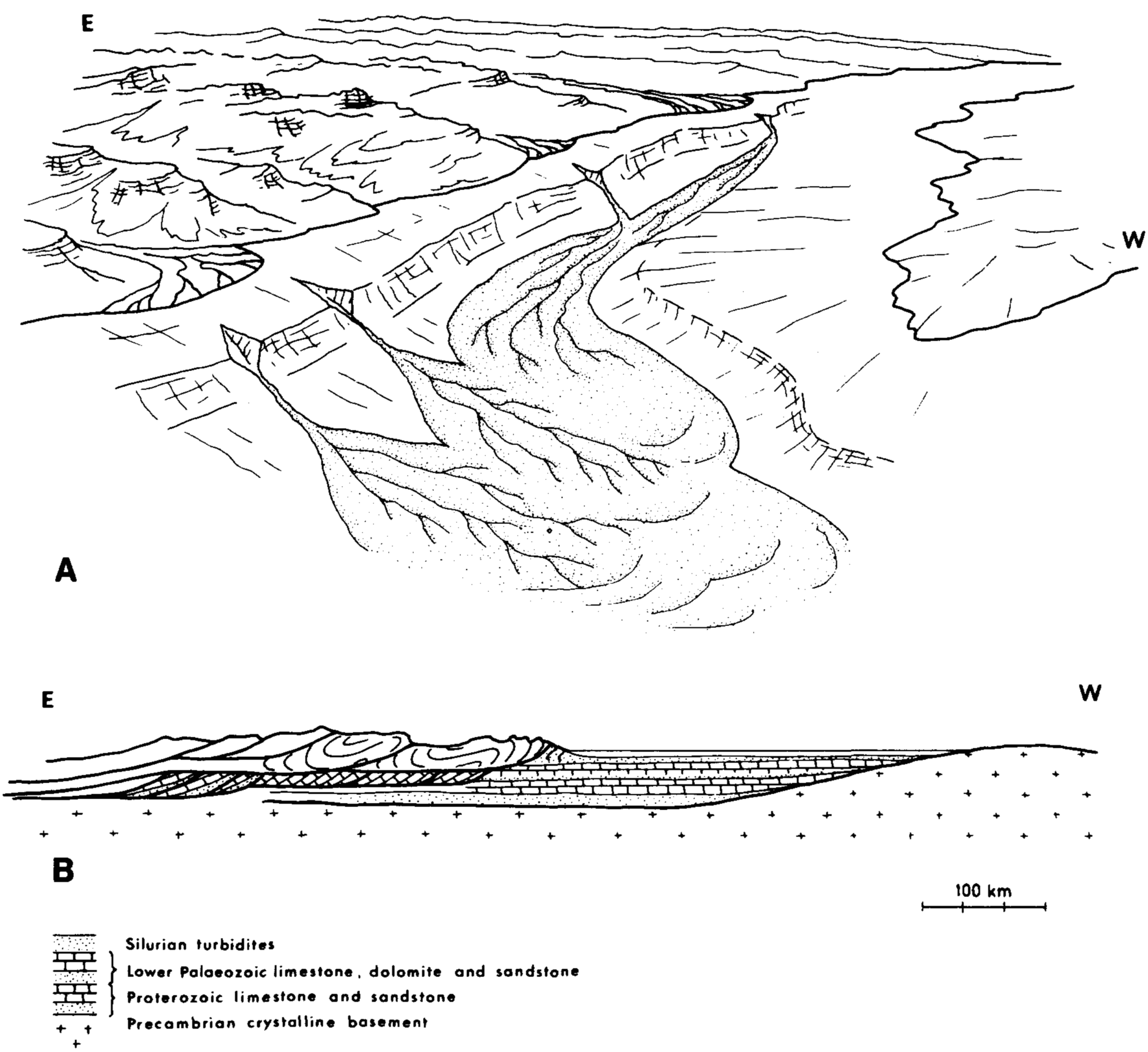

FIG. 4. Tectonic-sedimentological model of the North Greenland turbidite basin in front of the advancing Caledonian nappes in the latest Llandovery at the beginning of platform subsidence. **A**, View towards the E. The mountain arch to the E (left) is formed by the nappes. The low land area to the W (right) is the surface expression of the Victoria Fjord Arch. Fringing the arch is a shallow marine carbonate platform and to the N is a deep-water basin with extremely elongate submarine fans fed from the eastern highlands. Strongly vertically exaggerated. **B**, Simplified structural cross-section illustrating the advancing Caledonian nappes loading and downwarping the eastern edge of the carbonate platform.

sufficient scale to affect the whole carbonate platform to the E of the Victoria Fjord Arch (Fig. 1). The northward transport direction of the turbidites in western Kronprins Christian Land (Figs 2 and 4) can thus be explained by axial currents in the trough ahead of the advancing nappes.

The major period of turbidite deposition in North Greenland occupied about 24 Ma (McKerrow *et al.* 1980) from the Llandovery to the Ludlow. Applying an erosional time constant of 0.1 km/Ma × km of surface height (*cf.* England & Richardson 1977; Johnson 1981) is can be shown that, over a period of 24 Ma, a nappe pile with a mean surface elevation of 1 km would be eroded to a depth of 1.9 km, and because of isostatic rebound the surface height at the end of this period would still be in excess of 0.5 km.

