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East Greenland Caledonides: stratigraphy, structure and geochronology

Edited by
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Caledonides, East Greenland, geochronology, stratigraphy, structure.

Cover
West-dipping white and rusty brown quartzites of the Lower Cambrian Slottet Formation, at Slottet in the Eleonore Sø foreland window, resting unconformably on dark clastic sediments of the Palaeoproterozoic Eleonore Sø complex. The summit of Slottet (1933 m high) is 600 m above the glacier surface.

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Preface

The East Greenland Caledonides extend from 70° to 81°30′N, and have been the subject of a series of regional mapping programmes between 1968 and 1998. The entire orogen is now covered by five published 1:500 000 geological map sheets. The six papers in this bulletin concern a variety of topics relating mainly to Kronprins Christian Land (79°–81°30′N) and the Kong Oscar Fjord region (72°–75°N).

The paper by Smith *et al.* on Lower Palaeozoic stratigraphy proposes amendments to several stratigraphical units that occur in Kronprins Christian Land and nearby Lambert Land. In the Kong Oscar Fjord region, two new formations are defined for quartzite and limestone/dolostone units that crop out in foreland windows, and the Lower Palaeozoic succession of the fjord region of East Greenland is formally placed in the Kong Oscar Fjord Group. The second paper by Smith *et al.* describes and formally defines the Neoproterozoic Rivieradal Group of Kronprins Christian Land. The paper by Higgins *et al.* analyses the thin-skinned fold-and-thrust belt that marks the transition between foreland and orogen in Kronprins Christian Land, and presents a balanced cross-section restoration.

The two geochronological papers by Thrane report the results of ion microprobe zircon analyses from orthogneisses in the Charcot Land window (72°N), and results of reconnaissance Pb-Pb dating by the step-leaching method.

The final paper by Higgins & Leslie reviews the history of geological research in the Eleonore Sø and Målebjerg areas of the Kong Oscar Fjord region (72°–75°N). Recognition that the two areas are part of the Caledonian foreland implies that the two thrust sheets structurally overlying the Eleonore Sø and Målebjerg windows have large displacements (~ 100 km each), and that the 'stockwerke' concept of the orogen that focused on *in situ* vertical movements can finally be laid to rest.

A.K. Higgins

Lower Palaeozoic stratigraphy of the East Greenland Caledonides

M. Paul Smith, Jan Audun Rasmussen, Steve Robertson, A.K. Higgins and A. Graham Leslie

The Lower Palaeozoic stratigraphy of the East Greenland Caledonides, from the fjord region of North-East Greenland northwards to Kronprins Christian Land, is reviewed and a number of new lithostratigraphical units are proposed. The Slottet Formation (new) is a Lower Cambrian quartzite unit, containing *Skolithos* burrows, that is present in the Målebjerg and Eleonore Sø tectonic windows, in the nunatak region of North-East Greenland. The unit is the source of common and often-reported glacial erratic boulders containing *Skolithos* that are distributed throughout the fjord region. The Målebjerg Formation (new) overlies the Slottet Formation in the tectonic windows, and comprises limestones and dolostones of assumed Cambrian–Ordovician age. The Lower Palaeozoic succession of the fjord region of East Greenland (dominantly limestones and dolostones) is formally placed in the Kong Oscar Fjord Group (new). Amendments are proposed for several existing units in the Kronprins Christian Land and Lambert Land areas, where they occur in autochthonous, parautochthonous and allochthonous settings.

Keywords: Early Palaeozoic, North-East Greenland, stratigraphy.

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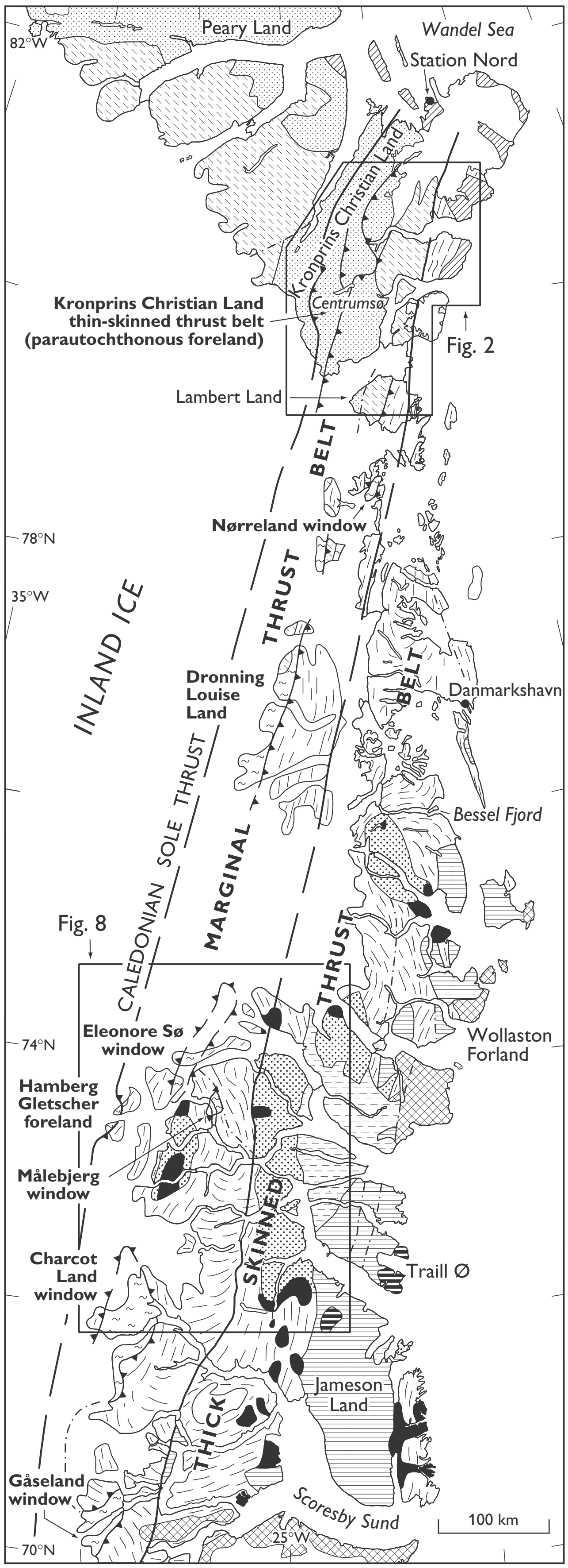
The East Greenland Caledonides extend for over 1300 km between Scoresby Sund (70°N) and Kronprins Christian Land (81°30′N), cropping out in an ice-free coastal strip of variable width (Fig. 1). In the south, the exposed width of the orogen is 300 km, but in the north this is reduced to less than 100 km. The orogen has been the subject of a series of systematic mapping programmes by the Survey since 1968, supplementing and revising work by other groups, most notably Lauge Koch's long series of geological expeditions between 1926 and 1958 (see Haller 1971). This paper documents the key stratigraphical observations on Lower Palaeozoic rocks made during expeditions from 1993 to 1995 by the former Geological Survey of Greenland (GGU) to Kronprins Christian Land and Lambert Land (78°–82°N), and the 1997–1998 field work by the Survey in the Kong Oscar Fjord region (72°–75°N). A number of new Lower Palaeozoic lithostratigraphical units are proposed on the basis of this work and amendments are proposed for some existing units.

The Lower Palaeozoic sediments of Kronprins Christian Land and Lambert Land (Fig. 2) were deposited on a subtidal to peritidal platform that constituted the south-easternmost part of the Franklinian Basin (Higgins *et al.* 1991), and lay at a marked inflexion of the Laurentian margin where it turns through 90° between the present-day E–W-trending coast of North Greenland and the N–S-trending coast of East Greenland. The stratigraphy erected in the Caledonian foreland of eastern North Greenland (Peary Land and western Kronprins Christian Land; Peel 1985; Higgins



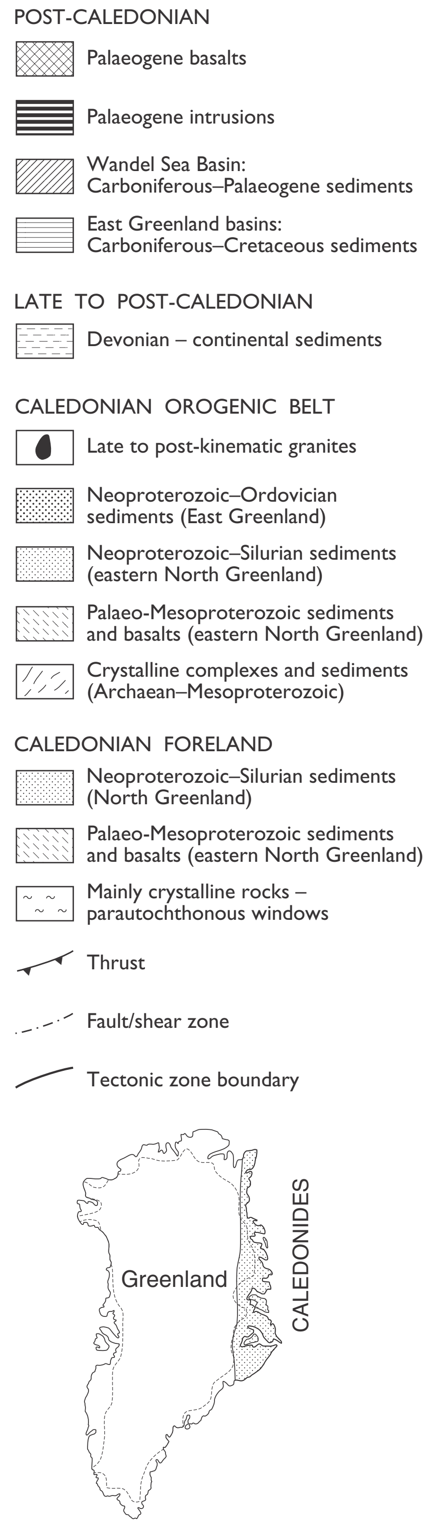


Fig. 1. Geological map of the East Greenland Caledonides, showing location of the foreland windows in the western marginal thrust belt. Modified from Higgins & Leslie (2000). Frames indicate the regions shown at larger scales in Figs 2 and 8.

et al. 1991; Smith & Bjerreskov 1994) can, to a significant degree, be applied to the successions farther to the east and south within the study area (Figs 2, 3), although many of the units differ in detail. This region is the only part of the Franklinian Basin to have been subsequently affected by the Caledonian orogeny, and the Lower Palaeozoic units described here occur both in the foreland and in the thin-skinned parautochthonous fold-and-thrust belt beneath the Vandredalen thrust sheet (Fig. 2; Higgins *et al.* 2001b).

The Lower Palaeozoic successions of the fjord region of the southern parts of North-East Greenland (72°–74°30′N; see Fig. 8) have been the subject of a more protracted research effort that extends back to the 19th century. The Cambrian–Ordovician of the fjord region has become one of the classic reference areas for this stratigraphical interval, but it was only during the 1997–1998 Survey field seasons that the tectonic context was fully elucidated (Higgins *et al.* 2004a). It is now clear that the Cambrian–Ordovician of the fjord region, together with the underlying, Neoproterozoic Tillite Group and Eleonore Bay Supergroup, make up the upper part of the highest thrust sheet in the orogen, which has been transported several hundred kilometres from the east-south-east (Higgins & Leslie 2000; Higgins *et al.* 2004a). Furthermore, notably different developments of Lower Palaeozoic rocks were discovered cropping out in tectonic windows adjacent to the Inland Ice; the successions within these windows are disturbed by Caledonian deformation, and are interpreted as autochthonous to parautochthonous representatives of the foreland (Smith & Robertson 1999a, b; Higgins *et al.* 2004a, b, this volume). The latter are fully documented for the first time here, and provide data critical for interpreting the Lower Palaeozoic evolution of the Iapetus passive margin and its subsequent deformation during the Caledonian orogeny.

Kronprins Christian Land

The Lower Palaeozoic units cropping out over a *c.* 5000 km² area in southern Kronprins Christian Land, eastern North Greenland (Figs 2, 3), were mapped and documented in 1993–1995 as part of the 1:500 000 mapping programme carried out by GGU. Within the thin-skinned parautochthonous fold-and-thrust belt forming much of this region (Higgins *et al.* 2004b, this volume) exposure is often poor due to an extensive cover of recent glacio-fluvial sediments, and the best exposures are on the slopes of the main valleys, with more scattered outcrops on the plateaus. The discontinuous exposure is disrupted by a series of eastward-dipping thrusts with displacements of several hundred metres to a few kilometres. Correlation of superficially similar Middle Ordovician to Silurian sediments in alternating units of peritidal dolostone and subtidal burrow-mottled limestones required detailed sedimentary facies analysis. Macrofaunal biostratigraphy in the field was supplemented by the biostratigraphic analysis of conodonts, which in almost all cases verified the field determinations (Rasmussen & Smith 2001). Cambrian sediments are restricted to the sandstones of the Kap Holbæk Formation (see below), scattered representatives of which occur in autochthonous, parautochthonous and allochthonous settings.

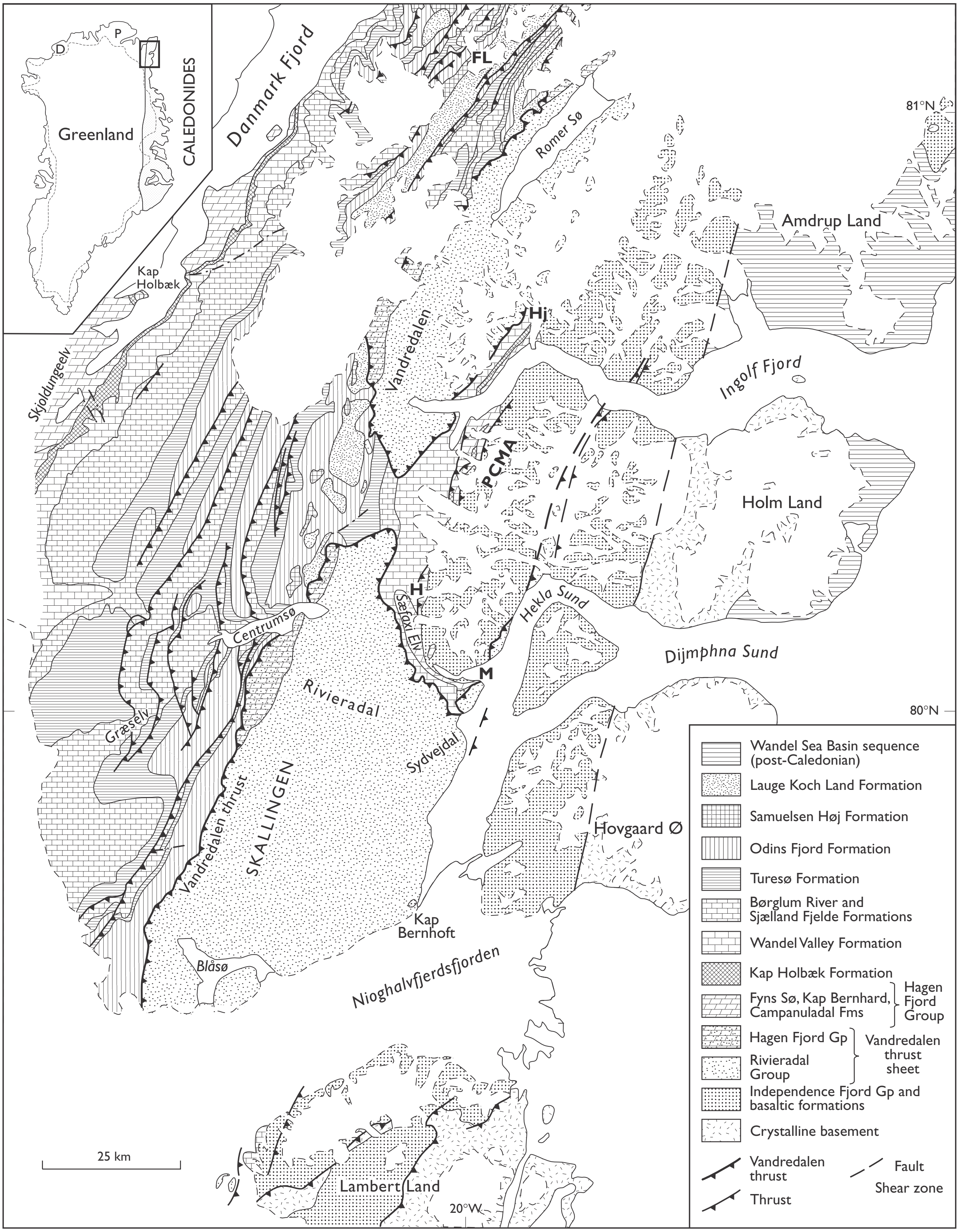
Kap Holbæk Formation

revised

History. The Kap Holbæk Formation was first documented by Adams & Cowie (1953) during a geological reconnaissance around the head of Danmark Fjord, and was informally divided into five members. Fränkl (1954) demonstrated that the unit was also present in Kronprins Christian Land around Sæfaxi Elv, and Hurst & McKerrow (1985) interpreted it as occurring within thrust sheets north of Romer Sø. Initial biostratigraphical determinations (Peel & Vidal 1988) concluded that, on the basis of acritarchs, the unit was of latest Vendian (late Ediacaran) age.

Clemmensen & Jepsen (1992) revised the Hagen Fjord Group of Haller (1961) to encompass a phase of Neoproterozoic shallow marine sedimentation which succeeds the Palaeoproterozoic–Mesoproterozoic Independence Fjord Group and the Mesoproterozoic Zig-Zag Dal Basalt Formation, and pre-dates Franklinian Basin sedimentation. Since the Kap Holbæk Formation was thought to be of Vendian age, the formation was considered to be representative of the youngest phase of sedimentation in the Hagen Fjord Group basin. However, two schemes of possible stratigraphic correlation could still be used to express the relationship of the Kap Holbæk Formation to the underlying Fyns Sø Formation, with radically different consequences in terms of basin evolution models and correlation with East Greenland.

These alternatives were outlined by Sønderholm & Jepsen (1991):


Greenland
CALEDONIDES
D
P
Kap Holbæk
Danmark Fjord
FL
Romer Sø
81°N
Amdrup Land
Hj
Vandredalen
Ingolf Fjord
PCMA
Holm Land
Skjoldungeelv
H
Sæfaxi Elv
Hekla Sund
Centrumsø
Dijmphna Sund
M
Rivieradal
Græselv
80°N
Sydvejdal
SKALLINGEN
Vandredalen thrust
Hovgaard Ø
Kap Bernhoft
Blåsø
Nioghalvfjerdsfjorden
25 km
Lambert Land
20°W
Wandel Sea Basin sequence (post-Caledonian)
Lauge Koch Land Formation
Samuelsen Høj Formation
Odins Fjord Formation
Turesø Formation
Børglum River and Sjælland Fjelde Formations
Wandel Valley Formation
Kap Holbæk Formation
Fyns Sø, Kap Bernhard, Campanuladal Fms
Hagen Fjord Group
Hagen Fjord Gp
Rivieradal Group
Vandredalen thrust sheet
Independence Fjord Gp and basaltic formations
Crystalline basement
Vandredalen thrust
Thrust
Fault
Shear zone

1. The late Ediacaran Kap Holbæk Formation could rest conformably on the Fyns Sø Formation, in which case the whole of the Hagen Fjord Group would probably be of Vendian age (Sønderholm & Jepsen 1991, fig. 18B).

2. The formation could rest disconformably on the Fyns Sø Formation; the latter could then be representative of the late Riphean to Sturtian carbonate developments that characterise the North Atlantic area. In this case, a substantial hiatus would span the Vendian, and the Hagen Fjord Group would be of Riphean to Sturtian age (Sønderholm & Jepsen 1991, fig. 18A).

The Kap Holbæk Formation overlies stromatolitic dolostones of the Fyns Sø Formation at Kap Holbæk with a well-defined, but in detail obscured, contact. Clues that might have helped to differentiate between these two hypotheses include the occurrence of a single clast of Fyns Sø Formation-like lithology in the Morænesø Formation, a glacially influenced deposit of presumed Varanger age in central Peary Land (Collinson *et al.* 1989; Sønderholm & Jepsen 1991). An additional indication was provided by Fränkl (1955) who had interpreted the Kap Holbæk Formation as being the fill of karstic cavities in the top of the Fyns Sø Formation at a single locality in Sæfaxi Elv.

Field work in Sæfaxi Elv in 1994 confirmed and expanded on Fränkl's observations. The uppermost part of the Fyns Sø Formation was found to contain cave systems, infilled with sandstone, which are of typical phreatic character (Smith *et al.* 1999). The Fyns Sø Formation is unconformably overlain by the Wandel Valley Formation, which is sandy at the base but passes upwards into typical dolomitic lithofacies of the Danmark Fjord Member. Confirmation of the lithostratigraphical relationships came from a locality at the junction of Hjørnegletscher and Ingolf Fjord; here the Fyns Sø Formation is overlain by the Kap Holbæk Formation but infilled caves are preserved in the uppermost Fyns Sø Formation (Smith *et al.* 1999). Deep channels are incised into the top of the latter and both the caves and the channels are infilled by lithofacies that can be directly matched to the lower part of the Kap Holbæk Formation (Smith *et al.* 1999). The channels and caves constitute one of the most spectacular and well-preserved examples of pre-Carboniferous palaeokarst recorded to date.

The demonstration of a hiatus between the Fyns Sø and Kap Holbæk Formations lends support to correlation alternative 2 above (scheme A of Sønderholm & Jepsen 1991), which invokes a major time gap between the two units (Fig. 3). Further support comes from the interpretation of Bjørnøya (western Svalbard) as a detached North Greenland terrane (Smith 2000). On Bjørnøya, a carbonate unit similar to the Fyns Sø Formation is overlain by a sparse diamictite interpreted as a glacial horizon by Harland *et al.* (1993), indicating that the carbonate is pre-Vendian. The glacial unit, the Sørhamna Formation, is unconformably overlain by the 'Younger Dolomite', a peritidal dolostone containing a mid-Early Ordovician fauna that is closely comparable with the Wandel Valley Formation (Smith 2000).

Efforts to internationally standardise the position of the Vendian–Cambrian boundary have produced a wealth of biostratigraphic data in recent years. The redefined boundary has the effect of including a considerable time interval, the Nemakit–Daldyn (544–535 Ma), within the Early Cambrian that was previously included within the Neoproterozoic. Furthermore, deep *Skolithos* burrows are now known to have a first appearance in the Tommotian (mid-Early Cambrian). Their presence close to the base of the Kap Holbæk Formation means that the unit is of Early Cambrian age, and is thus a probable correlative of the Buen Formation of North Greenland, as originally postulated (Peel 1980; Peel *et al.* 1981; see Fig. 7). Because of the substantial time gap between the Fyns Sø Formation and the Kap Holbæk Formation, probably corresponding to the whole of the Vendian, the younger unit is here removed from the Hagen Fjord Group.

Type section. Kap Holbæk, a headland close to the head of Danmark Fjord on its western side (Fig. 2).

Thickness. Estimates of the thickness of the Kap Holbæk Formation in the vicinity of Danmark Fjord range from 135 m (Adams & Cowie 1953) to 150 m (Clem-

Facing page:
Fig. 2. Geological map of Kronprins Christian Land and Lambert Land; see inset outline map and Fig. 1 for location. The region shows the well-exposed transition from autochthonous foreland in the west around Kap Holbæk and Danmark Fjord, eastwards through a thin-skinned fold-and-thrust belt, to the allochthonous Vandredalen thrust sheet and higher thrust sheets. **FL**, Finderup Land; **H**, Harefjeld; **Hj**, Hjørnegletscher; **M**, Marmorvigen; **PCMA**, Prinsesse Caroline-Mathilde Alper. On inset map of Greenland; **D**, Daugaard-Jensen Land; **P**, Peary Land.

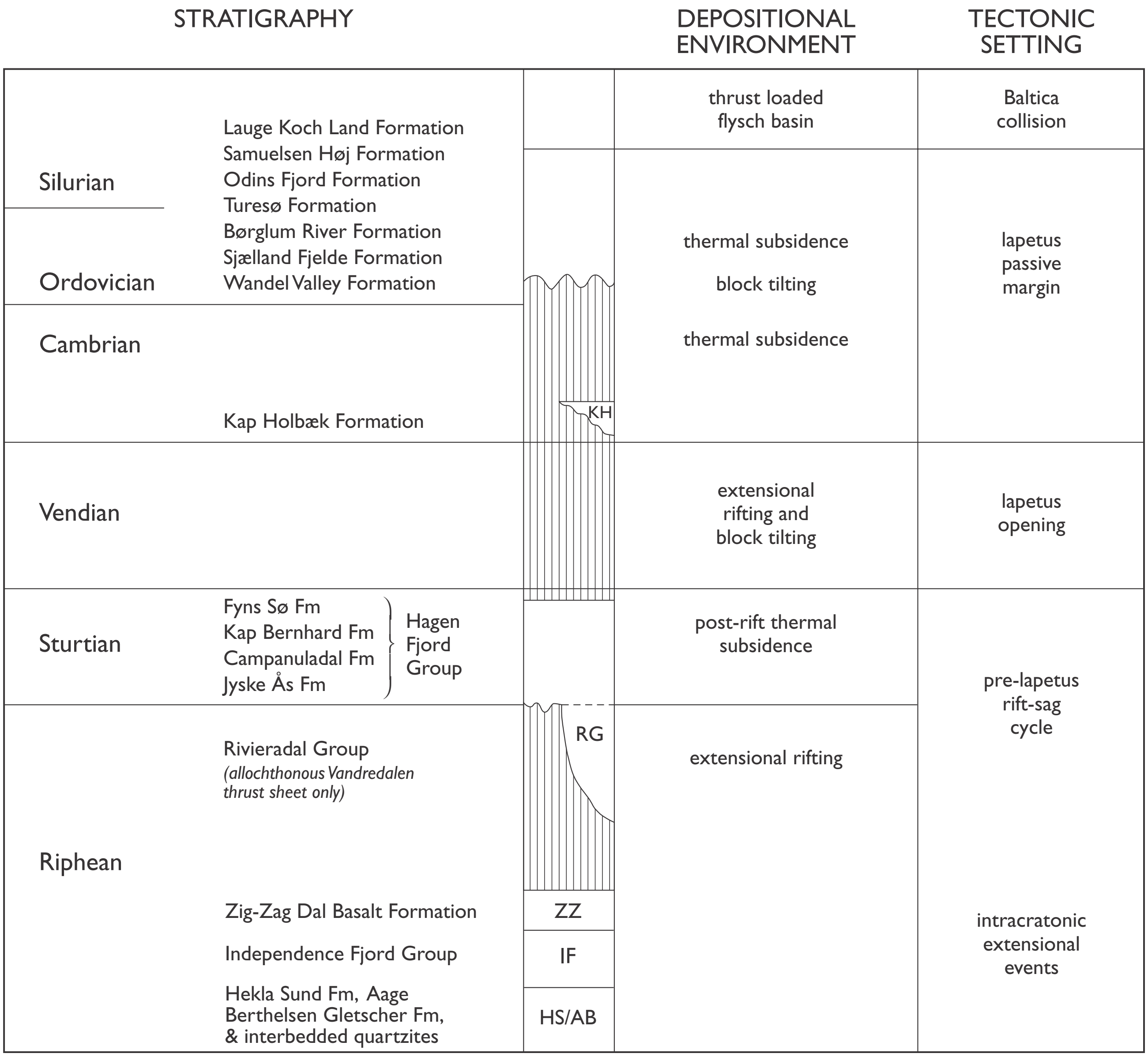


Fig. 3. Pre-Caledonian stratigraphy and tectonic history of Kronprins Christian Land and Lambert Land. Modified from Smith *et al.* (1999).

mensen & Jepsen 1992). Farther to the east, in the inner part of Ingolf Fjord, the formation is 180 m thick but thins southwards, along the western flanks of the Prinsesse Caroline-Mathilde Alper, to zero around Sæfaxi Elv. At Sæfaxi Elv, the Ordovician Wandel Valley Formation rests unconformably on the Fyns Sø Formation and Kap Holbæk sediments are present only as the fill of palaeokarst cavities (Smith *et al.* 1999). The allochthonous Vandredalen thrust sheet does, however, contain the Kap Holbæk Formation (see below), indicating that the formation was present farther to the east prior to thrusting (Higgins *et al.* 2001b). The thinning of the formation to zero is coincident with the position of the rift shoulder of the Hekla Sund basin, the name given by Fränkl (1955) to the half-graben rift basin in which the Neoproterozoic Rivieradal Group accumulated (see also Smith *et al.* 1999; Higgins *et al.* 2001b; Smith *et al.* 2004, this volume), suggesting that the structure continued to exert an influence on sedimentation into the earliest Palaeozoic.

Boundaries. At the type locality, the Kap Holbæk Formation disconformably overlies the Fyns Sø Forma-

Fig. 4. Harefjeld viewed from the south showing steep or cliff-forming burrow-mottled limestones of the Amdrup Member and Danmarks Fjord Member of the Wandel Valley Formation (**WV**), which unconformably overlie the Fyns Sø Formation (**FS**). The recessive pale weathering cap of the hill is the lower part of the Alexandrine Bjerge Member (**AB**). Sæfaxi Elv in the foreground is 200–400 m wide. Slightly modified from Rasmussen & Smith (1996).

tion with a hiatus that probably corresponds to most of the Vendian. It is disconformably overlain by the Wandel Valley Formation, which is mid-Early Ordovician in age at the base (Smith 1991; Smith & Bjerreskov 1994). These relationships pertain throughout the outcrop area, including the palaeokarst localities (Smith *et al.* 1999).

Distribution. The Kap Holbæk Formation crops out around the southern end of Danmark Fjord, extending southwards along the western side of Skjoldungeelv to the Inland Ice (Fig. 2). Farther east, it crops out along the western side of Ingolf Fjord south of Hjørnegletscher and along the western flanks of the Prinsesse Caroline-Mathilde Alper. At the junction of Hjørnegletscher and Ingolf Fjord it additionally occurs infilling fossil caves in the Fyns Sø Formation, and this is the only context in which it occurs around Sæfaxi Elv. The formation is also present in the frontal part of the Vandredalen thrust sheet in Finderup Land, north of Romer Sø, where it was first described in the context of the 'Finderup Land Nappe' (Hurst & McKerrow 1981a, b; Hurst *et al.* 1985).

Biota and age. Peel & Vidal (1988) noted a low diversity palynomorph assemblage from the formation and considered that the flora 'in general suggests an age older than Cambrian'. However, as noted above, the base of the Cambrian has now been extended significantly downwards. The sandstones of the Kap Holbæk Formation also contain deep *Skolithos* burrows which extend vertically for many tens of centimetres (Clemmensen & Jepsen 1992, fig. 29) and occur to within 30 m of the base (Adams & Cowie 1953). The presence of deep *Skolithos* burrows indicates a Tommotian (Early Cambrian) or younger age (Crimes 1992a).

Ryder Gletscher Group

Wandel Valley Formation

Remarks. The development of the Wandel Valley Formation in southern and eastern Kronprins Christian Land is very similar to that documented in the northern and western parts by Peel & Smith (1988). In the Sæfaxi Elv – Vandredalen area, the Danmarks Fjord Member (21 m) is overlain by 200 m of highly strained burrow-mottled lime mudstones (Amdrup Member) in which the burrows are considerably stretched. This unit is in turn overlain by 115 m of recessive dolostones of peritidal origin (Alexandrine Bjerge Member). Extensive conodont sampling has verified this lithostratigraphic interpretation.

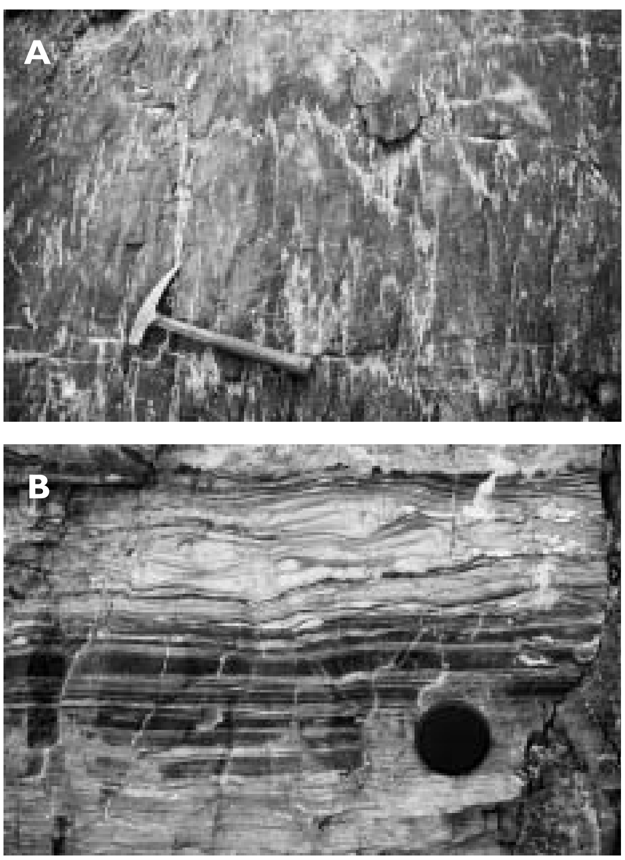


Fig. 5. **A**: Stylolites in highly strained burrow-mottled facies of the Amdrup Member (Wandel Valley Formation) on Harefjeld. The stylolites are concentrating the buff-weathering, dolomitic burrow fills, and other burrows are highly stretched and flattened. **B**: Highly strained wavy laminated facies in the basal part of the Wandel Valley Formation, probably representing the Danmarks Fjord Member, in westernmost Lambert Land. Bedding parallel, cylindrical, dolomite-filled burrows are seen in cross-section. Lens cap for scale; from Rasmussen & Smith (1996).

The three members of the Wandel Valley Formation can be traced along the whole length of Sæfaxi Elv to a point opposite Harefjeld (Fig. 4), the type locality of the 'Harefjeld Formation' of Hurst (1984). The latter unit was considered to be a deep-water equivalent of the Lower Palaeozoic platform succession that was present only in a single thrust sheet, the 'Sæfaxi Elv nappe', with a postulated displacement of over 100 km (Hurst & McKerrow 1981a, b, 1985; Hurst *et al.* 1985). However, a number of sections examined around Harefjeld in 1994–1995 demonstrated an identical succession to that in Sæfaxi Elv with sandy Danmarks Fjord Member overlying the Fyns Sø Formation, and in turn overlain by burrow-mottled lime mudstones of the Amdrup Member. Harefjeld is capped by poorly exposed, but distinctive, recessive buff dolostones assigned to the Alexandrine Bjerge Member (Fig. 4). The 'thrust' at the base of the 'Sæfaxi Elv nappe' of Hurst & McKerrow (1981a, b, 1985) was recognised to be an unconformity with associated palaeokarst development (Rasmussen & Smith 1996; Smith *et al.* 1999; see Kap Holbæk Formation above). The succession differs from that in the remainder of Kronprins Christian Land only in exhibiting particularly high levels of strain. Rasmussen & Smith (1996) therefore proposed the abandonment of the 'Harefjeld Formation'.

The lower member of the Wandel Valley Formation, the Danmarks Fjord Member, varies in thickness from 12 m around inner Danmark Fjord (Smith & Peel 1986) to 20–21 m at Marmorvigen and the inner parts of Ingolf Fjord. The upper part of the unit is strongly brecciated by evaporitic collapse at Ingolf Fjord and Marmorvigen (up to 10 m in thickness), whereas a 2.5 m thick breccia occurs in the middle part of the member on the east side of inner Danmark Fjord.

East of Vandredalen, the Danmarks Fjord Member is overlain by highly strained burrow-mottled lime mudstones (200 m) in which the burrows are considerably stretched (Fig. 5). These have yielded conodonts of late Early Ordovician age and are assigned to the Amdrup Member of the Wandel Valley Formation. This member is in turn overlain by recessive dolostones of peritidal origin (115 m) containing Whiterockian (Middle Ordovician) conodonts, together indicative of the Alexandrine Bjerge Member (Fig. 4). In summary, all three members of the Wandel Valley Formation in the Sæfaxi Elv – Harefjeld – Ingolf Fjord area are very similar to their development in the Danmark Fjord area on the foreland**.** Intervals with shallower water lithofacies in the southernmost representatives of the formation in western Lambert Land (see section on Lambert Land below) suggest that a southern or eastern margin of the platform is being approached.

Sjælland Fjelde Formation

Remarks. The Sjælland Fjelde Formation in the type section near Danmark Fjord is around 100 m thick and comprises a lower dark grey, burrow-mottled dolostone/limestone unit and an upper, grey dolostone unit (Ineson *et al*. 1986). The thickness and character of the formation are maintained in the eastern and southern parts of Kronprins Christian Land. East of Vandredalen, the Vandredalen thrust follows a long flat in the upper Alexandrine Bjerge Member before ramping up westwards to a flat in the upper dolostone unit of the Sjælland Fjelde Formation. The formation has been traced northwards along strike from Sæfaxi Elv as far as the western side of Hjørnegletscher, a distance of around 70 km, and the Vandredalen thrust maintains both the same topographic level and the same stratigraphic level within the Sjælland Fjelde Formation.

The southernmost exposure of the Sjælland Fjelde Formation is close to the Inland Ice, 30 km west of Centrumsø. The Alexandrine Bjerge Member is there overlain by 36 m of highly fossiliferous limestones that may be equivalent to the '*Opikina* Limestone' of Scrutton (1975). The remainder of the interval beneath the Børglum River Formation is covered, but the likely overall thickness of the Sjælland Fjelde Formation at this locality is around 110 m.

Morris Bugt Group

Børglum River Formation

Remarks. The Børglum River Formation comprises lithologically monotonous, burrow-mottled lime mudstones and wackestones. The formation is generally highly fossiliferous in the upper part with abundant stromatoporoids, corals, gastropods and cephalopods together with rarer brachiopods and trilobites. A distinctive 10 m thick dolostone horizon occurs 20 m below the top of the formation and constitutes a useful marker horizon in sections where the overlying Turesø Formation is intensely deformed.

Substantial areas of Børglum River Formation were mapped in 1995, and the formation remains uniform throughout the mapping area. It is difficult to provide an accurate estimate of the thickness since, owing to tectonics and exposure, no sections were found in which both the upper and lower boundaries were exposed. The value of 430 m estimated by Smith *et al*. (1989) seems, however, to be a reasonably valid one.

Turesø Formation

Remarks. Previous to the 1993–1995 mapping programme, the Turesø Formation was known to show a marked increase in thickness from around 150 m in Peary Land to over 200 m in northern Kronprins Christian Land (Peel 1985). This trend is maintained southwards, and a section measured 5 km west of Centrumsø (Fig. 6) had a thickness of 320 m in which subtidal burrow-mottled intervals of lime mud- and wackestone are more dominant than farther to the west in Peary Land. This produces a distinctive black and white striped appearance which is of considerable utility in identifying the formation from a distance.

The uppermost Ordovician(?) – lowermost Silurian succession in the western part of Vandredalen shows a slightly different development to the area west of Centrumsø. The tectonically deformed succession, in a major footwall ramp of the Vandredalen thrust, comprises a lower dolostone unit, a middle burrow-mottled unit and an upper dolostone unit. The lower unit is a minimum of 20 m thick (the base is unexposed) and comprises alternating dolostone beds and burrow-mottled limestones. It is succeeded by about 90 m of burrow-mottled limestones containing a diverse macrofauna, which includes brachiopods, tabulate corals, cephalopods and stromatoporoids. The 130 m thick upper dolostone member is made up of white-weathering dolostone beds and interbedded dark grey limestones that give the unit a distinctive, striped appearance. The upper dolostone unit is generally poor in macrofossils, but does contain sparse stromatoporoids and brachiopods.

The southernmost occurrence of the Turesø Formation is 10 km to the north-west of Blåsø, and the unit is here thinner (around 200 m) than farther north in Kronprins Christian Land (around 300 m). The base is marked by a 30 m thick, pale grey dolostone unit. The lowest occurrence of pentamerid brachiopods is about 140 m above the formation base, but it is prob-

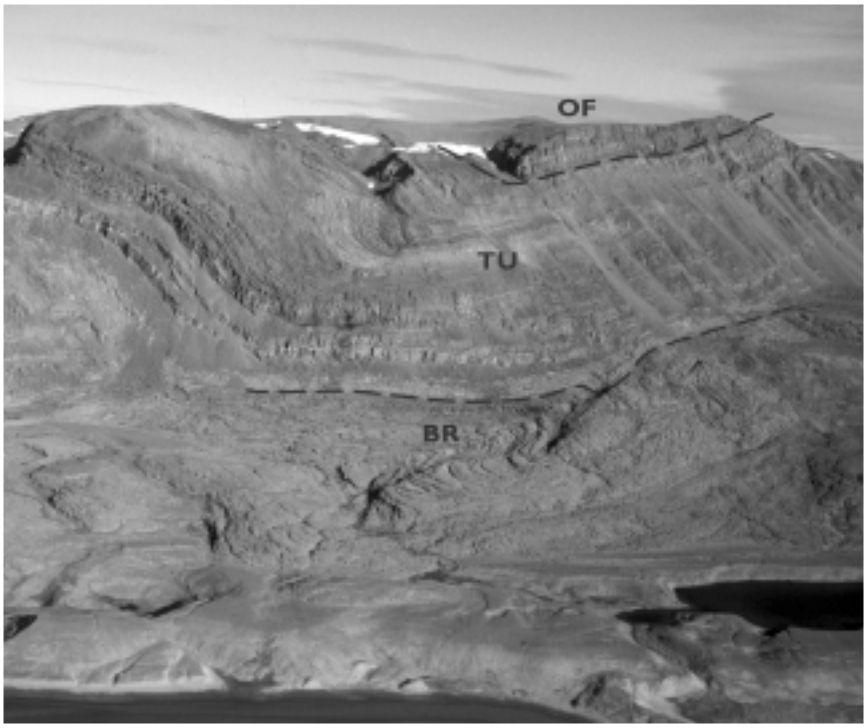


Fig. 6. Folded Middle Ordovician – Silurian carbonates within the parautochthonous thrust belt, 5 km to the west of Centrumsø, looking northwards. **BR**, Børglum River Formation; **TU**, Turesø Formation; **OF**, Odins Fjord Formation. Note the distinctive striped character of the Turesø Formation and the cliff-forming nature of the Odins Fjord Formation. The profile is 500 m high.

able that the Ordovician–Silurian boundary occurs well below this level.

Washington Land Group

Odins Fjord Formation

Remarks. Although the Odins Fjord Formation is widely exposed across the area, it is rather uniformly developed, and was examined in detail only at its most southerly occurrence west of Blåsø. The minimum thickness in this part of southern Kronprins Christian Land is 220 m. This compares with a thickness of 200 m in southern Peary Land, which increases northwards to around 300 m approaching the shelf margin in central Peary Land (Hurst 1984).

The transition from the Turesø Formation to the Odins Fjord Formation at Blåsø is marked by a change in weathering colour from pale grey to pale brown. At the same level, the lithology alters from dolostone-dominated to limestones rich in tabulate corals and stromatoporoids. The lower 100 m are dominated by brown-weathering, burrow-mottled limestones, some of which are floatstones.

A very distinctive pale dolostone interval occurs 70–103 m above the base, and contains abundant calcite-cemented vugs, probably representing pseudomorphed evaporitic nodules. The pale weathering, dark grey limestones are notably bituminous. This interval is at approximately the same level within the Odins Fjord Formation as the peritidal sediments of the Melville Land Member in Peary Land (Hurst 1984) and it is likely that they are broadly correlative. The interval was not initially recognised in the Centrumsø area, but a much thinner development at around 100 m above the base may be the correlative. As with the Wandel Valley Formation, the presence of intervals with shallower water lithofacies in southernmost Kronprins Christian Land suggests that a southern or eastern margin of the platform is being approached.

Samuelsen Høj Formation

Remarks. Although reefs of the Samuelsen Høj Formation had previously been documented on the northern side of Centrumsø (Fränkl 1954; Hurst 1984), they had not previously been recognised farther to the south. However, in 1994–1995 a single small reef was located within a thrust sheet that extends southwards from the western end of Centrumsø for around 10 km along the eastern side of Græselv. The small reef directly overlies stromatoporoidal biostrome facies of the Odins Fjord Formation. The reef, approximately 50 m in diameter and 20 m high, is typical of the formation, with a massive, unbedded core facies and radially dipping flank beds.

Peary Land Group

Lauge Koch Land Formation

Remarks. The southernmost occurrence of the Lauge Koch Land Formation in Kronprins Christian Land is in the parautochthonous fold-and-thrust belt immediately to the south of Centrumsø. In contrast to the typical development of the Samuelsen Høj Formation reef in this area, that of the overlying flysch is atypical. Hurst & Surlyk (1982) assigned all of the Silurian flysch in Kronprins Christian Land to the 'Profilfjeldet Shales' of Fränkl (1954), and the unit was given member rank within the Lauge Koch Land Formation. In the type section on the west side of Vandredalen, the lower part of the Profilfjeldet Member is dominated by quartz conglomerates and sandstone turbidites. Locally, black mudstones with rare starved ripples and thin-bedded muddy siltstones are developed up to a thickness of a few metres.

In distinct contrast, the lower part of the section south of Centrumsø contains approximately 50 m of black siltstones and sandstones with interbedded carbonates overlying the Odins Fjord Formation and the Samuelsen Høj Formation reef. The black siltstones and fine- to medium-grained sandstone beds are 5–30 cm thick and contain planar lamination. In places a rhythmic alternation of 1 cm sandstone with 1–3 cm shaly siltstone can be seen. The interbedded carbonates are very dark grey to black, bituminous, nodular and burrow-mottled with calcite concretions; there are abundant black silty partings. The abundant macrofauna includes graptolites, cephalopods and gastropods. The interbedding of turbiditic clastic sediments with burrow-mottled carbonates is somewhat unusual, but presumably represents intermittent distal turbidite deposition in a deep subtidal setting which, during times of low clastic influx, allowed the re-establishment of carbonate deposition and a burrowing infauna.

Above the lower black shale/carbonate unit, the Lauge Koch Land Formation is more typically developed. A 25 m thick interval of green-weathering, very thinly bedded, shaly siltstones and sandstones is overlain by cliff-forming sandstone turbidites. The latter contain $T_{a-c,e}$ and T_{b-e} units and 4 m thick, massive channel fills are present. Coarsening- and thickening-upward 20–30 m cycles are also present. The thrust-truncated thickness is approximately 150 m, well within the maximum thickness of 400 m cited for the member (Hurst & Surlyk 1982).

Lambert Land

Prior to the 1993–1995 mapping programme, the Wandel Valley Formation was not known to crop out south of Kronprins Christian Land. Escher & Jones (1994), however, pointed to the possible presence of Early Palaeozoic carbonates in westernmost Lambert Land, North-East Greenland (Fig. 2), resting unconformably upon Independence Fjord Group quartzites.

Examination of the quartzite-carbonate boundary near the Inland Ice margin in westernmost Lambert Land demonstrated that the carbonates unconformably overlie Independence Fjord Group quartzites, with a very slight angular discordance. The basal 25 m of the carbonates constitute a generally pale weathering unit, which is made up of current laminated dolostones with scours and some ripple lamination, together with darker wavy laminated dolostones containing ripples and drapes (Fig. 5B). Some cyclicity is evident, and the top of one cycle contains probable pseudomorphed evaporite nodules. This lower unit is overlain by highly strained, dark-weathering wavy laminated and burrow-mottled carbonates, dolomitised to greater or lesser degrees. The current laminated dolostones are absent above 25 m.

Taking into account the lithofacies present, the unconformable relationship with the Independence Fjord Group, and the recovery of fragmentary conodonts, the Lambert Land carbonates are assigned to the Wandel Valley Formation. It is probable that the lower 25 m unit represents the Danmarks Fjord Member and that the overlying carbonates are part of the Amdrup Member. The thickness of the upper unit in Lambert Land is difficult to estimate due to structural complications, but it does not exceed the 200 m seen in the Amdrup Member in Kronprins Christian Land.

The presence of the Wandel Valley Formation resting unconformably on the Independence Fjord Group demonstrates that the progressive overstep of the Early Ordovician from west to east across North Greenland (Peel & Smith 1988, fig. 6) continues into Kronprins Christian Land, where it rests on the Kap Holbæk Formation in the west and the Fyns Sø Formation in the east, and southwards to Lambert Land (Fig. 7). The pattern is suggestive of a strong N–S component in addition to the well-documented west to east over-

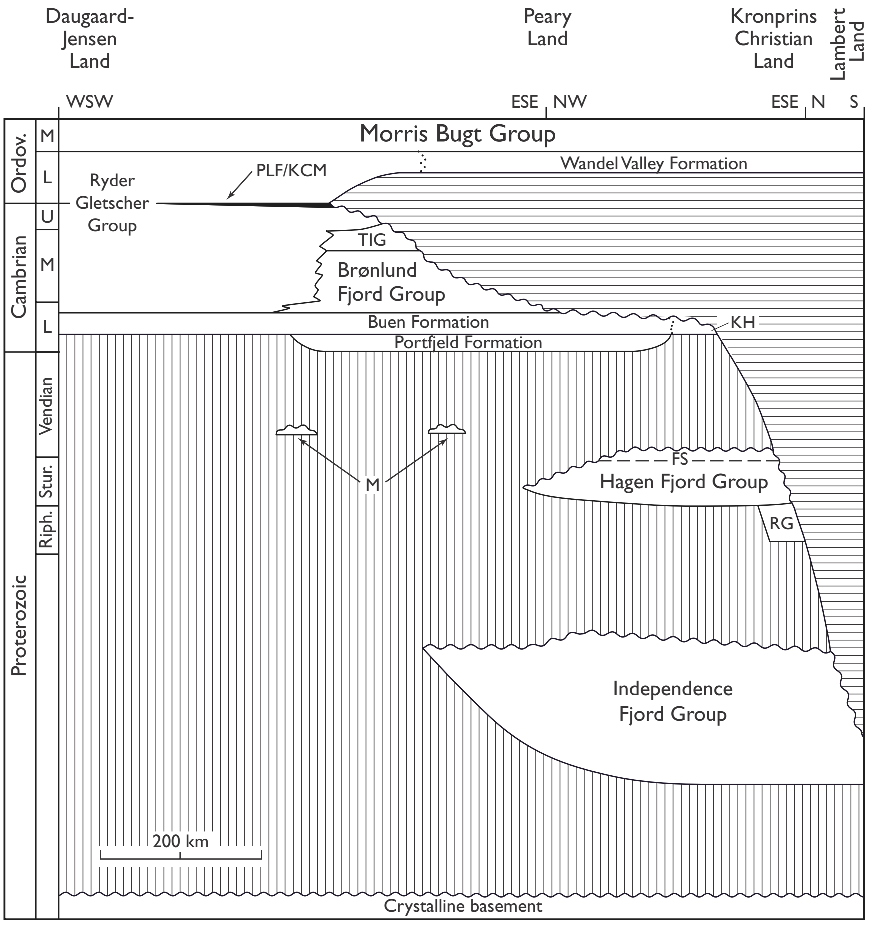


Fig. 7. Proterozoic – Middle Ordovician stratigraphic relationships on the platform area of North and North-East Greenland, showing the extent and magnitude of the sub-Wandel Valley unconformity. Maximum uplift and associated erosion was in Lambert Land, at the extreme right hand side of the diagram. The locations of Daugaard-Jensen Land and Peary Land are indicated on the inset map of Greenland in Fig. 2. **FS**, Fyns Sø Formation (Hagen Fjord Group); **KH**, Kap Holbæk Formation; **M**, glacial sediments of the Moræneso Formation; **PLF/KCM**, quartz arenite sandstone sheet assigned to the Permin Land Formation and the Kap Coppinger Member; **RG**, Rivieradal Group (see Smith *et al.* 2004, this volume); **TIG**, Tavsens Iskappe Group. Modified from Smith (2000).

step, and perhaps indicates that maximum pre-Wandel Valley Formation uplift was farther to the south than hitherto anticipated. The depositional environments are broadly comparable with the development to the north, but the burrow-mottled upper unit in Lambert Land seems to be of slightly shallower water origin than the Amdrup Member, suggesting proximity to a southern and/or eastern margin to the Franklinian platform in Lambert Land.