Thus, assuming a mean thickness of the nappes of 5 km, erosion of the nappe pile could not have produced a turbidite blanket of greater thickness than 2 km over an equivalent area by the end of Ludlow times. The area once occupied by the Silurian turbidites in the northern Llandovery basin and later on the carbonate platform greatly exceeds the area of the Caledonide fold belt of Kronprins Christian Land. Even if the nappes were once far more extensive, it appears unlikely that they alone could account for the full volume of Silurian turbidites. Consequently, additional sediment sources must be invoked and several possibilities present themselves.

The most obvious sources are the southerly parts of the East Greenland Caledonides contributing detritus which was transported northwards along the marginal nappe front trough. Another possibility is that the nappe extended northwards into what is now the Wandel Sea and shed sediment directly into the area. A third possible source is the Proterozoic sandstones of the Prinsesse Caroline-Mathilde Alper of Kronprins Christian Land (Fig. 1). In Kronprins Christian Land, the basal parts of the turbidites lying on the platform carbonates include many conglomerate beds. The majority of the clasts are rounded and spherical quartzites identical to the Proterozoic quartzites seen in the Prinsesse Caroline-Mathilde Alper to the E of the thrust belt. Thus, there is direct evidence of uplift and erosion of this autochthonous region to the E of the thrust belt (Fig. 1) at least partially contemporaneous with the emplacement of the nappes. Finally, the highest Silurian beds in eastern North Greenland (excluding Kronprins Christian Land) consist of chert pebble conglomerates (Christie & Peel 1977; Surlyk *et al.* 1980). No similar rocks are known from the autochthon or nappes in Kronprins Christian Land, indicating that there must have been substantial uplift and erosion of sediments (either in nappes or not) of which there is now no record.

Comparisons and conclusions

The classical interpretation of Alpine flysch involves the erosion of advancing nappes, but our model for eastern North Greenland has a direct Palaeozoic analogue, also on the north-western margin of the Iapetus Ocean, in the Humber zone of NW Newfoundland (Williams 1978; Kennedy 1979). In the Ordovician (Llandeilo/early Caradoc) Humberian Orogeny, major exotic nappes containing deep-water sediments and ophiolites were thrust over the early Ordovician carbonate platform, giving rise to middle Ordovician turbidites which are now thrust onto the platform and over-ridden by ophiolites of higher nappes. The situation in eastern North Greenland differs in timing in that the Humberian Orogeny was probably related to collision of the Lushs Bight island arc with the eastern margin of North America, long before the final closure of the Iapetus Ocean (McKerrow 1982). It also differs from eastern North Greenland in that ophiolites are present. The remnants of the northern part of the Iapetus Ocean to the E of Greenland are not present to the W of the modern North Atlantic, although there are several examples of ophiolite obduction in Norway.

The relationship of the Caledonian nappes to the Silurian turbidites of North Greenland is clearly demonstrable (Fig. 4). Initiation of turbidite deposition in the northern basin in earliest Llandovery time certainly indicates active erosion to the E of North Greenland in the rising Caledonides, but it is questionable as to whether this erosion was directly related at first to nappe emplacement. If the nappes were produced by gravity spreading (Elliott 1976), uplift must have preceded the first nappe emplacements, although the time difference would probably be geologically negligible. Alternatively, if the nappes were emplaced by westerly-directed tectonic compression (Chapple 1978), uplift due to stacking of the nappes would post-date the first displacements. Both possibilities are tenable.

The second stage in the evolution of the orogen is the subsidence of the carbonate platform in the latest Llandovery, due to its eastern portion, in Valdemar Glückstadt Land and Kronprins Christian Land (Fig. 1), being overlapped by the eastern nappe pile (Fig. 4). Sediment and directional characteristics of the Silurian turbidites both pre- and post-platform subsidence indicate derivation from very similar easterly sources. However, there is evidence in Kronprins Christian Land at least of additional sediment source supply from contemporaneous uplift of the Proterozoic sandstones in the Prinsesse Caroline-Mathilde Alper (Fig. 1).

A maximum age for the cessation of thrusting is indicated by the youngest strata preserved in the imbricated region, which are turbidites of middle Wenlock age (Hurst & McKerrow 1981*a*). If these rocks were deformed below the overriding nappes, movement must have continued until mid-Wenlock time or later. Since the nappes probably extended even further W, as far as Danmark Fjord or beyond (Fig. 1), movement is likely to have continued until later. However, as the oldest post-orogenic sediments in Kronprins Christian Land and eastern Peary Land are early Carboniferous (Håkansson 1979; Håkansson *et al.* 1981), the precise age for the cessation of thrusting is not known.

Finally, if the late Ordovician or early Silurian clastics in North Greenland are related to continental collision, as seems likely, then the continent colliding with NE Laurentia (of which Greenland forms the NE corner) is likely to have been Baltica. Distinct faunas in the latest Ordovician (Ashgill) of Scandinavia and North America suggest that the Iapetus Ocean was still very wide (*cf.* McKerrow & Cocks 1976). Perhaps the continent that collided with NE Laurentia in the early Silurian was Barentsia (Ziegler *et al.* 1979). This was a distinctly earlier event than the latest Llandovery collision with Scandinavia which produced the nappes in the E.

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