Dronning Louise Land

The extensive nunatak region of Dronning Louise Land (Fig. 1) was first documented geologically during the 1952–1954 British North Greenland expedition (Peacock 1956, 1958). The region was not re-investigated in detail until the systematic mapping programme conducted by GGU in 1989–1990 (Friderichsen *et al.* 1990; Holdsworth & Strachan 1991; Strachan *et al.* 1994). Dronning Louise Land is divided by a N–S-trending imbricate zone into an autochthonous foreland area to the west, and parautochthonous to allochthonous Palaeoproterozoic gneiss complexes with interbanded metasedimentary rocks to the east, transported westwards as thrust sheets. The foreland area comprises crystalline basement orthogneisses overlain by sequences of sedimentary rocks assigned to the 'Trekant' and 'Zebra series'. The older 'Trekant series' and underlying basement gneisses are intruded by dolerite dykes, and are overlain unconformably by the 'Zebra series'. The 'Zebra series' is also present in the imbricate zone where it overlies pale grey-green sandstones that are intruded by metadolerites.

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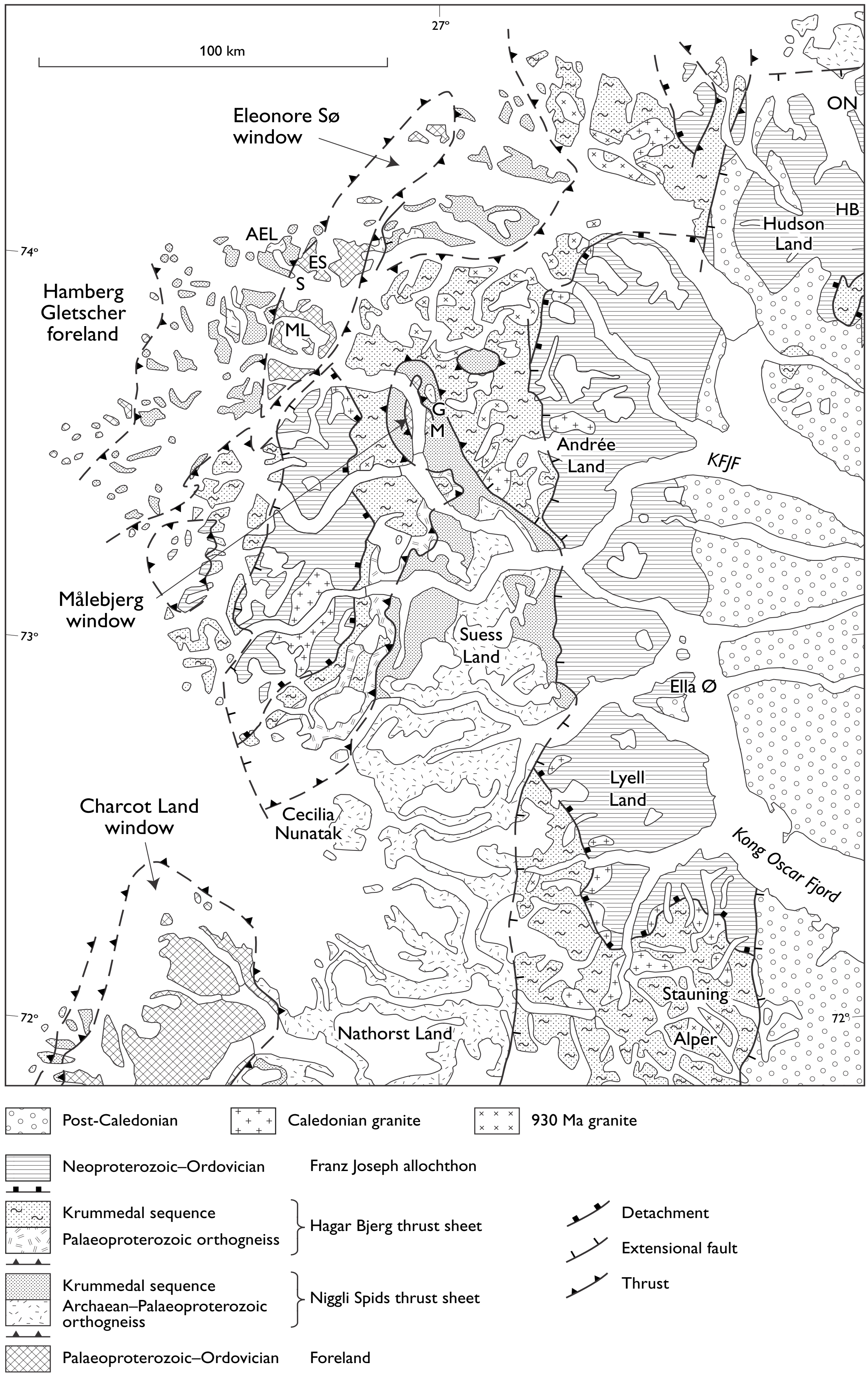
Fig. 8. Geological map of North-East Greenland 71°50′–74°30′N, showing location of the Eleonore Sø, Målebjerg, and Charcot Land windows. The legend depicts the units contained in the two thrust sheets and Franz Joseph allochthon, which overlie the windows. **AEL**, Arnold Escher Land; **ES**, Eleonore Sø; **G**, Gemmedal; **HB**, Albert Heim Bjerge; **KFJF**, Kejser Franz Joseph Fjord; **M**, Målebjerg; **ML**, J.L. Mowinckel Land; **ON**, C.H. Ostenfeldt Nunatak; **S**, Slottet.


27°
100 km
Eleonore Sø
window
AEL
ES
S
74°
Hamberg
Gletscher
foreland
ML
G
M
ON
HB
Hudson
Land
Andrée
Land
KFJF
Målebjerg
window
73°
Suess
Land
Ella Ø
Lyell
Land
Charcot Land
window
Cecilia
Nunatak
Kong Oscar Fjord
Stauning
Alper
72°
Nathorst Land
72°
Post-Caledonian
Caledonian granite
930 Ma granite
Neoproterozoic–Ordovician
Franz Joseph allochthon
Krummedal sequence
Palaeoproterozoic orthogneiss
Hagar Bjerg thrust sheet
Krummedal sequence
Archaean–Palaeoproterozoic
orthogneiss
Niggli Spids thrust sheet
Palaeoproterozoic–Ordovician
Foreland
Detachment
Extensional fault
Thrust

In the foreland of north-west Dronning Louise Land, the 'Zebra series' comprises 3–10 m of basal pebble conglomerates, overlain by 10–15 m of purple-white striped quartzites. These pass upwards into yellow-white medium- to coarse-grained quartzites (5–30 m) and interbanded magnetite sandstones, siltstones and mudstones (10 m; Friderichsen *et al.* 1990). These clastic rocks are overlain by around 10 m of fine-grained grey-black limestones. Deep *Skolithos* burrows are found *in situ* in the quartzites demonstrating, as with the Kap Holbæk Formation, that the 'Zebra series' is no older than Cambrian. The quartzites are thus correlative with the Kap Holbæk Formation of Kronprins Christian Land, the Slottet Formation of the Eleonore Sø and Målebjerg windows (see below), and the Kløftelv Formation (Kong Oscar Fjord Group – see below) of the Franz Joseph allochthon.

A similar succession is present within the 'Zebra series' of the imbricate thrust zone where, in central Dronning Louise Land, Friderichsen *et al.* (1990) recorded 2 m of pale green sandstones with thin lensoid pebble beds up to 20 cm thick at the base, overlain by 45 m of white to rusty weathering medium-grained quartzites with abundant tabular cross-bedding. These beds are overlain by a heterogeneous 50 m package of interbedded grey-green siltstone, dark mudstone, thin quartzites, yellow sandstones and limestones. The base of this latter unit contains ichnofossils assigned to *Cruziana* sp. (Strachan *et al.* 1994), which indicate a maximum age of Atdabanian (mid-Early Cambrian; Crimes 1992b). The quartzites are overlain by about 120 m of grey dolomitic limestones – a stratigraphic signature that is very similar to the successions in the Eleonore Sø and Målebjerg windows (see below). The precise age of the dolomitic limestones at the top of the 'Zebra series' in both the foreland and imbricate zone is uncertain, but they must be of Cambrian–Ordovician age.

Nunatak region 71°50′N–74°30′N

The presence of *in situ* Lower Palaeozoic sediments in the western nunatak region of the southern part of the East Greenland Caledonides (Fig. 8) had not been demonstrated prior to the 1997–1998 Survey mapping programme. However, several clues had been noted, namely the presence of erratic carbonate blocks containing Early Ordovician conodonts on Cecilia Nunatak (72°30′N; J.S. Peel *in* Higgins *et al.* 1981), and the abundant occurrence of quartz arenite blocks containing *Skolithos* throughout the Caledonides (see e.g. Haller 1971, fig. 48). Two tectonic windows through thrust sheets (Leslie & Higgins 1998, 1999) discovered in 1997 revealed the presence of Vendian tillites, Cambrian sandstones and Cambrian–Ordovician carbonates in the footwall immediately underlying the bordering thrusts; these distinctive successions record the effects of Caledonian deformation, and have been interpreted as representing autochthonous to parautochthonous Caledonian foreland (Higgins *et al.* 2001a). While the strain levels in these units are high, sufficient sedimentary detail can be observed to allow confident interpretation and correlation.

Slottet Formation

new formation

History. The 'Slottet Quartzite' was first described by Katz (1952) from the Eleonore Sø region (74°N), and was included within a group of rocks that was correlated with the upper part of what is now the Nathorst Land Group (lower Eleonore Bay Supergroup). Subsequently, Haller (1971), following a suggestion of Wenk (1961), assigned the quartz-arenite unit to his 'Basal Series' of the Eleonore Bay Supergroup. This complex of rocks included a wide variety of lithologies, and it is now clear that a wide range of ages is also represented (Leslie & Higgins 1998, 1999). As part of the systematic re-mapping programme of 1997–1998, the Eleonore Sø region was revisited, and it was recognised that the rock units were located within a major

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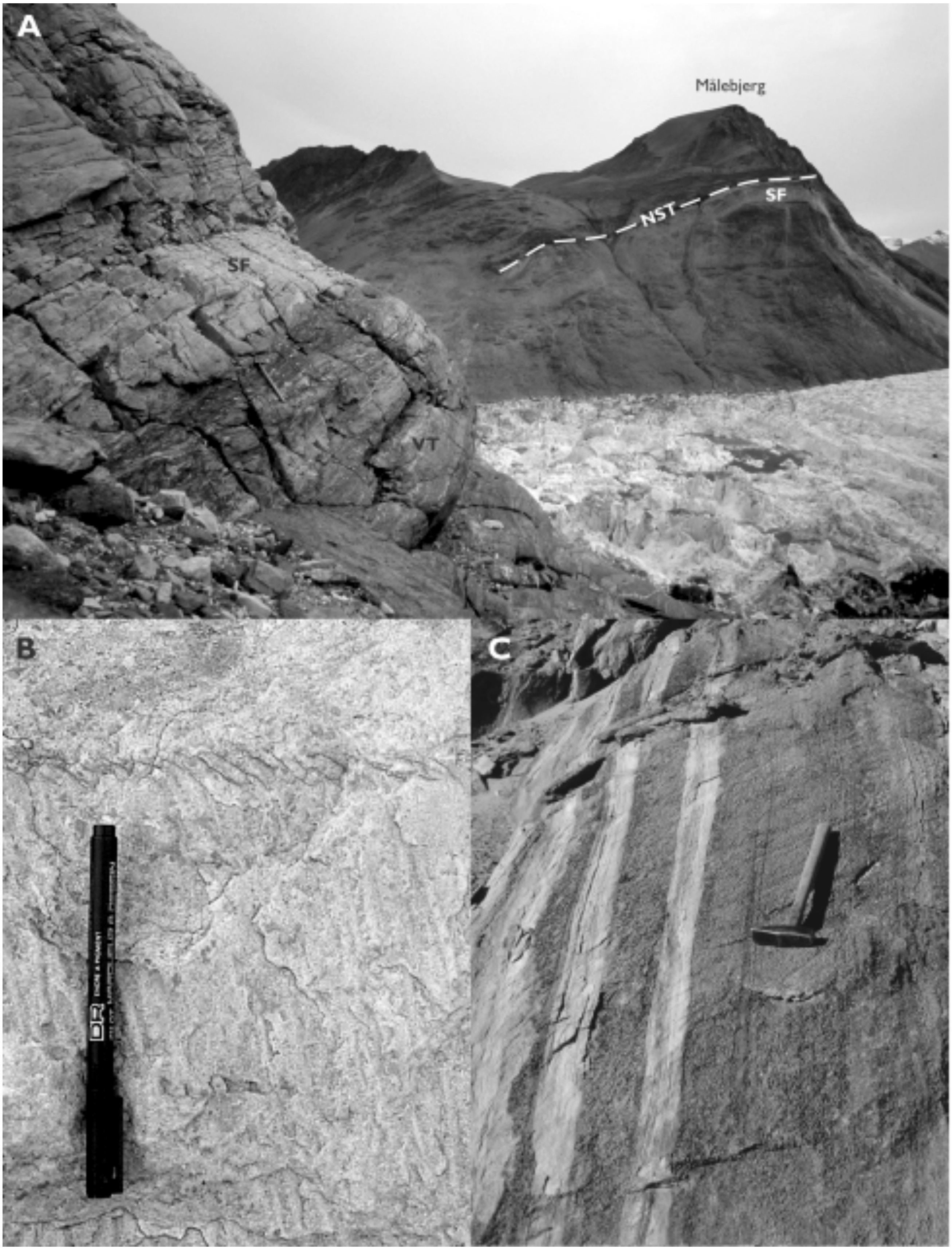
Fig. 9. **A**: Quartzites of the Slottet Formation (**SF**) a few hundred metres north of the type section, overlying a clastic unit that includes diamictites (**VT**). The light coloured quartzites of the Slottet Formation are clearly visible in the cliffs of Målebjerg in the background. A few metres of carbonate (not visible) represent the Målebjerg Formation, with the Niggli Spids thrust (**NST**) marking the upper limit of the unit. View looking south to Målebjerg (1873 m high), the summit of which is about 1500 m above the ice-dammed lake and glacier. **B**: *Skolithos* burrows in quartzite from the Slottet Formation of the Eleonore Sø window. Distortion of the upper part of the burrows, along bedding planes, is a consequence of westward displacement of the overriding Caledonian thrust sheets. **C**: Highly strained, parallel laminated dolostones and burrow-mottled limestones of the Målebjerg Formation at the type section, to the north of Målebjerg, in the Målebjerg window.


A
Målebjerg
NST
SF
SF
VT
B
C

window through a Caledonian thrust sheet. When the effects of Caledonian deformation were restored, it became clear that Haller's (1971) supposed 'Basal Series' in this region is a complex of volcanic and sedimentary rocks deposited in a rift setting and unconformably overlain by the Slottet Formation (Leslie & Higgins 1998). The older group of rocks was informally termed the 'Eleonore Sø complex', while the discovery of *Skolithos* burrows in the younger 'Slottet quartzite' indicated the Cambrian age of the unit (Leslie & Higgins 1998; Smith & Robertson 1999b).

Further outcrops of the 'Slottet quartzite' were located 70 km east of the Eleonore Sø region at the foot of Målebjerg, in another smaller tectonic window through a Caledonian thrust, now known as the Målebjerg window. These outcrops were originally mapped by Haller (1953), and their resemblance to the 'Slottet quartzite' was pointed out by Haller (1971) who also placed them in his 'Basal Series' of the Eleonore Bay Supergroup.

Name. The formation is named after the promontory of Slottet ('the castle') to the south of Eleonore Sø, where the unit crops out spectacularly and was first described by Katz (1952).

Type section. The north side of the ice-dammed lake in Gemmedal, north of Målebjerg (Fig. 9A).

Thickness. At the type section, the formation is 143 m thick (Fig. 10). In the vicinity of Slottet, photogrammetric calculations suggest that the unit is considerably thicker, of the order of 350 m (see photograph on front cover of this volume) although this is much less than the > 1000 m estimate derived from Katz's observations that was quoted by Haller (1971).

Lithology. In the type section north of Målebjerg (Figs 9A, 10), the lower 10 m comprise structureless or planar laminated, fine- to coarse-grained quartz arenites in 10–30 cm beds. From 10–36 m, the maximum grain size diminishes, and fine- to medium-grained sandstones occur in 0.2–1.6 m beds. The quartz arenites are parallel laminated and cross-bedded, the latter sometimes being of very large scale, with sets up to 1.6 m. Some beds are lenticular at outcrop scale, and shaly interbeds are sometimes present. Above 36 m, the fine-grained quartz arenites are in beds of 0.3–1.5 m thickness, and are either structureless or cross-bedded with sets up to 1 m and very low angle foresets. The beds are mainly tabular, but some are seen to

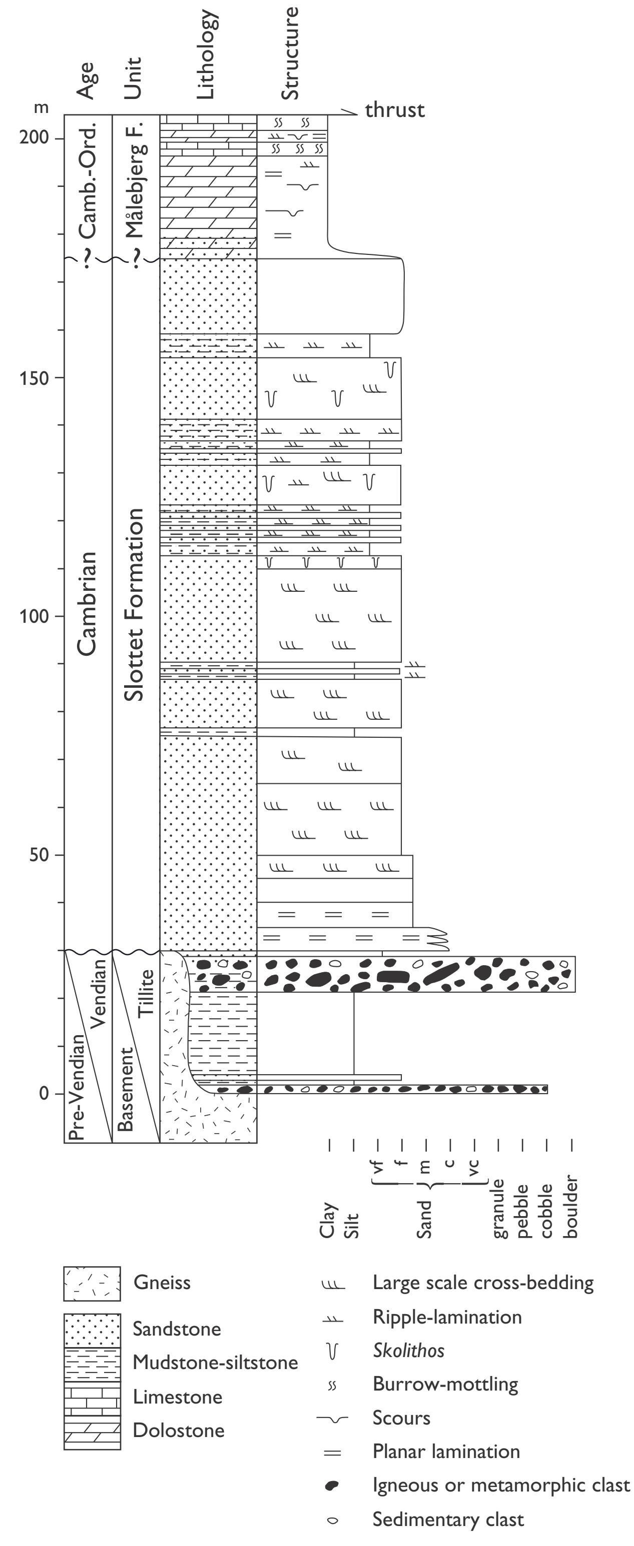


Fig. 10. Composite log of the Slottet and Målebjerg Formations at the type locality in the Målebjerg window. The lenticular clastic succession beneath the Slottet Formation, with two diamictite levels, occupies a depression in the gneissic basement, and is interpreted as a Vendian tillite.

wedge out at outcrop scale. Interbeds of thin sandstones and sandy shales up to 0.4 m thick occur. Current directions determined from foreset orientation are predominantly towards the south-east.

At 79 m, there is a conspicuous change from golden brown-weathering quartz arenites to a rusty weathering alternation of interbedded quartz arenites and sandy shales. This unit is 50 m thick (79–129 m) although above 112 m the mud content falls off. The quartz arenites are in beds of < 15–60 cm and are largely structureless, although hints of cross-bedding do occur. The sandy shales comprise mudstones (now slaty) with lenticular sand bodies up to a few centimetres thick and traces of ripple lamination. In some places, mud drapes were observed on foreset laminae. The formation is capped by a 14 m thick massive quartz arenite that is structureless and virtually unbedded.

Boundaries. North of Målebjerg, in the type section on the north side of the ice-dammed lake in Gemmedal (Fig. 8), the Slottet Formation lies unconformably on gneisses of probable Palaeoproterozoic age. However, a few hundred metres farther north the gneisses are overlain by a lenticular tillite unit with a maximum thickness of 31 m (Figs 9A, 10). The unit contains two beds of diamictite separated and overlain by platy quartzites, phyllites and semi-pelites. This unit can be seen to gradually wedge out southwards, and occupies a hollow on a peneplaned surface of basement gneisses. The lower part of the lower diamictite bed (1.4 m) comprises clast-supported pebbles and cobbles resting on sheared granitic gneiss, but within 30 cm there is a gradation up into matrix-supported diamictites. The matrix is composed of fine sand which in places is micaceous and phyllitic. The upper diamictite bed is up to 7.6 m thick, but thickens and thins markedly along strike. The clasts are dominated by fine- to coarse-grained granitic lithologies but also include metasandstones and carbonates, with the latter up to 6 × 1.5 × 1 m in size. The unit is considered to be of Varanger age and is disconformably overlain by the Slottet Formation.

Distribution. The Slottet Formation occurs around the margins of the Eleonore Sø and Målebjerg tectonic windows. Within the Eleonore Sø window, the formation is present in J.L. Mowinckel Land, Arnold Escher Land and around Eleonore Sø itself, and in the Målebjerg area it crops out on either side of the N–S-trending glacier that bisects the window.

Fauna and age. The Slottet Quartzite is characterised by the presence of *Skolithos* burrows that attain lengths of several tens of centimetres (Fig. 9B). The first unequivocal appearance in the type section is at the base of the rusty weathering unit (79 m), but more equivocal examples are present as low as 45 m. As noted in the discussion of the Kap Holbæk Formation, the presence of deep *Skolithos* indicates an age for the unit that is no older than Tommotian (mid-Early Cambrian).

Målebjerg Formation

new formation

History. Katz (1952) recognised and mapped a carbonate unit above his 'Slottet quartzite' in the eastern Eleonore Sø region, but considered it to represent mylonitised Eleonore Bay Supergroup. In the 1997–1998 field seasons it was recognised that the carbonate unit, although highly strained, conformably overlies the Slottet Formation and lies in the footwall of the thrust that bounds the Eleonore Sø and Målebjerg windows (Leslie & Higgins 1998; Smith & Robertson 1999b).

Name. Named after the mountain Målebjerg, which lies immediately to the south of the type section.

Type section. The type section of the Målebjerg Formation is a continuation of the Slottet Formation type section, on the northern side of the ice-dammed lake in Gemmedal, north of Målebjerg (Fig. 10). A better exposed, but less accessible, reference section is present on a nunatak (73°41′N, 28°40′W) south of J.L. Mowinckel Land, within the Eleonore Sø window.

Thickness. In the type section (Fig. 10), 32 m of sediment are preserved beneath the thrust that terminates the section. In the reference section, the formation is 45 m thick, and a similar thickness is present wherever it crops out within the Eleonore Sø window.

Lithology. In both of the measured sections, the Slottet Formation is overlain by 1.5 m of sandy dolostones. In the type section the next 20 m are poorly exposed, but dark grey weathering medium grey dolostones and pale grey weathering pale grey dolostones with current lamination were observed. The uppermost 9 m comprise buff-weathering, parallel laminated dolostones (Fig. 10) interbedded with dark grey limestones with buff dolomite burrow fills. In places these can be seen to be shallowing-upward, subtidal burrow-mottled limestone – peritidal dolostone cycles similar to those that commonly occur elsewhere in the Laurentian Cambrian–Ordovician.

In the reference section in J.L. Mowinckel Land, the basal sandy dolostones become progressively less sandy upwards; parallel lamination and ripple lamination with dolomitic mud drapes are present. This unit is overlain by 3.5 m of dolostones in which 2–3 cm beds of fine-grained dolostone alternate with 0.5 cm beds of coarser, sand-grade, dolomite. The latter are parallel laminated and low amplitude ripples are also developed. From 5–20 m, massive buff-weathering pale grey dolostones occur in beds up to 2.5 m thick. For the most part these beds are structureless but traces of burrow-mottling are present in places, as are fenestral, laminated dolostones and current lamination. More thinly bedded dolostones make up the interval from 20–40 m; these are predominantly structureless or current laminated, and extensively veined with quartz and carbonate. The uppermost 5 m comprise dark, burrow-mottled limestones with buff burrow fills that become increasingly strained and mylonitised towards the thrust that terminates the section.

Boundaries. In both sections, the basal sandy dolostones overlie the Slottet Formation with no angular discordance and the succession is truncated by the thrust that bounds the tectonic windows.

Distribution. As with the Slottet Formation, the carbonate unit is restricted to the margins of the Eleonore Sø and Målebjerg windows. However, because it is markedly thinner and less resistant to weathering it crops out less frequently.

Fauna and age. There is, to date, no fauna recorded from the Målebjerg Formation, although its tectonic context and the presence of bioturbation in the form of burrow-mottling, together with its conformable boundary with the underlying Slottet Formation, suggest a Cambrian–Ordovician age.

Fjord region 71°36′–74°17′N

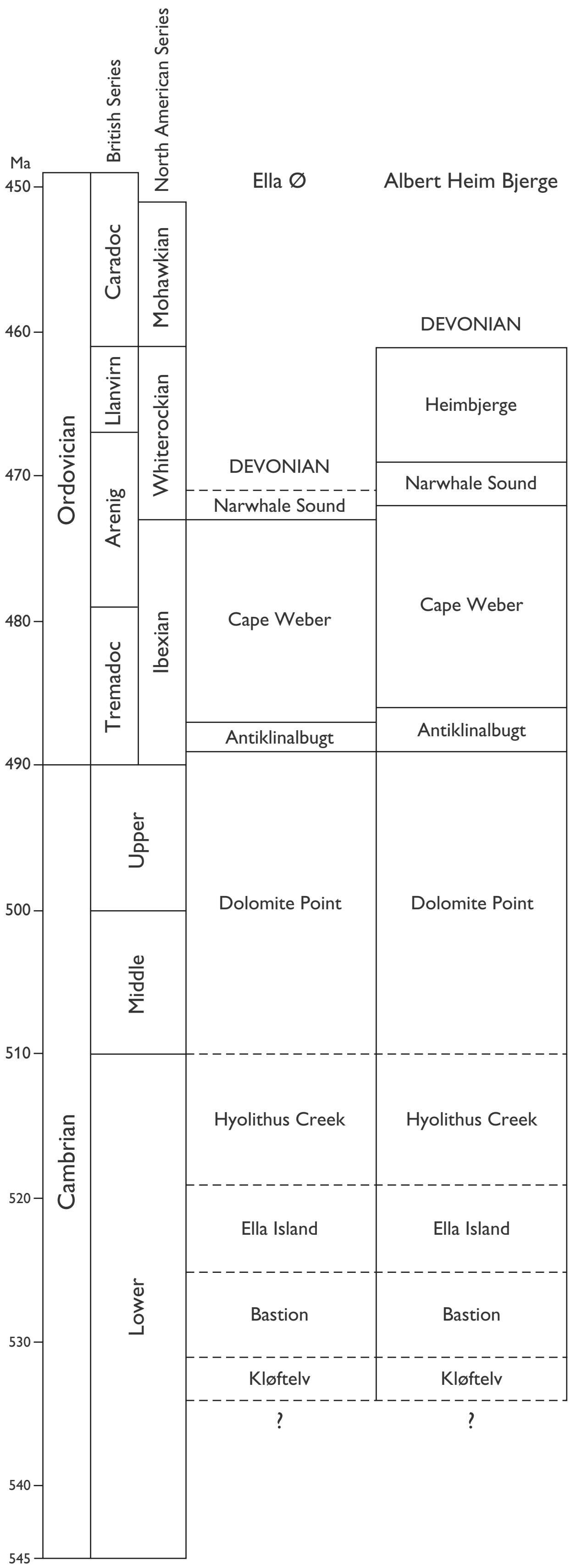
The presence of Cambrian–Ordovician sediments within the outer fjord region of North-East Greenland (71°36′–74°17′N; Fig. 8) has been known since the early work of Lauge Koch and Christian Poulsen. Their good exposure and relative ease of access has resulted in more research than areas to the north (for reviews see Cowie & Adams 1957; Henriksen & Higgins 1976; Smith & Bjerreskov 1994; Stouge *et al*. 2001). The tectonic setting has, however, remained rather more enigmatic since, although clearly incorporated within the Caledonian orogen, the units are relatively undeformed. Mapping of the underlying Eleonore Bay Supergroup in 1997–1998 has clarified this relationship, and it is now apparent that the Lower Palaeozoic rocks of the fjord region are part of the highest level thrust sheet in this sector of the orogen, and have been transported several hundreds of kilometres from the east-south-east (Smith & Robertson 1999a, b; Higgins & Leslie 2000; Higgins *et al*. 2004a) before involvement in syn- to post-orogenic collapse (Hartz & Andresen 1995; Andresen *et al*. 1998).

The Cambrian–Ordovician formations are here incorporated within the newly erected Kong Oscar Fjord Group (Fig. 11).

Kong Oscar Fjord Group

new group

History. Recorded observations of the Lower Palaeozoic rocks of the fjord region extend back to Karl Koldewey's expedition of 1869–1870 when Palaeozoic sediments similar to the 'Hekla Hoek Formation' of Spitsbergen were documented (Toula & Lenz 1874). Palaeontological confirmation of this stratigraphical determination came from A.G. Nathorst's expedition of 1899, which re-visited Kejser Franz Joseph Fjord and recovered 'Silurian' and Devonian fossils (Nathorst 1901). The Lower Palaeozoic was further examined by the Cambridge expedition of 1926 under the leadership of J.M. Wordie (Wordie 1927), and in the same year Lauge Koch led the first of a series of expeditions that were to make a major impact on the understanding of East Greenland Caledonian geology. The latter expeditions continued until 1958 with breaks only for the war years. Towards the end of this programme, P.J. Adams and J.W. Cowie carried out a detailed investigation of the Lower Palaeozoic, and the ensuing monograph (Cowie & Adams 1957) remains a key publication. K. Swett and co-workers carried out some sedimentological work in the early 1970s, including comparisons with coeval successions in north-east Spitsbergen and north-west Scotland (e.g.



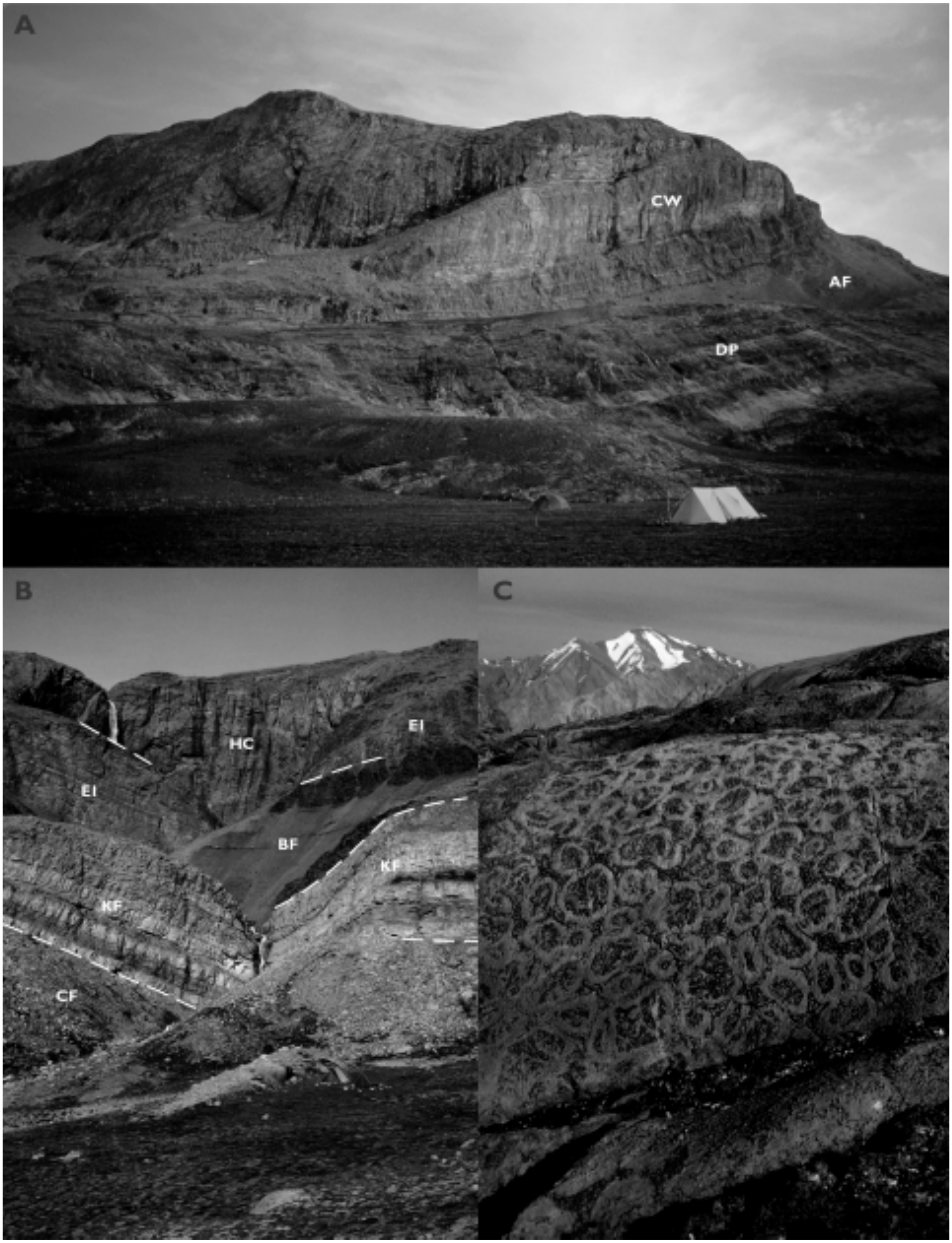
Swett & Smit 1972). Extensive logging and sample collecting for conodont work was carried out by P. Frykman in 1977, and by M.P. Smith and J.S. Peel in 1988. This has resulted *inter alia* in a refinement of biostratigraphical constraints, particularly in the Late Cambrian – Ordovician part of the group (Smith 1985, 1991; Smith & Bjerreskov 1994; Huselbee 1998). Additional field work has been carried out in the succession by Stouge *et al.* (2001, 2002), and documentation of Early Cambrian small shelly faunas was undertaken, with subsequent biostratigraphic refinements, by Skovsted (2003).

Name. Named after Kong Oscar Fjord, at the head of which lies the island of Ella Ø with the most easily accessible and most studied outcrops of the group (Fig. 12A).

Type area. In view of the above, the most suitable type area is Ella Ø. Important reference areas, which contain the only complete sections through the two youngest formations, are present in the north of the outcrop belt at Albert Heim Bjerge and C.H. Ostenfeld Nunatak (Fig. 8; Cowie & Adams 1957; Frykman 1979; Hambrey *et al.* 1989; Smith 1991; Smith & Bjerreskov 1994; Stouge *et al.* 2002).

Thickness. On Ella Ø, the group is 2625 m thick (Cowie & Adams 1957; Smith & Bjerreskov 1994) including a revised thickness of 1161 m for the Cape Weber Formation (Smith 1991). The upper part of the group thickens northwards (and perhaps also eastwards), and Frykman (1979) recorded an apparently unfaulted thickness of 1750 m for the Cape Weber Formation on C.H. Ostenfeld Nunatak. In addition, Frykman (1979) estimated a thickness of 1200 m for the Heimbjerge Formation on C.H. Ostenfeld Nunatak, rather than the maximum 320 m recorded beneath Devonian red beds on Albert Heim Bjerge (Cowie & Adams 1957). The Kong Oscar Fjord Group in the northernmost part of

Fig. 11. Correlation chart of units within the Kong Oscar Fjord Group on Ella Ø and Albert Heim Bjerge, showing component formations of Upper Cambrian – Ordovician age. The age of the base of the Kløftelv Formation is uncertain. The absolute ages of chronostratigraphic boundaries are compiled from Tucker & McKerrow (1995), Cooper (1999) and Encarnacíon *et al.* (1999). Stratigraphic dates for the unit boundaries are based on Henriksen & Higgins (1976), Pickerill & Peel (1990), Smith & Bjerreskov (1994) and Huselbee (1998).


A
CW
AF
DP
B
HC
EI
EI
BF
KF
KF
CF
C

the outcrop belt is thus likely to be around 4500 m thick, its maximum within the region.

Dominant lithology. The lower part of the group (Kløftelv Formation and Bastion Formation) is dominated by quartz arenites that fine upwards into glauconitic sandstones, and sandy micaceous and ferruginous shales. Clastic supply wanes in the upper Bastion Formation, and the remainder of the group is carbonate-dominated. The Ella Island Formation is limestone-dominated, but the succeeding two units, the Hyolithus Creek Formation and Dolomite Point Formation, are dolostone-dominated.

The Ordovician units comprise an alternation of thick, pale grey, homogeneous subtidal limestones (Cape Weber Formation and Heimbjerge Formation), with more thinly bedded units in which subtidal or subtidal–peritidal shallowing-upwards sequences are developed on the scale of 1–5 m (Antiklinalbugt Formation and Narwhale Sound Formation). Significant developments of thrombolitic–stromatolitic reefs are present in the basal part of the Antiklinalbugt Formation on Ella Ø (Fig. 12C) and the lower 100 m of the Cape Weber Formation on Albert Heim Bjerge and C.H. Ostenfeld Nunatak (Hambrey *et al.* 1989; Stouge *et al.* 2001).

Boundaries. The Kong Oscar Fjord Group overlies the Tillite Group. At outcrop scale, the boundary appears to be sharp but conformable. However, northwards along strike the uppermost unit of the Tillite Group, the Spiral Creek Formation (maximum thickness 55 m) wedges out and the Kløftelv Formation rests on the underlying Canyon Formation (Fig. 12B; Hambrey & Spencer 1987; Hambrey *et al.* 1989). It is thus probable that a regional hiatus and/or low angle unconformity is present at the base of the Kløftelv Formation.

Stouge *et al.* (2001, 2002) inferred the presence of a significant disconformity or condensed interval at the Antiklinalbugt Formation – Cape Weber Formation boundary. The Antilklinalbugt Formation contains early Ibexian macro- and microfaunas, and a cephalopod identified as ?*Cyptendoceras* sp. indet. recovered from the basal beds of the Cape Weber Formation was considered to be of late Ibexian age. Together with the absence of a middle Ibexian macrofauna, this evidence was used to invoke the presence of a disconformity or condensed interval spanning the middle Ibexian. However, closely spaced conodont samples throughout the interval from the upper Dolomite Creek Formation to the top of the Cape Weber Formation (Smith 1985, 1991; Huselbee 1998) demonstrate that there is a complete succession, and that there is no significant disconformity or condensed interval present.

The upper part of the group is cut by the Caledonian erosion surface, and is overlain by Devonian molasse of the Kap Kolthoff Group. On Ella Ø, the erosion level is within the middle part of the Narwhale Sound Formation, and on Albert Heim Bjerge it cuts through the lower part of the Heimbjerge Formation, whereas on C.H. Ostenfeld Nunatak a much thicker section in the latter unit is preserved. Complete sections through the Narwhale Sound Formation and the overlying Heimbjerge Formation are thus present only in the northern part of the outcrop belt.

Distribution. The group is present in a narrow belt that extends from Canning Land (71°36′N) through the fjord region to C.H. Ostenfeld Nunatak (74°17′N), and is confined to the Franz Joseph allochthon. The main outcrop forms part of the Neoproterozoic–Ordovician division shown in Fig. 8; the detached outcrops on Canning Land lie 90 km east-south-east of the south-east corner of Fig. 8.

Geological age. Early Cambrian – Upper Whiterockian (Middle Ordovician – upper Llanvirn *sensu* Fortey *et al.* 1995).

Subdivision. The Kong Oscar Fjord Group contains nine formations: Kløftelv Formation, Bastion Formation, Ella Island Formation, Hyolithus Creek Formation, Dolomite Point Formation, Antiklinalbugt Formation, Cape Weber Formation, Narwhale Sound For-

Facing page:
Fig. 12. **A**: The Kong Oscar Fjord Group on Ella Ø, showing Upper Cambrian – Ordovician formations. **AF**, Antiklinalbugt Formation; **CW**, Cape Weber Formation; **DP**, Dolomite Point Formation. The highest summit visible is 500 m above the tent in the foreground. **B**: The Kong Oscar Fjord Group on Albert Heim Bjerge, showing Lower Cambrian formations, with the lowermost Kløftelv Formation (**KF**) unconformably overlying the Neoproterozoic Canyon Formation (**CF**) of the Tillite Group. **BF**, Bastion Formation; **EI**, Ella Island Formation; **HC**, Hyolithus Creek Formation. Tent at lower right for scale. The height of the profile is *c*. 600 m. **C**: Thrombolitic–stromatolitic reefs in the basal part of the Antiklinalbugt Formation on Ella Ø. The oval to rounded thrombolites are about 25 cm in diameter.

mation and the Heimbjerge Formation (Fig. 11). The Cambrian–Ordovician boundary occurs within the uppermost part of the Dolomite Point Formation (Miller & Kurtz 1979; Huselbee 1998).

The Lower Palaeozoic units of the East Greenland foreland, observed in the parautochthonous setting of the Eleonore Sø and Målebjerg tectonic windows (Slottet Formation and Målebjerg Formation formally erected above), are specifically excluded from the group because of the significantly different depositional context, located high on the craton in an attenuated Neoproterozoic – Lower Palaeozoic succession.

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The Neoproterozoic Rivieradal Group of Kronprins Christian Land, eastern North Greenland

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The Rivieradal Group, formally defined here, is confined to the Vandredalen thrust sheet of the Caledonian orogen in Kronprins Christian Land, eastern North Greenland. It comprises a succession of Neoproterozoic siliciclastic sediments that represent the fill of a half-graben basin. The syn-rift Rivieradal Group is overlain by post-rift sediments of the Hagen Fjord Group. The latter succession is present in both the thrust sheet and the Caledonian foreland to the west. In the foreland, where the Rivieradal Group is not represented, the Hagen Fjord Group disconformably overlies Palaeoproterozoic–Mesoproterozoic sandstones of the Independence Fjord Group.

Keywords: Caledonian, North Greenland, Precambrian, Proterozoic, stratigraphy

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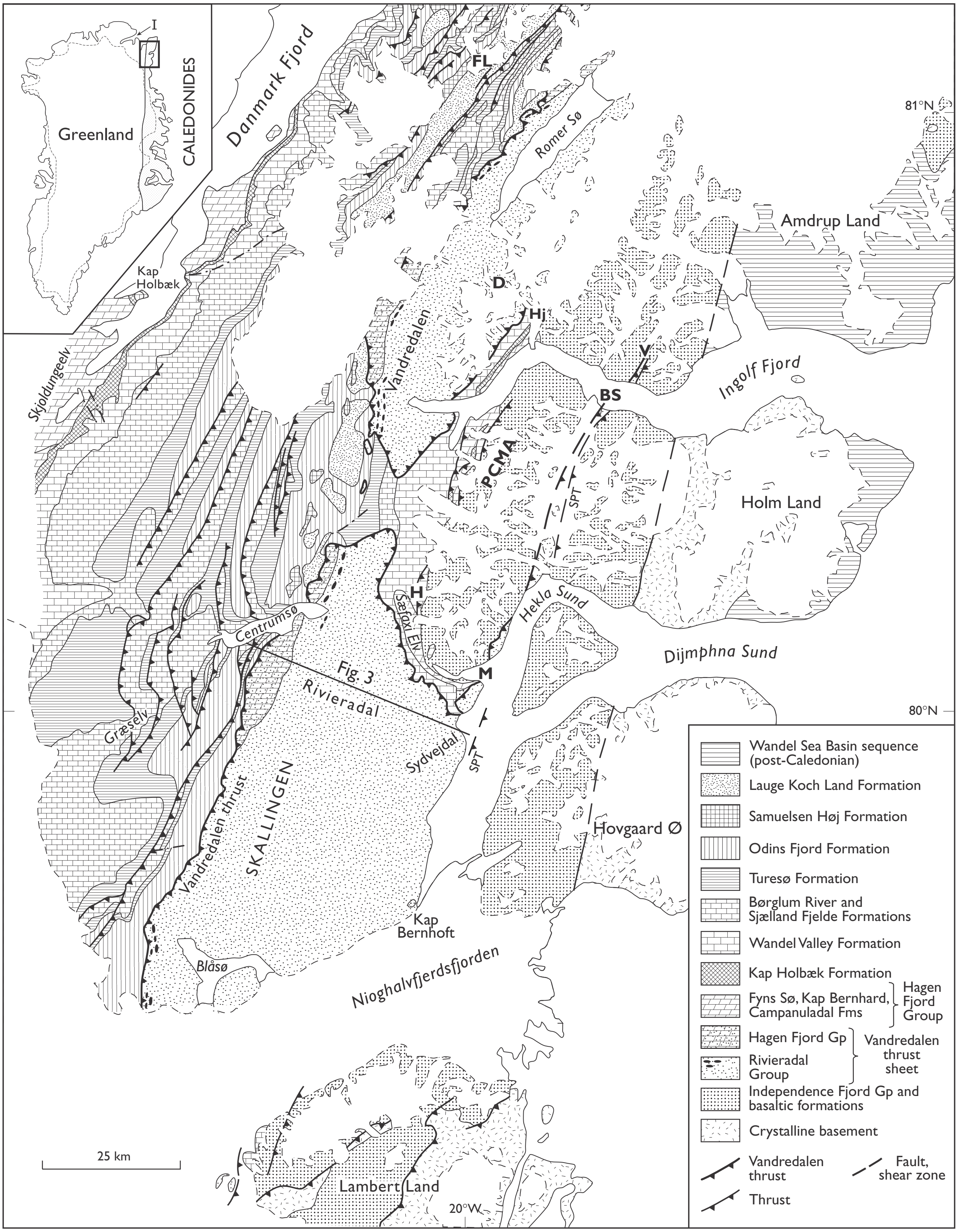
Kronprins Christian Land lies at the northern termination of the East Greenland Caledonides, and constitutes a key area for studies of the western border zone of the orogen (Fig. 1). This region exposes continuous sections from the undisturbed foreland in the west, across parautochthonous foreland affected by folding and thin-skinned thrusting to allochthonous thrust sheets in the east (Higgins *et al.* 2001a, b). The foreland comprises three principal lithostratigraphical divisions: (1) Palaeoproterozoic–Mesoproterozoic sandstones of the Independence Fjord Group, the Mesoproterozoic Zig-Zag Dal Basalt Formation and associated dolerites (Midsommersø Dolerite Formation); (2) Neoproterozoic shallow marine sediments of the Hagen Fjord Group (Sønderholm & Jepsen 1991); (3) Cambrian–Silurian shelf sediments of the Franklinian Basin (Higgins *et al.* 1991). The Hagen Fjord Group is also represented within the allochthon, in the Vandredalen thrust sheet, where it overlies the clastic sediments of the Rivieradal Group, which are the subject of this paper.

In Kronprins Christian Land the parautochthonous Lower Palaeozoic sediments lie in the foot wall of the Vandredalen thrust sheet, and are deformed by a series of thin-skinned thrusts that constitute a duplex below the Vandredalen thrust (Figs 1, 2). This parautochthonous area extends as a 30–50 km wide belt to the west of the 200 km long, N–S-trending Vandredalen thrust front. The Vandredalen thrust displays a classical staircase trajectory with very long (20+ km) flats developed in dolomitic horizons, and ramps developed in the more resistant subtidal carbonate units of the Franklinian Basin succession (cf. Smith *et al.* 2004, this volume). The thrust roots to the east along the Spærregletscher – Hekla Sund lineament and has a total westward displacement estimated at *c.* 40 km, of which *c.* 18 km are taken up in the thin-skinned parautochthonous belt (Higgins *et al.* 2001b, 2004). The


Greenland
CALEDONIDES
I
Kap Holbæk
Danmark Fjord
FL
Romer Sø
81°N
Amdrup Land
D
Hj
Vandredalen
V
Ingolf Fjord
BS
Skjoldungeelv
PCMA
SPT
Holm Land
H
Sæfaxi Elv
Hekla Sund
Centrumsø
Dijmphna Sund
Fig. 3
M
Rivieradal
80°N
Græselv
Sydvejdal
SPT
SKALLINGEN
Vandredalen thrust
Hovgaard Ø
Kap Bernhoft
Blåsø
Nioghalvfjerdsfjorden
25 km
Lambert Land
20°W
Wandel Sea Basin sequence (post-Caledonian)
Lauge Koch Land Formation
Samuelsen Høj Formation
Odins Fjord Formation
Turesø Formation
Børglum River and Sjælland Fjelde Formations
Wandel Valley Formation
Kap Holbæk Formation
Fyns Sø, Kap Bernhard, Campanuladal Fms
Hagen Fjord Group
Hagen Fjord Gp
Rivieradal Group
Vandredalen thrust sheet
Independence Fjord Gp and basaltic formations
Crystalline basement
Vandredalen thrust
Fault, shear zone
Thrust

Vandredalen thrust sheet, in turn, is structurally overlain by a thrust sheet that transported Palaeoproterozoic to Mesoproterozoic clastic and volcanic rocks westwards. The allochthonous quartzites have traditionally been viewed as equivalents of the Independence Fjord Group on the foreland (see Figs 1, 2), but SHRIMP isotopic studies on rhyolites interbedded with the quartzites that yielded an age of 1740 Ma (Kalsbeek *et al.* 1999) have cast some doubt on this interpretation (see also Pedersen *et al.* 2002). Still farther to the east, higher thick-skinned thrust sheets incorporate crystalline basement gneisses.

This paper provides a formal stratigraphic basis, at group level, for the rocks that underlie the Hagen Fjord Group within the Vandredalen thrust sheet, and collates available field data regarding this succession. As noted below, formal definition of the constituent formations awaits more detailed field analysis of the Rivieradal Group. The informal units of Fränkl (1954, 1955) were found to be generally usable as field divisions, although there is uncertainty in places about their correlation.

Stratigraphy of the Vandredalen thrust sheet

Restoration of the displacement associated with the Vandredalen thrust sheet demonstrates that much of the sediment within the thrust sheet was deposited in an east-facing extensional half-graben (Hekla Sund basin) that originally lay immediately to the east of the Spærregletscher – Hekla Sund lineament (Higgins *et al.* 2001b). This basin fill was thrust out of the half-graben and transported westwards on the Vandredalen thrust (Fig. 2). These syn-rift sediments are assigned to the Rivieradal Group, which is formally erected below. They are overlain by sediments of the Hagen Fjord Group, which were deposited during post-rift thermal subsidence and extended westwards beyond the confines of the Hekla Sund basin. The Hagen Fjord Group, in consequence, is present both in the foreland and the hanging wall of the Vandredalen thrust whereas the Rivieradal Group is restricted to the hanging wall (Higgins *et al.* 2001b). The Hagen Fjord Group within the Vandredalen thrust sheet is represented by the Campanuladal, Kap Bernhard and Fyns Sø Formations. The Campanuladal Formation comprises 200 m of variegated sandstones, siltstones and mudstones of generally similar appearance to successions of the same unit in the foreland around Danmark Fjord. A lower, greenish weathering unit containing parallel and trough cross-laminated sandstones, and mudstones with desiccation cracks, is overlain by an upper, dark red weathering unit dominated by calcareous mudstones with some trough cross-bedded sandstones (Jepsen & Sønderholm 1994). The Kap Bernhard Formation comprises brownish red weathering, finely laminated algal limestones and the Fyns Sø Formation contains pale stromatolitic dolostones; both correspond very closely to their counterparts in the foreland.

In the northernmost part of the outcrop area of the Vandredalen thrust sheet, in Finderup Land (Fig. 1), the Fyns Sø Formation is unconformably overlain by sandstones of the Kap Holbæk Formation. This latter unit was included within the redefined Hagen Fjord Group of Clemmensen & Jepsen (1992), but stratigraphic data obtained during the 1994–1995 field seasons demonstrated that a significant hiatus occurs between the two units. In particular, a well-developed palaeokarst horizon developed at the top of the Fyns Sø Formation is infilled by the Kap Holbæk Formation (Smith *et al.* 1999). It is probable that the carbonates of the Fyns Sø Formation are correlatives of similar late Riphean to Sturtian units, which are widely developed in the North Atlantic region, while the presence of deep *Skolithos* burrows in the Kap Holbæk Formation indicates a Lower Cambrian age (Smith *et al.* 2004, this volume). Since the hiatus between the two units probably spans the entire Vendian, Smith *et al.* (2004) proposed that the Kap Holbæk Formation be removed from the Hagen Fjord Group.

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Fig. 1. Geological map of Kronprins Christian Land, eastern North Greenland, and Lambert Land, North-East Greenland. Black oval symbols in the Rivieradal Group, in legend and on map, indicate conglomerates. **BS**, Brede Spærregletscher; **D**, 'Dunkeldal'; **FL**, Finderup Land; **H**, Harefjeld; **Hj**, Hjørnegletscher; **M**, Marmorvigen; **PCMA**, Prinsesse Caroline Mathilde Alper; **SPT**, Spærregletscher thrust; **V**, Vardedalen. On index map: **I**, Independence Fjord. See Figs 2 and 3 for cross-sections along Rivieradal. Modified from Rasmussen & Smith (2001). Note that the traditional interpretation of the allochthonous quartzites as equivalents of the foreland Independence Fjord Group (as depicted here and on Fig. 2), has been brought into doubt by the 1740 Ma age on interbedded rhyolites (see discussion in Kalsbeek *et al.* 1999 and Pedersen *et al.* 2002).

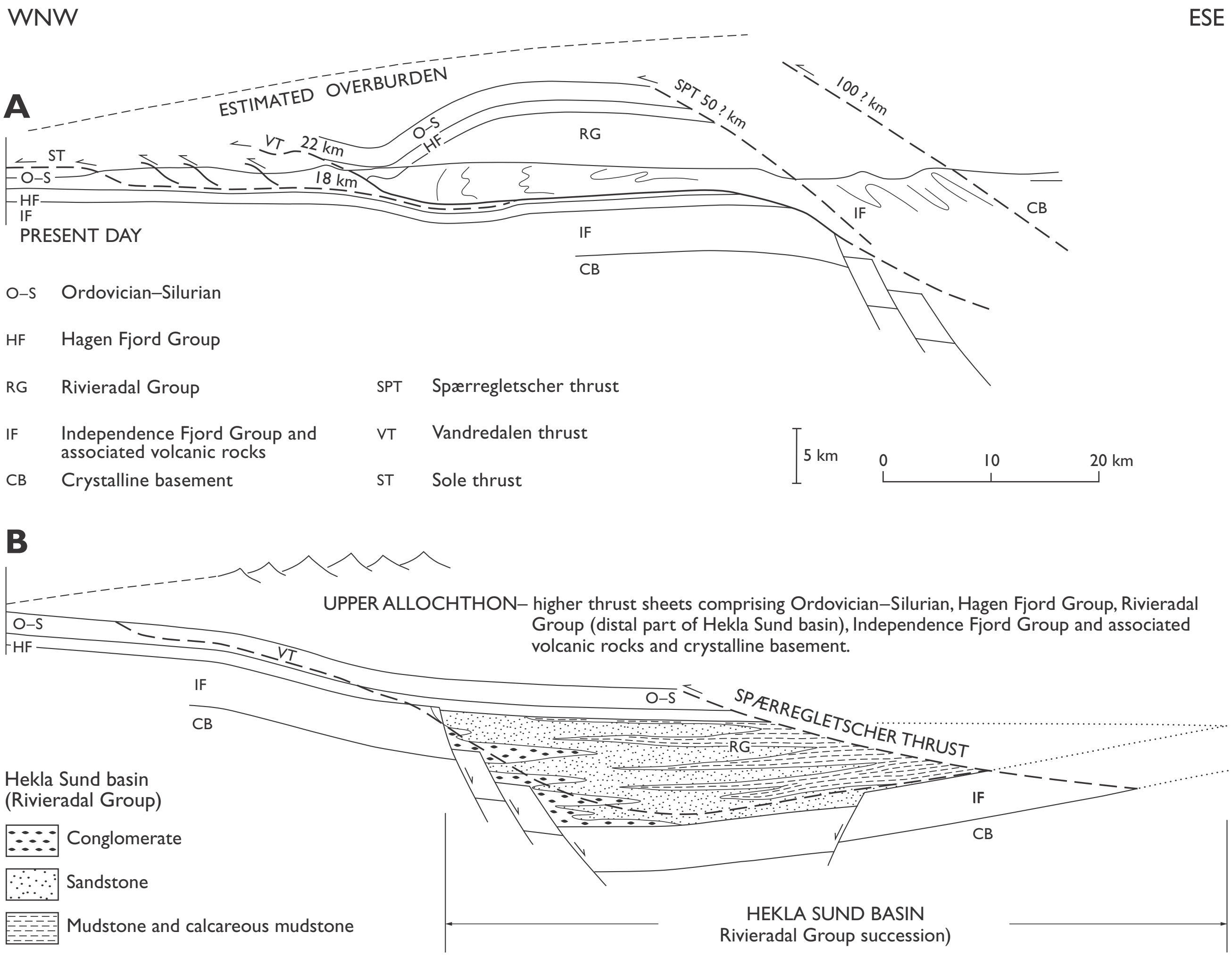


Fig. 2. Schematic NW–SE cross-sections of the Vandredalen rift system, approximately along the section line of Fig. 3 shown on Fig. 1, but with extensions to both south-east and north-west. **A**: Present-day section, with overburden calculated from conodont alteration temperatures (after Rasmussen & Smith 2001). **B**: With displacements on the thrusts restored, illustrating the fault-bounded control of the west margin of the Hekla Sund Basin. Modified from Higgins *et al.* (2001b).

Rivieradal Group

new group

History. The Proterozoic rocks of Kronprins Christian Land were first examined systematically by geologists of Lauge Koch's 1926–1958 expeditions. The region around Danmark Fjord was documented by Adams & Cowie (1953), and that around Centrumsø by Fränkl (1954, 1955). Fränkl recognised that the Neoproterozoic succession could be divided into autochthonous and allochthonous parts, the two separated by a major thrust upon which his 'main nappe' was transported. The metasediments of the nappe were divided into a lower, more metamorphosed part, comprising the Stenørkenen Phyllites (> 1000 m) and the Sydvejdal Marbles (100–400 m), and an upper less metamorphic part. The latter included, from base to top, the Taagefjeldene Greywackes (> 700 m) with a layer of alum shales at the base (*c.* 150 m), the Rivieradal Sandstones (1000–2000 m), the Ulvebjerg Sandstones & Tillites (20–35 m), the red, shaly Campanuladal Limestone and the Fyns Sø Formation. The two last-named units were also identified as lying in the foot wall of the nappe (Fränkl 1954, 1955). The succession present in the 'main nappe' was recognised as having been deposited in a basin located to the east, which Fränkl (1955) termed the 'Hekla Sund Basin'; the latter term is retained here for the depositional basin in which the Rivieradal Group accumulated.

Haller (1961, 1971) erected the Hagen Fjord Group for Proterozoic sediments of the autochthon and allochthon in Kronprins Christian Land, including volcanic rocks now referred to the Zig-Zag Dal Basalt Formation, Hekla Sund Formation and Aage Berthelsen Gletscher Formation, and Lower Cambrian carbonates now referred to the Portfjeld Formation. Clemmensen & Jepsen (1992) restricted the group, following work by the Geological Survey of Greenland in 1978–1980, to include only the Neoproterozoic shallow water carbonate and siliciclastic succession present in the area between Lambert Land and Independence Fjord. Additional formations were also erected by Clemmensen & Jepsen, to improve the stratigraphical framework of the group.

Hurst & McKerrow (1981a, b), on the basis of reconnaissance field work in Kronprins Christian Land in 1980 by the former Geological Survey of Greenland (GGU), concluded that all of the units beneath the Campanuladal Formation within the main thrust sheet were representative of a single unit of deep-water turbidites, mud and resedimented conglomerates; they collectively referred to this succession as the 'Rivieradal sandstones'. Although sedimentological interpretations of the succession have been refined (see below), this is the concept that we here formalise as the Rivieradal Group.

Hurst & McKerrow (1981a, b) and Hurst *et al.* (1985) recognised a number of thrust sheets in the Kronprins Christian Land sector of the East Greenland Caledonides. These included the Vandredalen Nappe (which corresponds to Fränkl's 'main nappe'), the Finderup Land Nappe and the Sæfaxi Elv Nappe. The Finderup Land Nappe was a geographically isolated structure rimming the western edge of the main ice sheet, and a succession that incorporated the Campanuladal, Fyns Sø and Kap Holbæk Formations was recognised. Subsequent regional mapping by GGU in 1994–1995 has demonstrated that the Finderup Land Nappe is a northward continuation of the Vandredalen Nappe (now the Vandredalen thrust sheet) in which only the higher stratigraphic levels are preserved. The Sæfaxi Elv Nappe was considered by Hurst & McKerrow to be a thrust sheet containing allochthonous Early Palaeozoic sediments that were deep-water equivalents of the platform succession, and these were assigned to the Harefjeld Formation by Hurst (1984). However, Rasmussen & Smith (1996) demonstrated that these sediments were highly strained equivalents of the platform succession, and that the lower contact with the underlying Fyns Sø Formation was an unconformity and not a thrust. The 'Sæfaxi Elv Nappe' is thus a succession of parautochthonous foreland carbonates deformed in the foot wall of the Vandredalen thrust, and the concept of an independent thrust sheet (and of the Harefjeld Formation) has been abandoned (Rasmussen & Smith 1996).

Name. The group takes its name from Rivieradal, the E–W-trending valley south-east of Centrumsø that contains the most complete section through the unit (Higgins & Soper 1994, 1995).

Type area and reference sections. The type area for the group is Rivieradal itself, where an excellent reference section through the upper part of the group occurs and the lower part, although highly deformed, is also present. Additional reference sections through parts of the group are available through 'Dunkeldal' (between northern Vandredalen and inner Ingolf Fjord; Fig. 1), and along much of the western side of Vandredalen between the western end of Ingolf Fjord and Romer Sø.

Thickness. Hurst *et al.* (1985) estimated a thickness of 2.5 km for the 'Rivieradal sandstones'. Structural studies in Rivieradal and 'Dunkeldal', carried out during the 1994 and 1995 field seasons, suggest that the combined thickness of the highly deformed lower part of the Rivieradal Group and the less deformed upper part is substantially higher, in the order of 7.5–10 km (Higgins *et al.* 2001b).

Lithology, facies associations and depositional environments. The sedimentological and stratigraphical variations within the Rivieradal Group should be viewed in the context of the internal structure of the Vandredalen thrust sheet, which is best exposed in the 35 km long section along Rivieradal between the thrust sheet front at the east end of Centrumsø and its trailing edge near Marmorvigen (Fig. 3). The western frontal region of the thrust sheet is characterised by simple, large-scale folds developed in the Fyns Sø and Kap Bernhard Formations; these overlie the Rivieradal Group sediments, which are well exposed throughout the valley of Rivieradal. Steep to vertical dips characterise much of the western third of the section, with occasional west-facing fold pairs showing flat common limbs. The central third of the section begins with an abrupt change to tightly developed folds, which become progressively more intense eastwards with the inclination of the axial surfaces decreasing from moderate eastward dips to almost horizontal. In the eastern third of the section deformation is intense with complete erasure of sedimentary way-up indicators in long-limbed isoclinal folds; the units exposed here correspond to the most distal parts of the Rivieradal Group.

The fold style and orientation of strata in the Rivieradal section suggest that the Vandredalen thrust follows a series of ramps and flats, and can be viewed as sampling an oblique segment of the half-graben Hekla Sund Basin in which the Rivieradal Group accumulated. The oldest and most distal parts of the succession are therefore preserved in the eastern part of the thrust sheet, and the younger and more proximal lithofacies are present in the west. The present-day distribution of remnants of the Rivieradal Group succession indicates that the original Hekla Sund Basin must have been at least 200 km long from north to south and 50 km wide from east to west.

The Rivieradal Group is lithologically variable and possesses a strong proximal to distal polarity. One of the most distinctive lithologies present is a coarse conglomerate, which occurs repeatedly along the leading edge of the Vandredalen thrust sheet. Substantial conglomerate units are present in three discrete areas (Fig. 1). The northernmost is along a 15–20 km strike section on the west side of Romer Sø, the second is a 20 km long strike section on the west side of central Vandredalen, and the southernmost is found in southern Skallingen near Blåsø.

The best known of the conglomeratic successions is that in central Vandredalen where several thick sections have been measured. Quartzite clasts (90–95%) dominate everywhere over dolerite clasts (5–10%), and are probably derived from the Independence Fjord Group and the Midsommersø Dolerite Formation; these units are presumed to have been exposed to active erosion to the west of the basin. Clasts vary in size from a few decimetres to well over a metre in the thicker beds, with occasional outsize clasts as much as 3–4 m across; these large clasts are indisputably proximal. Viewed from a distance, the thick conglomerate units appear to have a lensoid form, suggesting deposition in a series of nested channels.

In E–W valley sections to the west of Romer Sø, rapid lateral facies changes are well exposed. Thick conglomerate-dominated units pass eastwards, over a

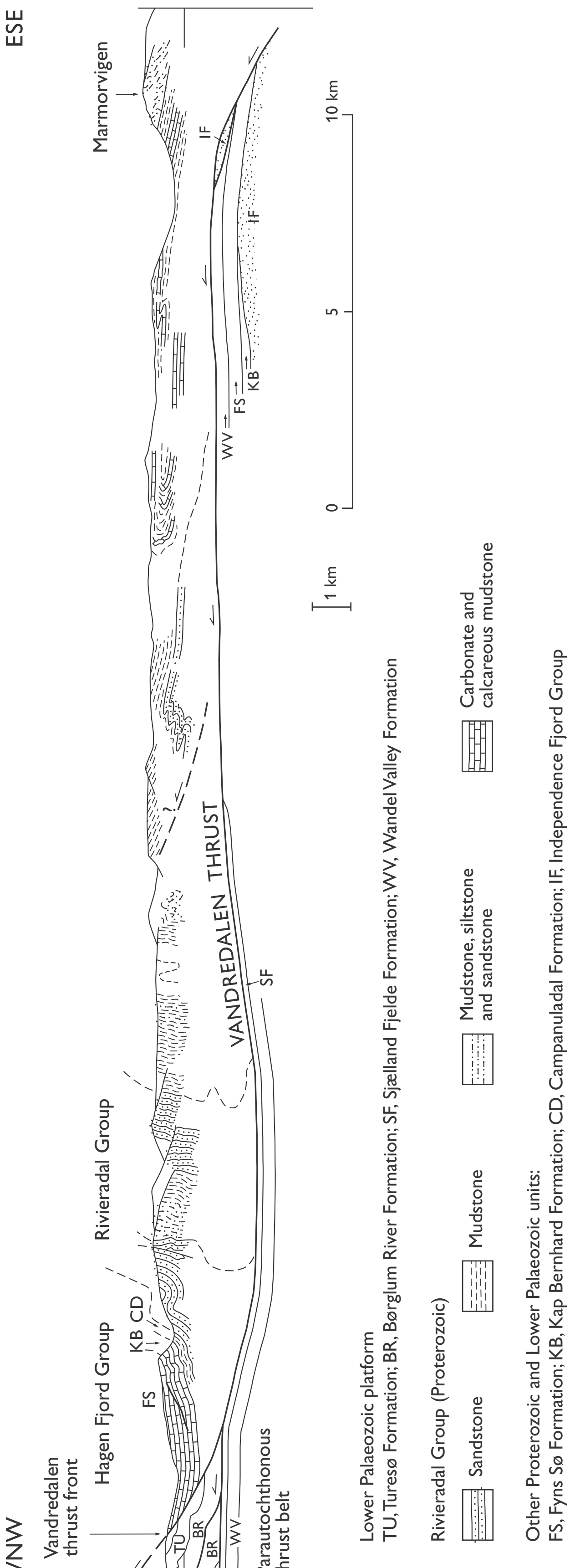


Fig. 3. Cross-section through the Vandredalen thrust sheet along Rivieradal. See Fig. 1 for section line. Modified from Higgins *et al.* (2001b).

distance of 1–2 km, into upward-thickening packets of sandstone in which the individual beds coarsen upwards, sometimes into conglomerate. These in turn pass farther eastwards, over a similar distance, into upward-thickening and coarsening mudstone-siltstone-sandstone packets.

In the southern area of conglomerates near Blåsø, rounded granite and quartz pebbles (up to 20%) make an appearance, although most clasts are again quartzite and dolerite; a deeper erosion level was evidently reached in the southern source region.

The geometry of the conglomerate deposits, together with their discrete occurrences, suggests the presence of three discrete fan delta systems that acted as major feeder distributary systems on the western side of the original basin. While the three main conglomerate developments are all in the upper part of the Rivieradal Group succession, they may not be at exactly the same stratigraphical level. Input might have been via a single major fluvial system, which varied in position with time, and if so the Blåsø fan delta with its crystalline clasts may be the youngest of these. The repeated cycles of conglomeratic deposition, and the upward-coarsening sandstone cycles in other areas at the frontal part of the thrust sheet, may have been controlled by displacements on the basin-margin fault system.

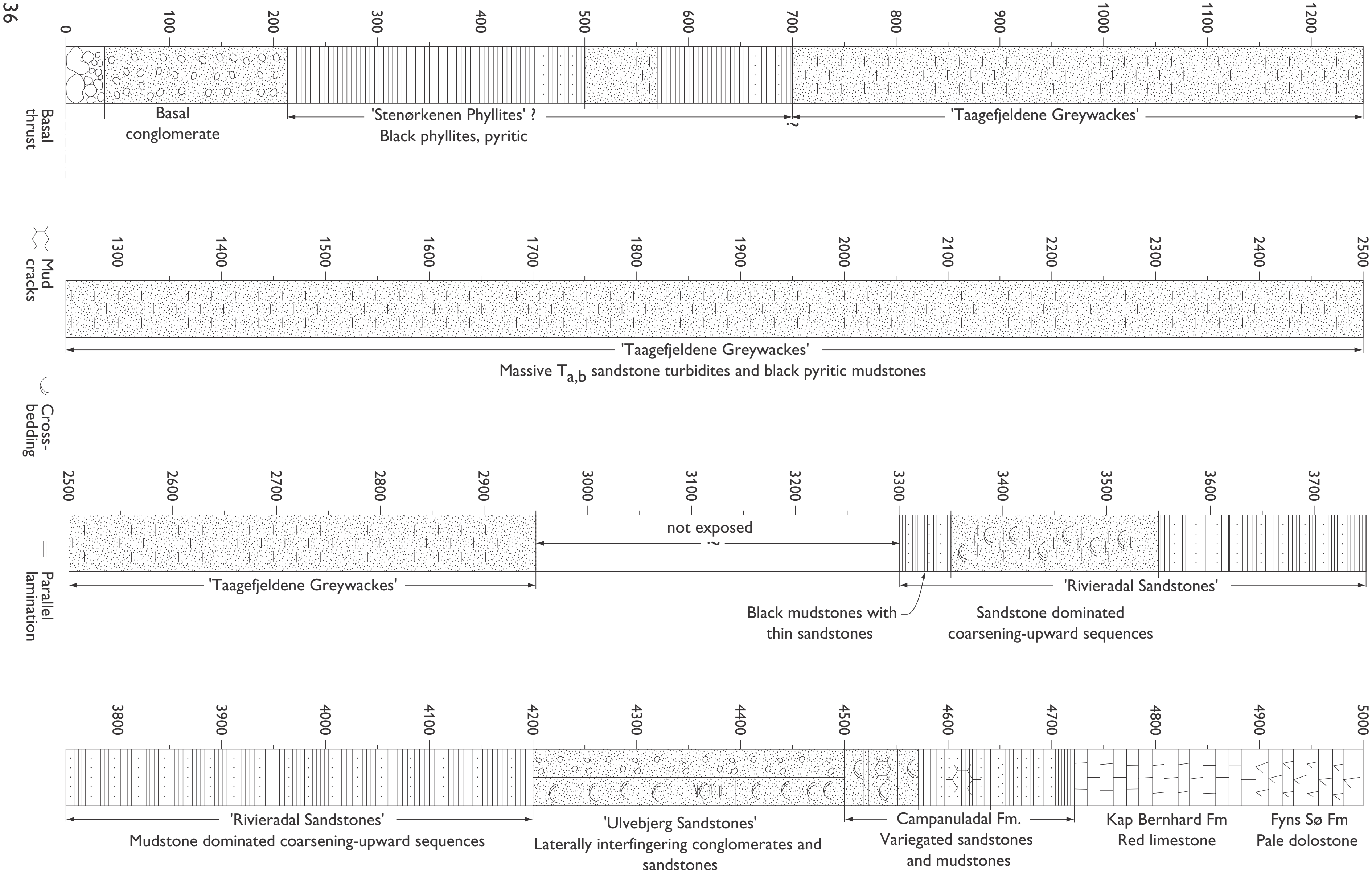
In 'Dunkeldal', a valley on the east side of Vandredalen, a total thickness of 3000 m has been measured in a continuously exposed section (lower part of measured section in Fig. 4). The basal 200 m of this section lie above a thrust contact with Ordovician carbonates, and comprise strongly sheared conglomerates. The conglomerates are overlain by a 500 m thick phyllite-dominated unit ('Stenørkenen Phyllites' of Fränkl 1955), and then by over 2200 m of sandstone turbidites interbedded with dark pyritic mudstones ('Taagefjeldene Greywackes' of Fränkl). Laterally and vertically, this sandstone-dominated succession grades into homogeneous black mudstones, and equivalent phyllitic rocks, which are widely exposed around the innermost branch of Ingolf Fjord. The lack of marker horizons and non-exposure in the flat valley bottom of Vandredalen makes thickness estimates in these areas difficult; thus the notional gap of 350 m in the measured section of Fig. 4 may in fact correspond to several kilometres of section.

On the west side of Vandredalen, to the north-west of innermost Ingolf Fjord, a 900 m thick succession comprises coarsening-upwards sequences of parallel laminated mudstone, lenticular and wavy-bedded mudstones, sandstone-dominated heterolithic sediments with parallel lamination, trough cross-lamination and hummocky cross-stratification, overlain by trough and planar cross-bedded sandstones with occasional herringbone cross-bedding (upper part of section in Fig. 4). These correspond to the original 'Rivieradal sandstones' of Fränkl (1955). Current directions are predominantly towards the north-east and are interpreted as the products of storm- and tide-dominated shallow marine deposition. This facies association in the upper part of the Rivieradal Group can be recognised throughout the outcrop area, from Romer Sø in the north to Blåsø in the south. On the west side of Vandredalen, the succession of Fig. 4 continues with about 300 m of interfingering conglomerates and sandstones (the 'Ulvebjerg Sandstones and Tillites' of Fränkl – equivalent to the conglomeratic developments described above), which are overlain by sediments referred to the Hagen Fjord Group. The latter shallow marine succession constitutes the post-rift fill of the basin.

The most distal representatives of the Rivieradal Group are seen in the valley of Rivieradal itself. At the eastern end of the valley, pelitic slates with sandstones form the coastal mountains south of the mouth of Rivieradal. These are overlain farther to the west by pelitic and calcareous slates and siltstones with prominent yellow-weathering carbonate units, which correspond to the 'Sydvejdal Marbles with chloritic shales' of Fränkl (1955). This unit is overlain, in turn, by phyllites and turbidites corresponding to those seen in the 'Dunkeldal' section (Fig. 4).

Overall, the Rivieradal Group is characterised by point sources of sediment input which generated substantial conglomerate fan deltas, and which are associated with sandy, proximal turbidites. Between the fans and in the eastern (distal) part of the basin, sedimentation was dominated by mud and calcareous mud. As the basin filled, the depositional style switched from deep to shallow marine, and less localised, more laterally persistent, tidal and storm-dominated deposition began to predominate.

Boundaries. Since the group is restricted to the Vandredalen thrust sheet, the Rivieradal Group is everywhere bounded on its lower surface by the Vandredalen thrust; a stratigraphic base to the group has not been identified within the thrust sheet. The upper boundary of the group is placed where sandstones and laterally equivalent conglomerates are overlain by a characteristic 200 m variegated unit comprising a



Basal thrust
Mud cracks
Cross-bedding
Parallel lamination
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
Basal conglomerate
'Stenørkenen Phyllites' ?
Black phyllites, pyritic
?
'Taagefjeldene Greywackes'
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
'Taagefjeldene Greywackes'
Massive $T_{a,b}$ sandstone turbidites and black pyritic mudstones
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500
3600
3700
not exposed
?
'Taagefjeldene Greywackes'
'Rivieradal Sandstones'
Black mudstones with thin sandstones
Sandstone dominated coarsening-upward sequences
3800
3900
4000
4100
4200
4300
4400
4500
4600
4700
4800
4900
5000
'Rivieradal Sandstones'
Mudstone dominated coarsening-upward sequences
'Ulvebjerg Sandstones'
Laterally interfingering conglomerates and sandstones
Campanuladal Fm.
Variegated sandstones and mudstones
Kap Bernhard Fm
Red limestone
Fyns Sø Fm
Pale dolostone

lower greenish sandstone and mudstone interval overlain by a dark red calcareous mudstone-dominated interval. The greenish sandstone and mudstone interval contains parallel and trough cross-laminated sandstones and abundant desiccation cracks. The variegated unit is identified as the Campanuladal Formation of the foreland and, as in the foreland, is overlain by brownish red weathering microbially laminated limestones of the Kap Bernhard Formation (Fig. 4).

Distribution. The Rivieradal Group is restricted to the Vandredalen thrust sheet, and crops out in a broad zone extending from Romer Sø southwards along Vandredalen; a further broad zone extends from the eastern end of Centrumsø southwards through Rivieradal and Skallingen to Blåsø (Fig. 1). A narrow strip of outcrops, in the hanging wall of the main thrust ramp, extends from Vardedalen (on the north side of central Ingolf Fjord) southwards to Brede Spærregletscher and along the west side of Hekla Sund to Marmorvigen. The southernmost outcrops of the Rivieradal Group are present in nunataks at the westernmost extremity of Lambert Land (Fig. 1).

Geological age. The group is older than the Hagen Fjord Group, specifically the Kap Bernhard and Fyns Sø Formations, thought to be of probable Riphean age (Smith *et al.* 1999). However, Frederiksen (2000) has suggested the Hagen Fjord Group is Sturtian, and equivalent to the Andrée Land Group of the Eleonore Bay Supergroup. The Rivieradal Group post-dates the Independence Fjord Group, Midsommersø Dolerite Formation and Zig-Zag Dal Basalt Formation, all of which are represented by clasts within the conglomeratic units. The dolerites of the Midsommersø Dolerite Formation were originally dated at *c.* 1230 Ma by Kalsbeek & Jepsen (1984), but a recent baddeleyite age on a dolerite of 1380 Ma has been obtained by Upton *et al.* (in press); this provides a maximum age limit for deposition. The Rivieradal Group was thus deposited in the interval between 1380 Ma and ~ 700 Ma.

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Fig. 4. Simplified measured section through part of the syn-rift Rivieradal Group succession, the lower part in 'Dunkeldal', and the upper part from the west side of Vandredalen. The corresponding lithostratigraphical terms of Fränkl (1955) are indicated. The designation '$T_{a,b}$' refers to Bouma cycle intervals in the sandstone turbidites. The Campanuladal, Kap Bernhard and Fyns Sø Formations form part of the post-rift Hagen Fjord Group. Slightly modified from Jepsen & Sønderholm (1994).

G. Vidal (*in* Hurst *et al.* 1985) recorded 'several comparatively well-preserved specimens' of acritarchs from the upper part of the Rivieradal Group which were thought indicative of an upper Proterozoic age. In particular, a single specimen of *Chuaria circularis* was considered to be indicative of an upper Riphean age since, elsewhere in Scandinavia and North America, the species occurs at around 800 Ma. Taken together with the evidence for a conformable upper boundary, this suggests that the Rivieradal Group was deposited in the younger part of the broad age range outlined above.

Subdivision. Fränkl (1954, 1955) recognised five units within the succession now assigned to the Rivieradal Group: 'Stenørkenen Phyllites', 'Sydvejdal Marbles with chloritic shales', 'Taagefjeldene Greywackes' with a layer of alum shales at the base, 'Rivieradal Sandstones', and the 'Ulvebjerg Sandstones and Tillites'.

These units were used as field terms during the 1994–1995 field seasons and proved to be recognisable throughout the area, although this is at least partly because they represent lithological types rather than coherent and homologous stratigraphic units. The 'Stenørkenen Phyllites' are present in Rivieradal and similar phyllites are present throughout the region, although thickness estimates and correlation is hampered by the paucity of marker horizons. Fränkl (1955) estimated a thickness of > 1000 m. The 'Sydvejdal Marbles with chloritic shales' are also present in eastern Rivieradal, and include pelitic and calcareous slates and siltstones with prominent yellow-weathering carbonate units. Fränkl (1955) estimated a thickness of 100–400 m. The 'Taagefjeldene Greywackes' are best seen in the section through 'Dunkeldal' (Fig. 4), where Jepsen & Sønderholm (1994) recorded a thickness of over 2200 m. This compares with Fränkl's (1954, 1955) estimate of > 700 m, of which 150–200 m were alum shales; multicoloured friable shales cover large areas around the head of Ingolf Fjord, and pass laterally (northwards) along Vandredalen into a sandstone-siltstone-mudstone succession. The 'Rivieradal Sandstones' *sensu* Fränkl have a thickness of 1400 m, measured in a section across Skallingen for which no base was present (Leslie & Jepsen 1995), and Jepsen & Sønderholm (1994) measured a thickness of 900 m on the western side of Vandredalen (Fig. 4). Fränkl (1954) estimated a range of 1000–2000 m, which appears to be the right order of magnitude. The 'tillites' of Fränkl's (1954, 1955) 'Ulvebjerg Sandstones and Tillites' unit were relatively soon re-interpreted as non-glacial conglomerate horizons (Haller 1971; Hurst & McKerrow 1981a), and they are one of the most spectacular stratigraphic developments within the group. On the western side of Vandredalen, a sandstone-dominated unit at least 300 m thick can be seen to pass laterally into thick conglomerates up to 500 m thick (Jepsen & Sønderholm 1994). As noted above, three of these major conglomerate developments are present within the region and represent fan deltas that supplied sediment to the basin.

Although these observations indicate that Fränkl's units may in time form the basis for a stratigraphic framework, any formal definition must await more detailed investigation of the Rivieradal Group.

Acknowledgements

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The Caledonian thin-skinned thrust belt of Kronprins Christian Land, eastern North Greenland

A.K. Higgins, N.J. Soper, M. Paul Smith and Jan A. Rasmussen

Kronprins Christian Land in the extreme north of the East Greenland Caledonides, exposes a thin-skinned thrust belt up to 50 km wide developed in Ordovician–Silurian platform limestones and dolostones of the Iapetus passive margin. This thrust belt is characterised by a series of SSW–NNE-trending and east-dipping Caledonian thrusts with westward displacements of generally a few kilometres each. It passes westwards into undisturbed autochthonous foreland. Based on a line and area restoration, total displacement along a well-exposed WNW–ESE section through the thrust belt amounts to 17.6 km, which represents a shortening of 45% in the line of section. Biostratigraphic control in the limestone and dolostone succession is based on conodonts and macrofossils. The alteration colours of the conodonts provide estimates of maximum burial temperatures, which show that the thickness of the overlying thrust sheets ranged from about 6 to 12.5 km from west to east across the thrust belt. Since the estimated former thickness of the Vandredalen thrust sheet above the thin-skinned parautochthonous thrust belt is insufficient to yield the temperatures attained, higher thrust sheets must once have extended across the region.

Keywords: Caledonides, conodonts, Greenland, Ordovician, thrust tectonics

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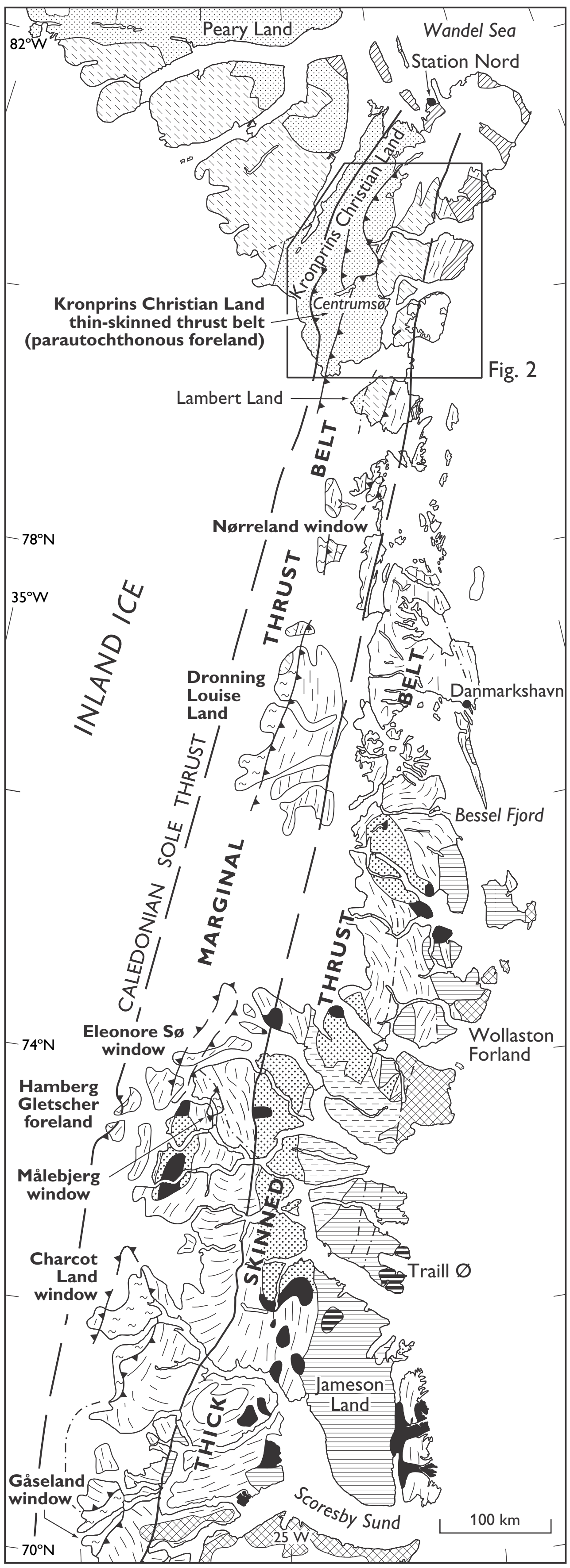
The East Greenland Caledonides extend for 1300 km along the coastal region of East Greenland between latitudes 70° and 82°N, in a belt up to 300 km wide. It can be broadly divided into an eastern thick-skinned thrust belt, and a western marginal thrust belt that in places is thin-skinned (Fig. 1). The western marginal thrust belt is characterised by the presence of foreland windows, in most of which a thin Lower Palaeozoic sequence is preserved beneath the bordering thrusts demonstrating that the thrusting episode is post-Ordovician (Higgins *et al.* 2001a). The thrust sheets overlying the foreland windows incorporate substantial units of reworked basement gneisses, derived from the thick-skinned thrust belt to the east. The Greenland Inland Ice obscures the western parts of the marginal thrust belt along most of its length, and the transition between the Caledonian orogenic belt and the autochthonous foreland is only completely exposed in Kronprins Christian Land (79°30′–82°N). Here the transition zone takes the form of a thin-skinned parautochthonous thrust belt, which is the subject of this paper.



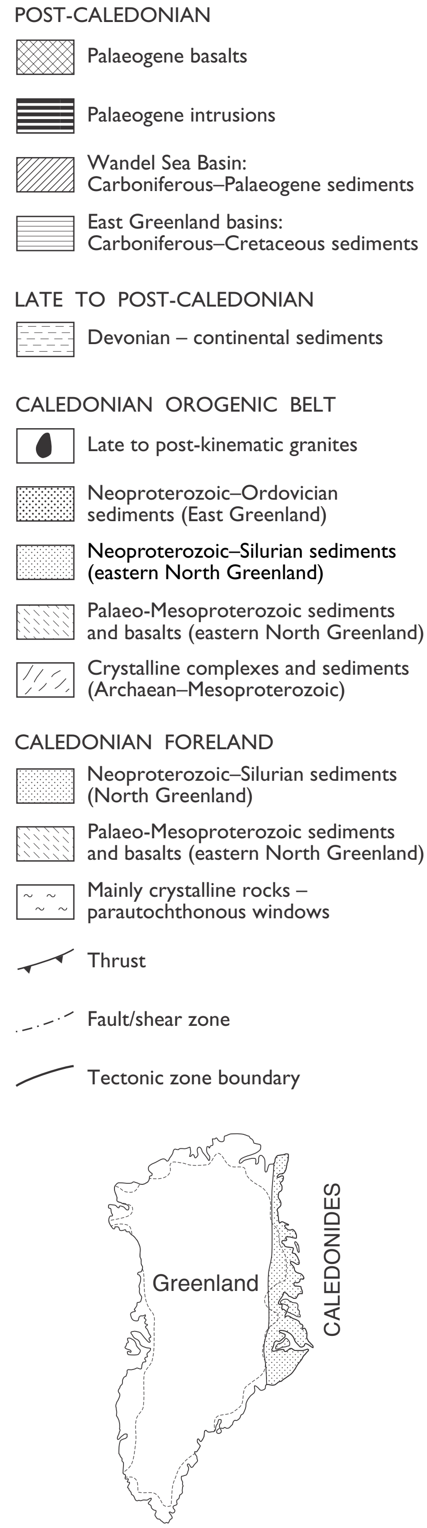


Fig. 1. General geological map of the East Greenland Caledonides, illustrating the division into western marginal and eastern thick-skinned thrust belts (modified from Higgins *et al.* 2001a). The main foreland windows along the length of the fold belt are shown, with the Kronprins Christian Land area in the extreme north. The frame indicates the area of Fig. 2.

Geological setting

Throughout most of its length, the East Greenland Caledonides are dominated by crystalline orthogneiss complexes (Fig. 1) that retain much of their 'basement' character despite Caledonian reworking. The protolith age of the orthogneisses has been determined as Archaean or Proterozoic on the basis of numerous isotopic ages (e.g. Steiger *et al.* 1979; Kalsbeek *et al.* 1993, 1999). Isotopic mineral ages are generally Caledonian, testifying to widespread medium- to high-grade Caledonian metamorphism (e.g. Dallmeyer & Strachan 1994; Dallmeyer *et al.* 1994; Brueckner *et al.* 1998).

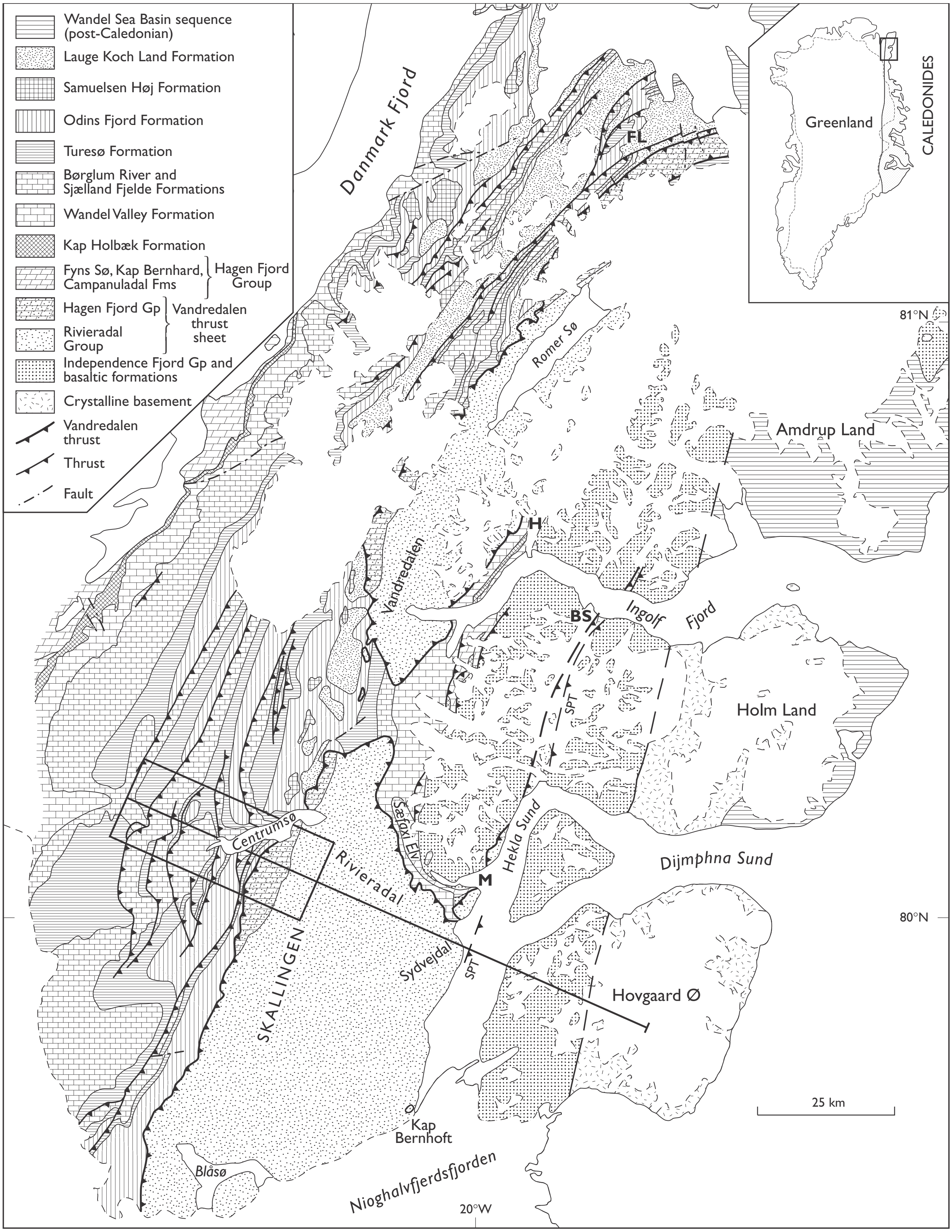
Proterozoic sedimentary successions overlying the crystalline gneiss complexes are widespread in the southern half of the Caledonides. An older late Mesoproterozoic to early Neoproterozoic succession (Krummedal supracrustal sequence and equivalents; Higgins 1988) preserves isotopic evidence of a pre-Caledonian (~ 930 Ma) thermal event, and in many areas hosts ~ 930 Ma augen granite intrusions (Jepsen & Kalsbeek 1998; Kalsbeek *et al.* 2000; Watt *et al.* 2000; Leslie & Nutman 2000, 2003). The younger, Neoproterozoic, Eleonore Bay Supergroup is conspicuous in the fjord region of East Greenland (72°–74°30′N), where it is unconformably overlain by the Vendian Tillite Group and Lower Palaeozoic sediments, forming a succession up to 18.5 km thick. Both sedimentary successions are variably affected by Caledonian metamorphism and deformation, and both host Caledonian granites (Kalsbeek *et al.* 2001a, b).

In the northern part of the East Greenland Caledonides, latest Palaeoproterozoic to Mesoproterozoic supracrustal successions are represented by the Independence Fjord Group and associated volcanic rocks (Figs 1, 2; see also below). These are widely exposed in the Caledonian foreland west of Danmark Fjord, and are also conspicuously developed within the Caledonian thrust complexes of Kronprins Christian Land, where they are overlain by the Neoproterozoic Rivieradal Group siliciclastic succession and Hagen Fjord Group (Fig. 2; see also stratigraphy section below).

Early work in southern Kronprins Christian Land by Fränkl (1954, 1955) established many of the principal structural features of this part of the East Greenland Caledonides. While subsequent interpretations of the frontal thrust systems were explained by Hurst & McKerrow (1981a, b, 1985) in terms of three nappes, later systematic Survey work has considerably simplified this view. The Vandredalen thrust sheet is now recognised as the westernmost major allochthonous tectonic unit along the entire > 200 km long thrust front in Kronprins Christian Land (Fig. 2; Rasmussen & Smith 1996). The Vandredalen thrust displaces the Neoproterozoic rift succession now known as the Rivieradal Group (Smith *et al.* 2004a, this volume) across the parautochthonous foreland succession (Higgins *et al.* 2001b).

The thin-skinned thrust belt west of, and structurally underlying, the Vandredalen thrust sheet is developed in an Ordovician to Lower Silurian succession, that continues westwards into the undisturbed foreland sequences west of Danmark Fjord. The succession in this 30–50 km wide, parautochthonous thrust belt is disrupted by a series of east-dipping and SSW–NNE-trending thrusts and associated belts of folding (Fig. 2). A thin-skinned deformation style was also suggested in the earliest studies by Fränkl (1954, 1955), and Peel (1980) distinguished numerous significant thrusts in an W–E traverse through the belt in Kronprins Christian Land west of Romer Sø. Observations by Peel indicated that the westernmost thrusts extend almost to Danmark Fjord. Regional mapping of the southern part of Kronprins Christian Land, including the parautochthonous thrust belt, was carried out during the 1993–1995 expeditions by the former Geological Survey of Greenland (GGU; Henriksen 1994a, b, 1995, 1996; Higgins 1995).

The Vandredalen thrust climbs a steep ramp along the Hekla Sund – Spærregletscher lineament, that is well exposed at the bay Marmorvigen (**M** on Fig. 2), is almost continuously exposed along the west side of Hekla Sund and extends northwards to the east side of Brede Spærregletscher (**BS** on Fig. 2). West of the ramp, the thrust follows a long flat in the Ordovician Wandel Valley Formation, that is continuously exposed along the west side of Sæfaxi Elv, the river draining into Marmorvigen. The > 200 km long Vandredalen thrust sheet front has a general SSW–NNE trend, and is traceable from west of Blåsø through the east end of Centrumsø to west of Romer Sø (Fig. 2). This trend line coincides with another ramp that cuts up through the Ordovician–Silurian platform limestones and dolomites and carries the Vandredalen thrust sheet up to overlie Silurian turbidites of the Lauge Koch Land Formation at present-day exposure levels. The root zone of the Vandredalen thrust sheet, along the SSW–NNE-trending Hekla Sund – Spærregletscher lineament, coincides approximately with the west margin of the original rift basin (Hekla Sund Basin) in which the Rivieradal Group succession accumulated (Higgins *et al.* 2001b).


Wandel Sea Basin sequence (post-Caledonian)
Lauge Koch Land Formation
Samuelsen Høj Formation
Odins Fjord Formation
Turesø Formation
Børglum River and Sjælland Fjelde Formations
Wandel Valley Formation
Kap Holbæk Formation
Fyns Sø, Kap Bernhard, Campanuladal Fms
Hagen Fjord Group
Hagen Fjord Gp
Rivieradal Group
Vandredalen thrust sheet
Independence Fjord Gp and basaltic formations
Crystalline basement
Vandredalen thrust
Thrust
Fault
Danmark Fjord
FL
Greenland
CALEDONIDES
81°N
Romer Sø
Amdrup Land
Vandredalen
H
BS
Ingolf
Fjord
SPT
Holm Land
Centrumsø
Sæfaxi Elv
Hekla Sund
Dijmphna Sund
Rivieradal
M
80°N
Sydvejdal
SPT
Hovgaard Ø
SKALLINGEN
25 km
Kap Bernhoft
Blåsø
Nioghalvfjerdsfjorden
20°W

East of the Hekla Sund – Spærregletscher lineament a broad zone of latest Palaeoproterozoic to Mesoproterozoic clastic and volcanic rocks crops out, and still farther east crystalline basement rocks extend to the eastern coast of Kronprins Christian Land (Fig. 2). These broad regions are bounded by steeply inclined shear zones, some of which probably represent major thrusts. The crystalline basement rocks underlying the post-Caledonian Wandel Sea Basin succession in the coastal zone incorporate eclogitic enclaves that testify to deep burial during the Caledonian orogeny, followed by rapid exhumation (e.g. Gilotti & Ravna 2002; Gilotti *et al.* 2003).

The pronounced SSW–NNE lineament that can be traced from Hovgaard Ø through western Holm Land to Amdrup Land, is generally not well exposed, but appears to have a complex history. This feature is often viewed as a northward continuation, or a splay, of the major, sinistral, Storstrømmen shear zone, described from Hertugen af Orléans Land (78°N) by Strachan & Tribe (1994). The latest movements on the lineament in Kronprins Christian Land are post-Caledonian, with eastward downthrow of the Wandel Sea Basin succession. However, in southern Hovgaard Ø and Lambert Land Jones & Escher (1995) record a series of late Caledonian ductile shear zones along the lineament, that preserve evidence of both sinistral and east-side-up displacement. In Lambert Land these shear zones post-date foreland-propagating thrust-stacking events, that place thrust sheets of high-grade crystalline gneisses (with eclogitic enclaves) above thrust sheets comprising Independence Fjord Group sandstones. It is considered likely that the high grade basement gneisses of Hovgaard Ø and Holm Land form part of major, thick-skinned thrust sheets that once projected westwards, structurally above the strongly sheared and folded Independence Fjord Group west of the Hovgaard Ø – Amdrup Land lineament (see also Fig. 5).

Facing page:
Fig. 2. Geological map of southern and central Kronprins Christian Land. The frame outline centred on Centrumsø indicates the position of the cross-section and geological map presented in Fig. 4; the extension of the section line beyond the frame is that of the cross-section in Fig. 5. The lineament traceable from Hovgaard Ø through western Holm Land to Amdrup Land, marked by a **dashed line,** has a complex history (see text). **BS**, Brede Spærregletscher; **FL**, Finderup Land; **H**, Hjørnegletscher; **M**, Marmorvigen; **SPT**, Spærregletscher thrust. Modified from Higgins *et al.* (2001a).

Stratigraphy

The autochthonous and parautochthonous foreland comprises thick latest Palaeoproterozoic to Mesoproterozoic successions (Hekla Sund Formation, Aage Berthelsen Gletscher Formation, Independence Fjord Group, Zig-Zag Dal Basalt Formation) and associated mafic intrusions (Midsommersø Dolerite Formation); see also Sønderholm & Jepsen (1991). These are overlain by Neoproterozoic shelf sediments (Hagen Fjord Group: comprising the Jyske Ås, Campanuladal, Kap Bernhard and Fyns Sø Formations). There is a hiatus between the Fyns Sø Formation dolostones and the overlying sandstones of the Kap Holbæk Formation with local developments of palaeokarst (Smith *et al.* 1999). Another hiatus occurs between the Kap Holbæk Formation (early Cambrian) and the overlying Ordovician–Silurian carbonate and siliciclastic rocks. The Neoproterozoic Rivieradal Group is represented only in the allochthonous Vandredalen thrust sheet, and its deposition can be linked to an episode of extensional rifting (Higgins *et al.* 2001b). All these units were involved to some extent in the Caledonian folding and thrusting, but in the thin-skinned parautochthonous belt the thrusts are essentially confined to the Ordovician–Silurian sequence.

The best exposed sections through the thin-skinned thrust belt follow the sides of Centrumsø and the valleys which branch off the west end of this lake. This is the only area where there is sufficient relief and ground control to permit reconstruction of a restorable section (see below). Other good partial sections occur in valleys to the north and south. The extensive plateau areas between valleys are often poorly exposed, and here mapping was carried out by spot checks of the sporadic exposures, supplemented by sampling and conodont studies (Rasmussen & Smith 2002). The main formations represented on the maps and cross-sections are listed in Fig. 3, and are briefly described below.

Hekla Sund Formation, Aage Berthelsen Gletscher Formation, Independence Fjord Group, Midsommersø Dolerite Formation, Zig-Zag Dal Basalt Formation

With the exception of the tholeiitic basalts of the Hekla Sund Formation and Aage Berthelsen Gletscher Formation, the type areas of these Proterozoic divisions were established on the Caledonian foreland west of

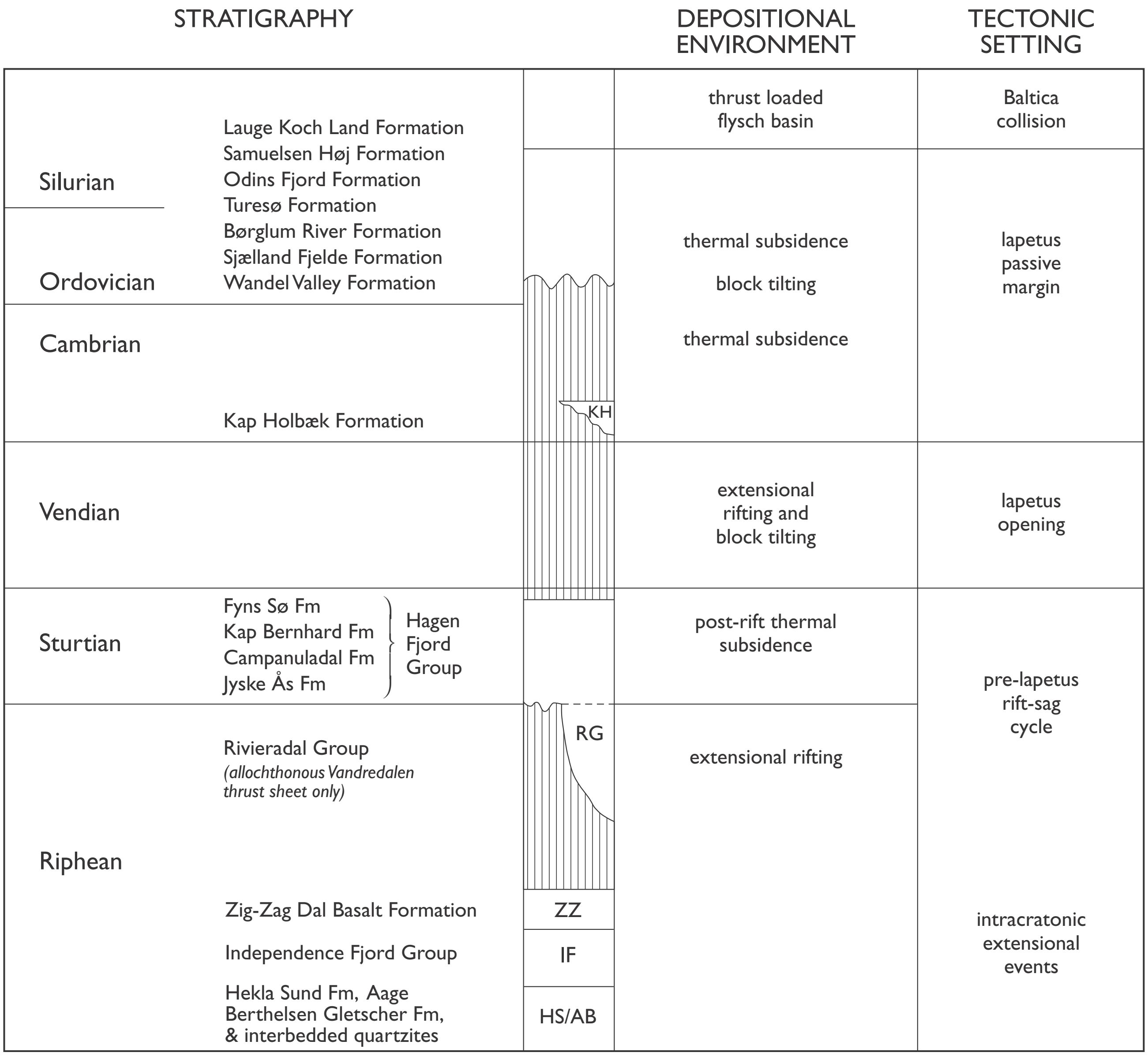


Fig. 3. Summary stratigraphic scheme of Proterozoic and Palaeozoic units depicted on the maps, and their relationships to Iapetus opening (modified from Smith *et al.* 1999). Non-deposition or erosion is depicted by vertical ruling.

Danmark Fjord (Sønderholm & Jepsen 1991). The Independence Fjord Group comprises a more than 2 km thick succession of mainly clastic alluvial deposits, dominantly white-weathering quartzitic sandstones (Collinson 1980, 1983). The Midsommersø Dolerite Formation consists of the widespread doleritic sheets, sills and dykes which invade the Independence Fjord Group sandstones (Jepsen 1971; Kalsbeek & Jepsen 1983). The Zig-Zag Dal Basalt Formation comprises at least 1350 m of lava flows which overlie the Independence Fjord Group (Jepsen *et al.* 1980; Kalsbeek & Jepsen 1984); they are considered to be the extrusive equivalents of the Midsommersø Dolerite Formation.

Highly deformed quartzitic sandstones, doleritic dykes and basaltic lava sequences which crop out in the alpine region of eastern Kronprins Christian Land within the Caledonian orogenic belt have traditionally been regarded as equivalents of the foreland divisions. However, the Survey's regional mapping revealed that the basaltic sequences found in the thrust complexes of Kronprins Christian Land do not overlie the Independence Fjord Group, but are interbedded with the lower levels of the quartzite succession. These basaltic sequences are distinguished as the Hekla Sund Formation and Aage Berthelsen Gletscher Formation (Pedersen *et al.* 2002). SHRIMP isotopic studies on rhyolites of the Hekla Sund Formation yielded an age of 1740 Ma (Kalsbeek *et al.* 1999). This result implies that either the age range of the Independence Fjord Group must be extended downwards to the later part of the Palaeoproterozoic, or there are two superficially indistinguishable quartzite sequences, of which the older unnamed succession is interbedded with the Hekla Sund and Aage Berthelsen Gletscher Formations. The first alternative is adopted here. Quartzite-dyke-basalt associations similar to the foreland succession are presumed to underlie the entire parautochthonous region.

Rivieradal Group

The succession of sandstones, mudstones, conglomerates and some carbonate rocks first mapped by Fränkl (1954, 1955), and assigned by Hurst & McKerrow (1981a, b) to a single sequence that they referred to as the 'Rivieradal sandstones', has been formally defined as the Rivieradal Group (Smith *et al.* 2004a, this volume). The Rivieradal Group is restricted to the Vandredalen thrust sheet, where it is overlain conformably by units of the Hagen Fjord Group. Fränkl had recognised that the Neoproterozoic Rivieradal Group was not represented on the foreland, and introduced the term 'Hekla Sund Basin' for its area of deposition. Field work by GGU in 1993–1995 demonstrated that the Rivieradal Group is 7.5–10 km thick. It was also shown that the sediments of the Rivieradal Group had accumulated in an east-facing, half-graben rift-basin, bounded to the west by extensional faults; this basin was estimated to have been at least 200 km long and 50 km wide (Higgins *et al.* 2001b). During the Caledonian orogeny the Rivieradal Group was displaced westwards across the western margin of the rift basin as the Vandredalen thrust sheet. The root zone of this thrust sheet and the remnants of the original rift basin can be traced in a narrow belt through the centre of the alpine region along the Hekla Sund – Spærregletscher lineament (Fig. 2).

Hagen Fjord Group (and Kap Holbæk Formation)

Representatives of the Hagen Fjord Group are preserved in the frontal portions of the Vandredalen thrust sheet, resting conformably on the Rivieradal Group. In the foot wall of the Vandredalen thrust, as elsewhere in eastern North Greenland, the Hagen Fjord Group rests directly on Independence Fjord Group lithologies, locally with an intervening basal clastic unit. The Hagen Fjord Group is thus viewed as a transgressive, post-rift sequence, and its presence in both the hanging wall and foot wall of the Vandredalen thrust enables the displacement on the Vandredalen thrust to be estimated at 35–50 km (Higgins *et al.* 2001b). The Jyske Ås Formation (Fig. 3) at the base of the group occurs only west of Danmark Fjord in the foreland, and is not considered further here. In the parautochthonous region with which this paper is concerned, four formations are recognised in addition to the basal clastic unit, although the uppermost unit (the Kap Holbæk Formation) is now formally excluded from the Hagen Fjord Group (see below).

1. *Basal clastic unit.* This dominantly conglomeratic unit directly overlies Independence Fjord Group quartzitic sandstones, and is overlain by siltstones and mudstones ascribed to the Campanuladal Formation. The unit was first recorded at Hjørnegletscher (**H** on Fig. 2) on the north side of inner Ingolf Fjord (Jepsen & Kalsbeek 1981) where it is a few metres thick. In 1993 two additional developments of the unit, respectively 35 m and 0–60 m thick, were located along the margin of the alpine region north of Sæfaxi Elv (Jepsen *et al.* 1994).

2. *Campanuladal Formation.* Dominated by green and red fine-grained sandstones, siltstones and mudstones, it is about 110–175 m thick in the foreland areas west of the head of Danmark Fjord (Clemmensen & Jepsen 1992). In the parautochthonous region between inner Ingolf Fjord and Sæfaxi Elv, Jepsen & Kalsbeek (1985) reported 0–80 m of mudstone and sandstone of the formation overlying either the basal conglomeratic unit or the Independence Fjord Group.

3. *Kap Bernhard Formation.* This comprises reddish-brown limestones with minor amounts of silt, and is about 150 m thick at the head of Danmark Fjord (Clemmensen & Jepsen 1992). The formation is up

to 400 m thick in the frontal region of the Vandredalen thrust sheet.

4. *Fyns Sø Formation*. At its type locality at the head of Danmark Fjord (Craig & Jepsen 1995), it is made up of 356 m of spectacular, cliff-forming, yellow-weathering dolostones, characteristically preserving well-formed stromatolites. A similar thickness (~ 400 m) is seen in both the foot wall and the hanging wall of the Vandredalen thrust.

5. *Kap Holbæk Formation*. This was originally the upper formation of the Hagen Fjord Group (Clemmensen & Jepsen 1992). Recognition that the formation is early Cambrian, and that the hiatus between it and the underlying Fyns Sø Formation covers the entire Vendian (Fig. 3), led Smith *et al.* (2004b, this volume) to formally exclude it from the Hagen Fjord Group. The formation was recognised in the parautochthonous belt in the inner parts of Ingolf Fjord in 1994 (Jepsen & Sønderholm 1994), and here is up to 180 m thick; it comprises variegated mudstones at the base overlain by a light and dark coloured sandstone succession. Sandstone-filled fissures and cave-like lenses in the upper surface of the underlying Fyns Sø Formation, first recorded by Fränkl (1954, 1955), have been interpreted as palaeokarst (Smith *et al.* 1999). The Kap Holbæk Formation was recognised in the hanging wall of the Vandredalen thrust by Hurst & McKerrow (1981a, b), who placed it in their 'Finderup Land nappe'.

Lower Palaeozoic platform

The Lower Palaeozoic platform strata of eastern North Greenland are the easternmost representatives of the Franklinian Basin succession, which is exposed in a broad, 900 km long belt across North Greenland (Higgins *et al.* 1991). The earliest Lower Palaeozoic platform strata in the parautochthonous belt of eastern Kronprins Christian Land are the Early Ordovician limestones and dolostones of the Wandel Valley Formation (Rasmussen & Smith 1996; Smith *et al.* 2004b, this volume), which rest unconformably on the Fyns Sø Formation or Kap Holbæk Formation. Uplift of eastern North Greenland and subsequent erosion have resulted in a progressive overstep of the Early Ordovician from west to east across North Greenland (Peel & Smith 1988). There is also a north–south component to the overstep, since south of Kronprins Christian Land, in Lambert Land, the Hagen Fjord Group is missing and the Wandel Valley Formation rests directly on Independence Fjord Group lithologies (Smith *et al.* 1999; Smith 2000). A fuller stratigraphical description of the Lower Palaeozoic platform limestone and dolostone succession is given by Smith *et al.* (2004b, this volume). The following formations are distinguished on the maps and cross-sections of this paper.

1. *Wandel Valley Formation* (Upper Ibexian – Middle Whiterockian). Three limestone and dolostone members are present in the parautochthonous belt, all very similar in their development to their counterparts on the foreland around Danmark Fjord, and with a total thickness of about 335 m.

2. *Sjælland Fjelde Formation* (Upper Whiterockian). About 100 m thick, it is divided into a lower dark grey burrow-mottled limestone and dolostone unit and an upper grey dolostone unit. The Vandredalen thrust follows a long flat in the middle part of the formation, well seen along the west side of Sæfaxi Elv, before climbing a ramp to another flat in the upper dolomite unit. Near the head of Ingolf Fjord, about 70 km to the north, the Vandredalen thrust occupies the same stratigraphic level.

3. *Børglum River Formation* (Mohawkian – Upper Cincinatian). The formation is widespread in the parautochthonous belt, where it comprises a thick succession of dominantly dark, nodular, burrow-mottled limestones with abundant fossils. A complete section through the unit is not seen in the parautochthonous belt, but is probably close to the thickness of 430 m measured in the autochthonous foreland areas further to the north-west (Smith *et al.* 1989).

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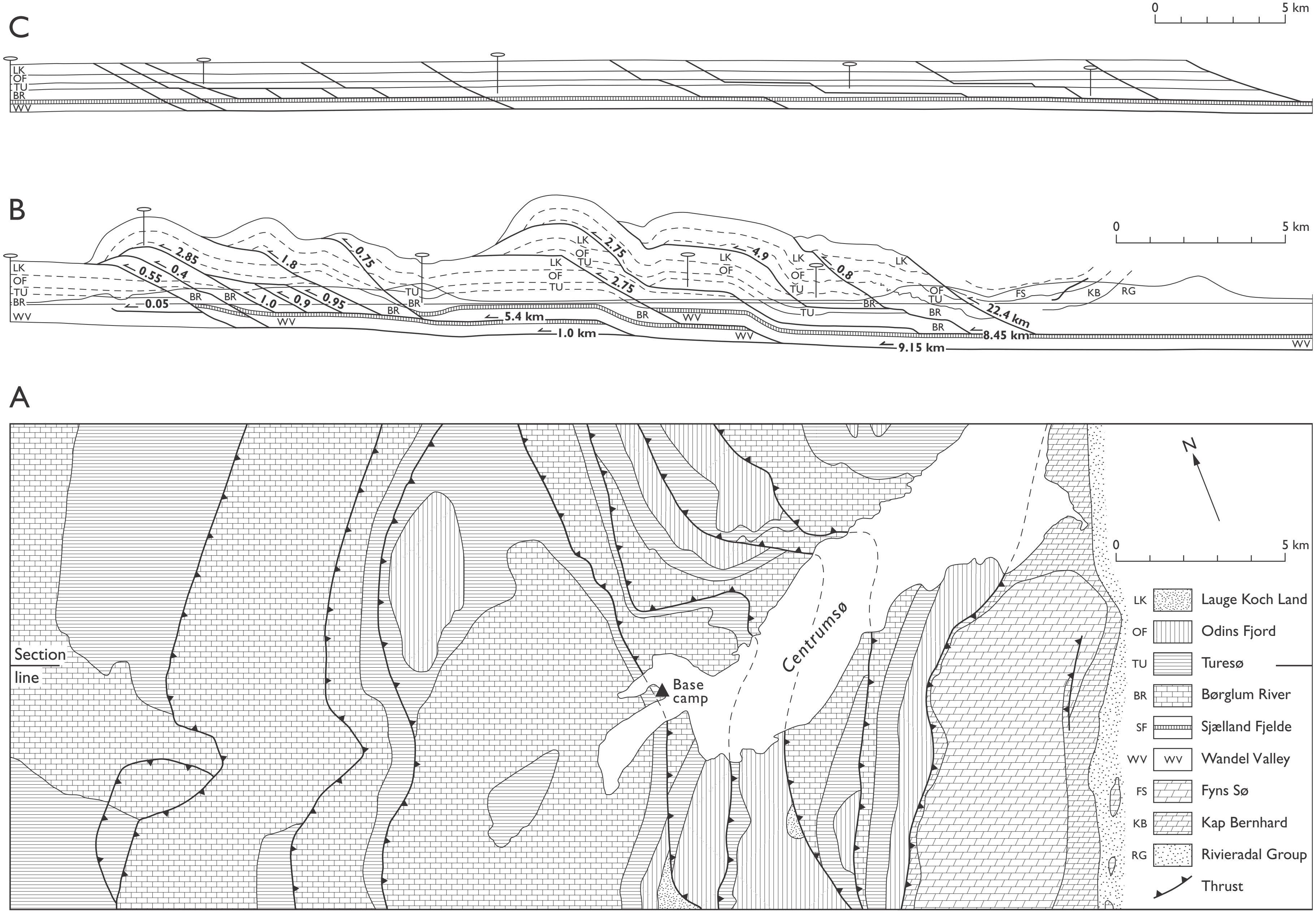
Fig. 4. Geological map and restored cross-section of the thin-skinned thrust belt in the Centrumsø region. **A**: Geological map and location of section line; see also frame in Fig. 2. Base camp indicated by filled triangle. **B**: Cross-section with calculated displacements on individual thrusts in kilometres (e.g. 2.75) based on a line and area balance; only the Sjælland Fjelde Formation is given a distinctive ornament, with other formations indicated by two-letter abbreviations (see legend on map of Fig. 4A). Note the gently eastwards-dipping floor thrust at the base of the Wandel Valley Formation. **C**: Model section with thrusts restored; note reproduced at a smaller scale than the cross-section in **B**. In both **B** and **C** the thrusts are indicated by thicker lines.


C
0
5 km
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OF
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2.85
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0.95
0.75
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2.75
4.9
0.8
5.4 km
1.0 km
9.15 km
8.45 km
22.4 km
FS
KB
RG
A
Section
line
Base
camp
Centrumsø
N
0
5 km
LK Lauge Koch Land
OF Odins Fjord
TU Turesø
BR Børglum River
SF Sjælland Fjelde
WV Wandel Valley
FS Fyns Sø
KB Kap Bernhard
RG Rivieradal Group
Thrust

4. *Turesø Formation* (Upper Cincinnatian – Lower Llandovery). The formation spans the Ordovician–Silurian boundary (Armstrong 1990), and where measured 7 km west of Centrumsø comprises about 200 m of variably coloured dolostones and limestones (see Fig. 6A). The colour variations make the formation conspicuous and easily recognisable. Towards the eastern end of Centrumsø, just west of the Vandredalen thrust sheet front, the formation thickens to at least 350 m; here trains of tight folds are developed in the dolostone-dominated intervals (see Fig. 6B).

5. *Odins Fjord Formation* (mid-Llandovery). The formation is widely exposed in southern Kronprins Christian Land close to the Vandredalen thrust sheet front, where it is at least 220 m thick, although deformation and poor exposure make this estimate uncertain. Christie & Peel (1977) estimated a thickness of 320 m in south-east Peary Land. The transition from the underlying Turesø Formation is marked by a change in colour from pale grey to pale brown, and in lithology from dolostone to limestone rich in tabulate corals and stromatoporoids.

6. *Samuelsen Høj Formation* (Upper Llandovery). Developed as conspicuous reefs, the formation is represented by several major bodies in northern Kronprins Christian Land; those in southern areas are generally smaller and mainly occur in a belt just west of the Vandredalen thrust sheet front (Fig. 2). Only one small body is known south of Centrumsø, and there are none in the line of section (Fig. 4).

7. *Lauge Koch Land Formation* (uppermost Llandovery – Wenlock). The Silurian flysch of Kronprins Christian Land was assigned by Hurst & Surlyk (1982) to Fränkl's 'Profilfjeldet Shales', which was given member rank within the Lauge Koch Land Formation. The sequence is widely involved in the major thrusts of northern Kronprins Christian Land, where a maximum thickness of 400 m was estimated (Hurst & Surlyk 1982). Further south the formation crops out mainly in a zone just west of the Vandredalen thrust sheet front. Only two thrust-bounded inliers occur south of Centrumsø; here the lower 50 m of the formation is characterised by black shaly siltstones interbedded with dark grey to black bituminous and nodular carbonate rocks (Smith *et al.* 2004b, this volume).

Structure

The most important thrusts within the 30–50 km wide thin-skinned thrust belt of Kronprins Christian Land are depicted in Figs 2 and 4. They make up a major imbricate stack beneath a former extension of the Vandredalen thrust sheet. Individual thrusts dip eastwards at angles varying from about 30° to 70°, although the steeper thrusts appear to represent over-steepening arising from further thrust displacement in the foot wall succession. Many thrusts can be followed for several tens of kilometres, some for as much as 75 km along strike. Major folding accompanied the thrusting, although this is normally conspicuous only in certain formations. About 25 km south of Centrumsø several major thrusts die out. Further south, only one major thrust has been traced for 30 km west of the Vandredalen thrust front, and this divides into two thrusts west of Blåsø (Fig. 2).

All the Ordovician–Silurian stratigraphic units from the Wandel Valley Formation to the Lauge Koch Land Formation are involved in the thrusting. Individual thrust movements range from a few hundred metres to several kilometres. Despite topographic relief of 1000 m, matching foot wall and hanging wall cut-offs are rarely observed. Estimates of thrust displacements therefore rely on the construction of a restorable cross-section. The best exposed sections are, in the north, the valley system west of Romer Sø (described by Peel 1980) and, in the south, the valley system containing Centrumsø with which this paper is mainly concerned. A restorable cross-section through the Centrumsø area constructed perpendicular to the thrust trends is presented in Fig. 4.

Prior to attempting to restore the cross-section, a series of cross-sections (not reproduced here) were constructed along profile lines north and south of Centrumsø to gain an impression of the possible range of displacements. The section line of Fig. 2 was chosen because of the excellent exposures on the cliff walls north and south of the lake, and because of the generally good ground control. Initial section construction was at a scale of 1:50 000, on the basis of enlarged copies of the Survey's 1:100 000 topographic maps. Thrust trajectories and fold shapes were projected into the line of section using the best available thickness estimates for formations as noted above. The maximum observed thickness estimate of 400 m for the Lauge Koch Land Formation was used. In respect of the Turesø Formation, the 200 m thickness was used in the west, and 350 m in the eastern part of the section.

Balancing was attempted initially assuming that a single floor thrust in the parautochthonous belt followed the base of the Børglum River Formation (as the Wandel Valley and Sjælland Fjelde Formations were not visibly involved in the thrusting along the line of profile). However, all attempts at a balance with this constraint produced an unrealistic undulating floor thrust (not illustrated here). The floor thrust was then reassigned downwards to the base of the Wandel Valley Formation with, in addition, a major thrust at the base of the Børglum River Formation. This change is justified on the grounds that: (1) The Wandel Valley and Sjælland Fjelde Formations are both involved in the thrusting in northern Kronprins Christian Land (see fig. 1 in Peel 1980); (2) Along Sæfaxi Elv, immediately north of the eastward extension of the Centrumsø cross-section, several highly disturbed bedding-parallel shear zones were observed near the base of the Wandel Valley Formation. The restoration of the Centrumsø cross-section achieved on this basis (Fig. 4B), exhibits a very gentle eastward inclination for the floor thrust at the base of the Wandel Valley Formation. In this model all the thrusts west of the end of Centrumsø root into the floor thrust, whereas the thrusts exposed along the margins of Centrumsø all root into the slightly higher flat thrust following the base of the Børglum River Formation.

The section restoration presented in Fig. 4 involved resolution of several problems. At the west end of the section there is a very broad mapped expanse of Børglum River Formation between two observed major thrusts (see map Fig. 4A). The 4.5 km long valley section shows the sequence dipping at moderate angles eastwards, with locally some dislocation and associated folding. However, since the maximum thickness of the Børglum River Formation is probably about 430 m, restoration could only be achieved assuming the formation to be repeated in a duplex with displacements of 400–1800 m on the individual thrusts. The positions of the duplex thrusts were not identified during the field work, mainly because the significance of the over-thickened section was not appreciated; thus, while depicted on the cross-sections (Fig. 4B, C), these thrusts are not shown on the map (Fig. 4A).

A further problem concerned a long central segment of the cross-section which exhibits a syncline at the west end (see Fig. 6A) and a broad flat anticline in the centre with the lowest levels of the Børglum River Formation exposed at valley level. This could only be satisfactorily accommodated by introducing a ramp duplicating the Wandel Valley and Sjælland Fjelde Formations over a distance of 5.4 km (central part of section in Fig. 4B).

In the cliff north of the base camp at the west end of Centrumsø, a long flat thrust brings the Børglum River Formation above a thin sequence of the Turesø Formation. South of Centrumsø the same thrust changes levels and takes the Turesø Formation above the Odins Fjord Formation on an equally long flat thrust. Similar long thrust flats are interpreted to exist at the eastern end of the section, with the largest displacement on an individual thrust estimated at 4.9 km. Intense folding at the eastern end of the section, just west of the Vandredalen thrust sheet front (see Fig. 6B), and the implications of such internal distortion in other parts of the section, cannot be accurately depicted.

Total displacement on the basis of the model restoration in Fig. 4B is estimated at 17.6 km. The thrusts depicted in the east part of the section along Centrumsø have a total displacement of 8.45 km rooting into the thrust at the base of the Børglum River Formation, which merges with the Vandredalen thrust at the Vandredalen thrust front. The thrusts west of Centrumsø root into a floor thrust following the base of the Wandel Valley Formation and have an estimated total of 9.15 km displacement; this thrust merges with the Vandredalen thrust east of the line of section in the vicinity of Marmorvigen (Fig. 2). The restoration implies that an original 43 km wide segment of the parautochthonous belt has been reduced to about 25.4 km in the line of section, a shortening of approximately 45%.

The restored section depicted in Fig. 4B demonstrates that the model chosen is realistic. It invokes only two major flat thrusts, both of which merge eastwards with the Vandredalen thrust.

Conodont geothermometry

Epstein *et al.* (1977) demonstrated that colour variations of conodont elements are principally related to temperature. They erected a scale of conodont alteration indices (CAI 1–5) ranging from pale yellow through shades of brown to black, corresponding to a temperature range from < 50°–300°C. Higher alteration indices (CAI 6–8), in which the conodont elements progressed from black through grey to white, were calibrated by Rejebian *et al.* (1987) as corresponding to a temperature range from 300°C to over 600°C. A regional description of conodont geothermometry

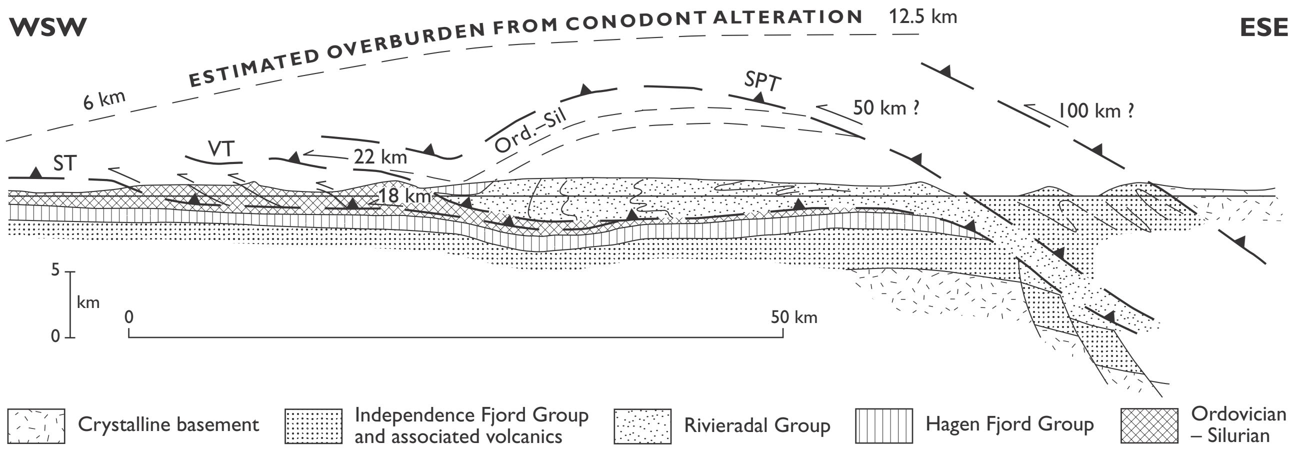

Fig. 5. Simplified cross-section through the Caledonian fold belt in Kronprins Christian Land, from Higgins *et al*. (2001b); for section line see Fig. 2. The maximum overburden deduced from conodont alteration indices (indicative of eastward increase in temperature) is also shown. **SPT**, Spærregletscher thrust; **ST**, Caledonian sole thrust; **VT**, Vandredalen thrust.

in the Kronprins Christian Land area has been presented by Rasmussen & Smith (2001).

Conodonts studied in Kronprins Christian Land were recovered from stratigraphic units ranging in age from mid-Early Ordovician (Wandel Valley Formation) to Llandovery (Lauge Koch Land Formation). Lithologies varied from unaltered platform dolostones and limestones to their highly sheared equivalents underlying the Vandredalen thrust sheet. Whereas the degree of internal shearing and deformation had a significant effect on the morphological character of the conodont elements, it had no apparent effect on the colour alteration indices. The CAI isothermal zones run parallel to the thrust trends and the Vandredalen thrust sheet front in southern Kronprins Christian Land. CAI values of 2–3 were seen west of Danmark Fjord. A broad zone of CAI 3 extends eastwards to approximately the west limit of the cross-section in Fig. 4. Most of the cross-section is within the zone of CAI 4, rising to CAI 5 at the eastern end adjacent to the front of the Vandredalen thrust sheet. The limestones and dolostones beneath the Vandredalen thrust sheet, exposed along Sæfaxi Elv, are in CAI zone 5 increasing to CAI 5–6 in the easternmost exposures at Marmorvigen.

The CAI temperatures indicate the maximum thickness of the Caledonian overburden, comprising the Vandredalen thrust sheet and possible higher thrust units. The thickness was determined from estimates of geothermal gradients and the thermal conductivity of the rock units involved (see Rasmussen & Smith 2001, for details). The results imply that the approximate thickness of the maximum overburden in the area of the cross-section (Fig. 5), ranged from about 6 km at the west end of the cross-section to 10.7 km farther east at the front of the Vandredalen thrust sheet (Fig. 6C). The highest CAI values at Marmorvigen point to an overburden of 12.5 km (Rasmussen & Smith 2001).

The assumed extent and thickness of the Vandredalen thrust sheet formerly present above the parautochthonous zone are also indicated in Fig. 5. The Hagen Fjord Group in the hanging wall exhibits a cut-off against the Vandredalen thrust along much of the Vandredalen thrust sheet front on the west side of Vandredalen. Thus, the former extent of the Vandredalen thrust sheet across the parautochthonous zone must have consisted essentially of a packet of Ordovician–Silurian carbonate and siliciclastic rocks. The thickness of this packet was probably not much greater than 2 km (Fig. 5). The only uncertainty in this estimation of the thickness concerns the contribution of turbidites of the Lauge Koch Land Formation. A maximum thickness of 400 m has been assumed for this unit in the cross-section, being the maximum thickness preserved in present-day exposures (Hurst & Surlyk 1982). The Silurian turbidites of North Greenland were derived from erosion of the rising Caledonian mountain chain. The thickness of the turbidite succession that may have accumulated in the western part of present Kronprins Christian Land before it was over-ridden by the westward-propagating Caledonian thrust sheets is unknown. Between 3 and 10 km of additional overburden above the Vandredalen thrust

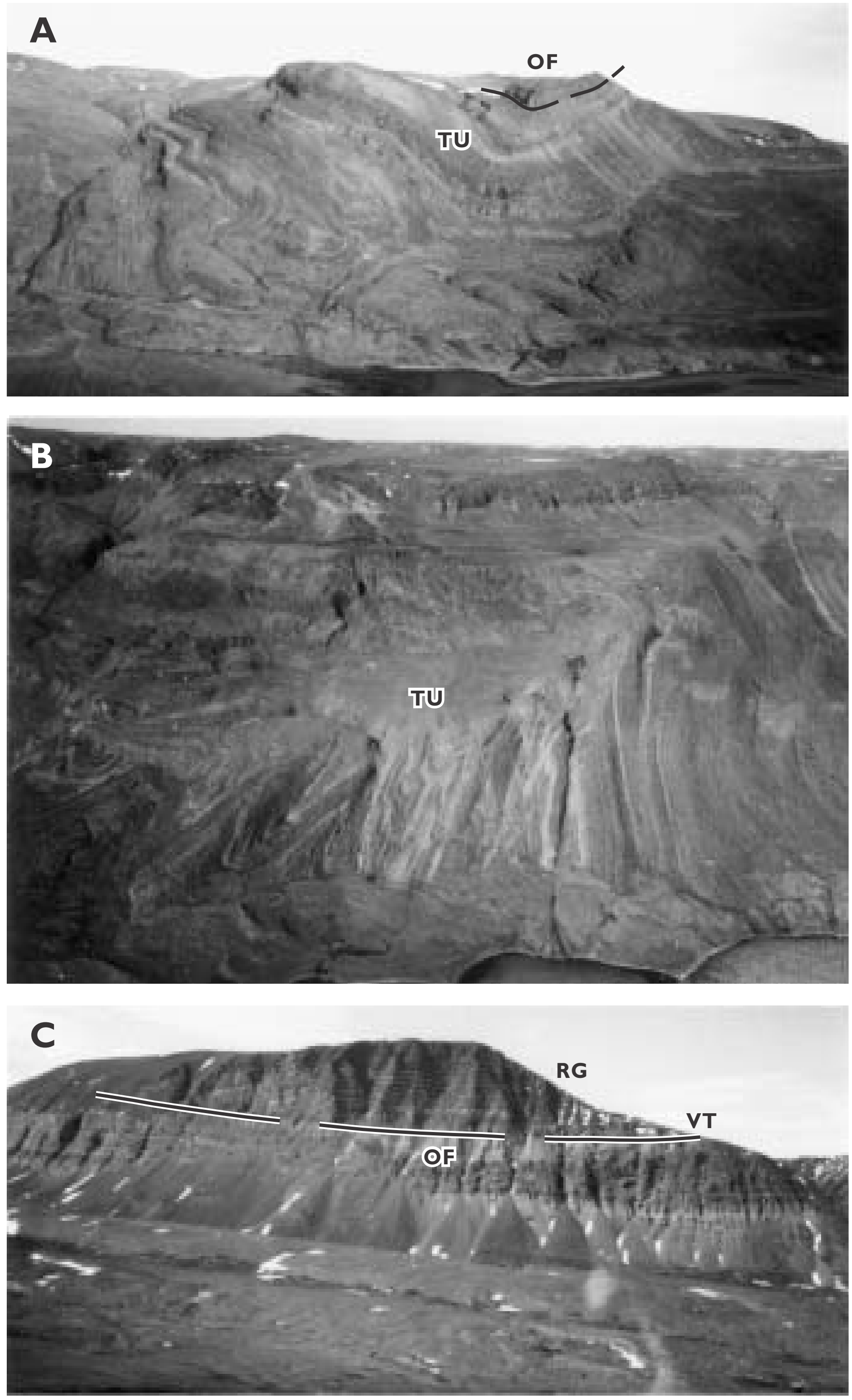

Fig. 6. **A**: Syncline in line of cross-section looking north, 7 km west of the Centrumsø base camp. **OF**, Odins Fjord Formation; **TU**, Turesø Formation. Cono-donts have CAI values of 4, indicative of a former overburden of about 6.8 km. Summit at centre is 500 m above the valley floor. Photo: J. Lautrup. **B**: Intense folding in variegated dolomites of the Turesø Formation (**TU**). North side of Centrumsø, about 3 km west of the Vandredalen thrust front. Conodonts have CAI values of 4–5, indicative of an overburden of about 8–9 km. Plateau is about 750 m above the lake level (foreground). Photo: J. Lautrup. **C**: Outlier of Rivieradal Group (**RG**) conglomerates and sandstones in the Vandredalen thrust sheet, overlying Ordovician carbonates of the Odins Fjord Formation (**OF**) on the west side of Vandredalen. The Vandredalen thrust (**VT**) follows the marked discordance. Conodonts from the carbonates of the Odins Fjord Formation have CAI values of 5, indicative of a former overburden of about 10.7 km. Summit is 850 m above the valley floor in the foreground.

sheet would be required to reach the temperatures demonstrated by the conodont alteration pattern, and it is considered unlikely that this can be accounted for by substantially increasing only the contribution of the Lauge Koch Land Formation turbidites. It is more probable that higher, westward-propagating thrust sheets were formerly present above the Vandredalen thrust sheet. These are likely to have comprised units such as the Independence Fjord Group quartzitic sandstones with associated dolerite dykes and sills, and the Hekla Sund Formation basalts (representatives of which crop out in the mountainous region east of the Hekla Sund – Spærregletscher lineament). These units would have been transported westwards on the Spærregletscher thrust (SPT in Figs 2, 5). Lower Palaeozoic formations may also have been present in the proximal parts of this thrust sheet.

All the CAI zones are based on sample collections from the parautochthonous zone structurally underlying the Vandredalen thrust sheet. This zone is part of a thin-skinned thrust belt, and therefore the most likely setting to account for the increased temperatures would be burial of the parautochthonous zone beneath a pile of westward-directed Caledonian thrust sheets. Allowing for subsidence of the parautochthonous zone that resulted from the weight of the overlying thrust burden, the thrust sheets must still have made up a substantial mountain chain, increasing in altitude eastwards where summits may have attained altitudes of about 3–4 km.

Conclusions

The rock units which constitute the up to 50 km wide thin-skinned thrust belt west of the Vandredalen thrust front extend westwards into undisturbed foreland. The thrust belt is therefore viewed as parautochthonous. The deformation associated with the eastward-dipping thrusts of the parautochthonous zone involves only Ordovician–Silurian rock units and is essentially thin-skinned in style.

A line-and-area restoration along the best exposed section through the thrust belt, i.e. along Centrumsø and adjacent valleys, can be achieved assuming that the observed thrusts root into two flat thrusts. One is depicted as the Caledonian floor or sole thrust, in this region located at the base of the Wandel Valley Formation; the second slightly higher thrust is assumed to lie at the base of the Børglum River Formation. Both thrusts are assumed to merge eastwards with the Vandredalen thrust. Total displacement of 17.6 km on the two flat thrusts in the model restoration implies that an original 43 km wide segment of the parautochthonous belt has been reduced to 25.4 km, a shortening of 45% in the line of section.

The colour changes experienced by conodont elements reflect variations in temperature which can be linked to the maximum thickness of overburden during the Caledonian orogeny. Overburden estimates increase systematically from 6 km at the west end of the cross-section to 10.7 km at the Vandredalen thrust front, and farther east to 12.5 km at Marmorvigen (Fig. 5). As the Vandredalen thrust sheet overlying the parautochthonous zone was probably not much more than 2 km thick, the remainder of the estimated overburden must have comprised higher thrust sheets, since eroded, that projected westwards across the parautochthonous belt.

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Palaeoproterozoic age of a basement gneiss complex in the Charcot Land tectonic window, East Greenland Caledonides

Kristine Thrane

The Charcot Land tectonic window exposes crystalline basement gneisses, which form part of the foreland of the East Greenland Caledonides. These gneisses were previously believed to be Archaean in age, on the basis of imprecise K-Ar analyses carried out in the early 1980s on hornblende from amphibolitic bands and inconclusive Rb/Sr isotope data. New U-Pb single-zircon ion microprobe analyses on the gneisses of the window yield upper intercept ages of 1916 ± 21 and 1928 ± 11 Ma, and are interpreted to represent the age of crystallisation of the igneous protolith. The foreland gneisses of the Charcot Land window are similar in age to parts of the allochthonous gneiss complexes of structurally overlying thrust sheets, but the two terranes have different lithological and structural characteristics. No Archaean rocks have been identified with certainty in any of the East Greenland Caledonian foreland windows.

Keywords: Caledonides, East Greenland, geochronology, Palaeoproterozoic

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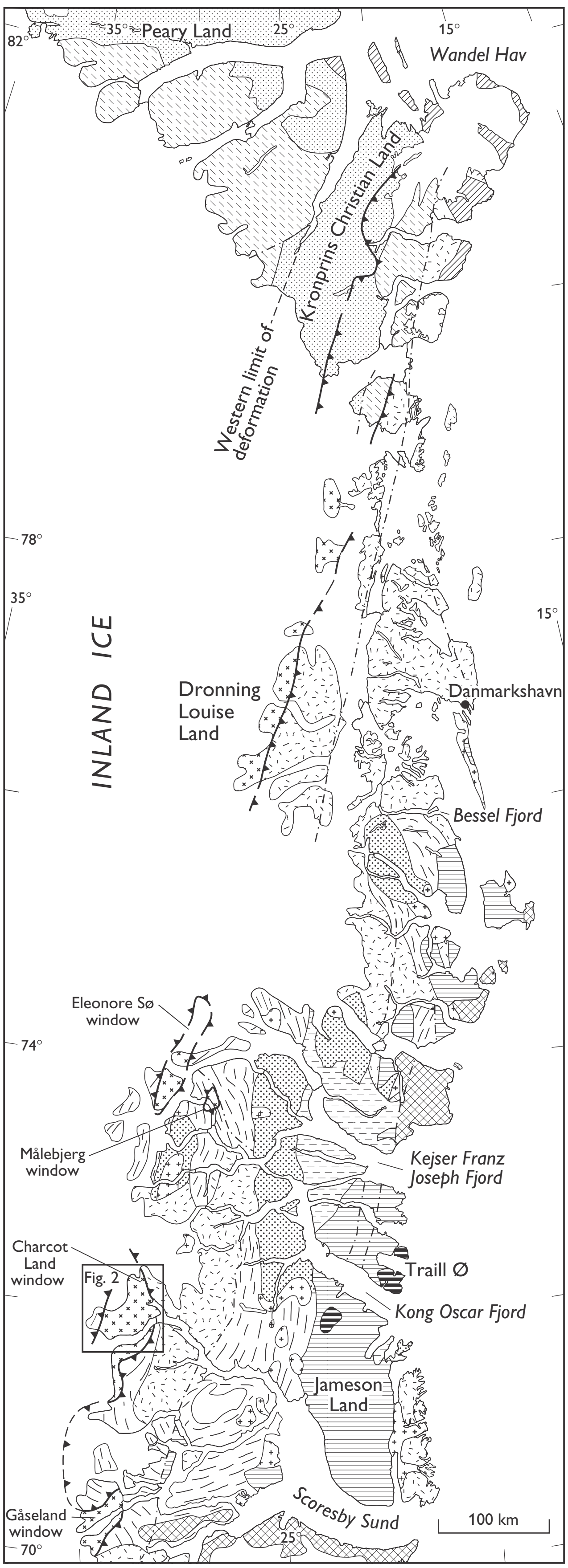
The Charcot Land window is located between latitudes 71°45′N and 72°15′N in the south-western part of the 1300 km long East Greenland Caledonides (Fig. 1). It is one of a series of tectonic windows, interpreted to expose parautochthonous foreland (Higgins & Leslie 2000), found along the western border of the Caledonian orogen. The Gåseland window is exposed to the south at *c*. 70°N (Wenk 1961; Phillips *et al*. 1973), and the Målebjerg and Eleonore Sø windows to the north between latitudes 73°30′–74°15′N (Leslie & Higgins 1998; Higgins & Leslie 2000, 2004, this volume). Further to the north, the foreland basement is also exposed in western Dronning Louise Land (76°–77°N; e.g. Strachan *et al*. 1992), and in the small Nørreland window (78°40′N; Hull & Friderichsen 1995). Apart from these restricted areas the foreland of the East Greenland Caledonides is not well known, as it is largely concealed beneath the Inland Ice to the west.

The Charcot Land window (Fig. 2) exposes a basement complex of grey gneisses with amphibolite bands, overlain by a cover of low to medium-grade supracrustal rocks including carbonates, volcanic rocks and siliciclastic sediments (Charcot Land supracrustal sequence; Steck 1971). Both basement and cover are cut by major Palaeoproterozoic granite intrusions (Hansen *et al*. 1981).

Structurally overlying the Charcot Land window are Caledonian thrust sheets comprising crystalline gneiss complexes (Flyverfjord infracrustal complex) and overlying high-grade metasedimentary rocks (Krummedal supracrustal sequence; Henriksen & Higgins 1969, 1976). The crystalline gneisses making up the Flyverfjord infracrustal complex in Hinks Land, south-east of Charcot Land (Fig. 2), are of late Archaean age (*c*. 2700 Ma; Rex & Gledhill 1974; Thrane 2002). The Flyverfjord infracrustal complex extends both southwards and northwards (Fig. 1); however, north of 72°50′N very similar looking orthogneisses have yielded Pal-



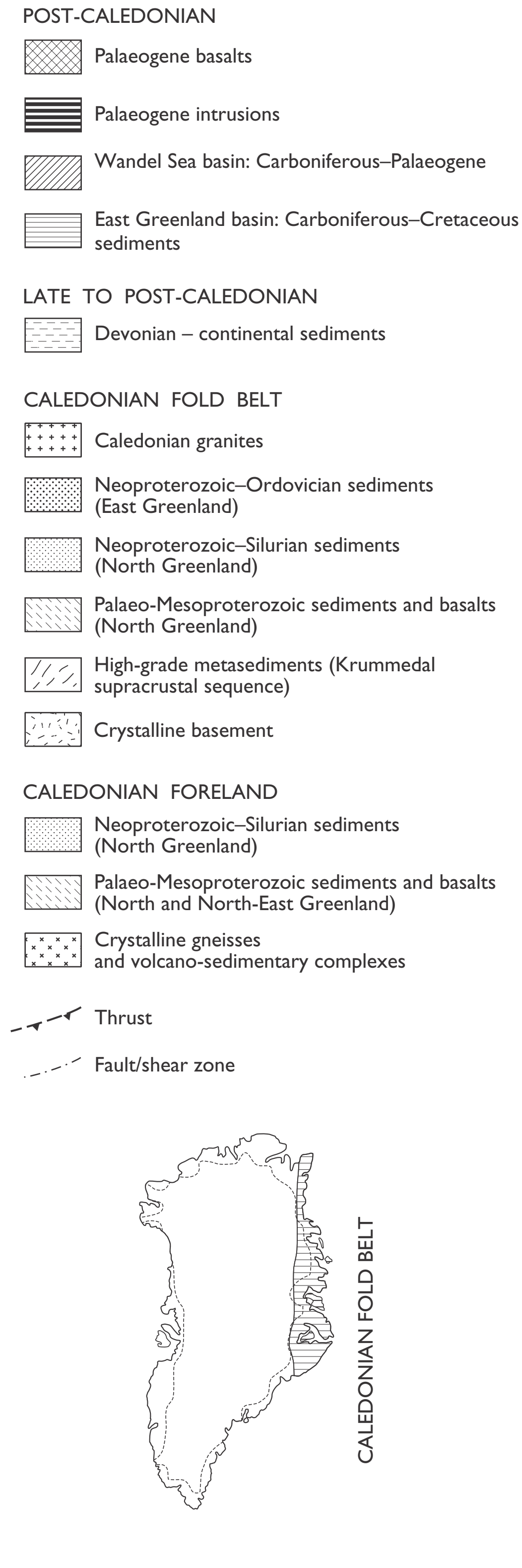


Fig. 1. Geological map of the East Greennland Caledonides. frame indicates study area shown at larger scale in Fig. 2.

aeoproterozoic ages (*c.* 1900 Ma; Rex & Gledhill 1981; Kalsbeek *et al.* 1993; Thrane 2002). The Krummedal supracrustal sequence, that overlies the Flyverfjord infracrustal complex as well as the similar gneiss complexes between latitudes 70° and 76°N, was deposited later than 1100 Ma ago, and underwent high grade metamorphism with generation of granites *c.* 940 Ma ago (Kalsbeek *et al.* 2000). The contact between the Krummedal supracrustal sequence and the structurally overlying Neoproterozoic–Ordovician sedimentary succession is a shear zone, interpreted as an extensional detachment or locally a thrust (Escher & Jones 1998; Leslie & Higgins 1998). The western border of the main Neoproterozoic–Ordovician outcrop in the fjord region from 72°–75°N is a late orogenic extensional fault system (e.g. Hartz & Andresen 1995). The *c.* 13 km thick Neoproterozoic Eleonore Bay Supergroup succession (Sønderholm & Tirsgaard 1993) together with the Vendian Tillite Group (800–1000 m) and Cambro-Ordovician shelf sequence (up to 4 km), constitute the highest part of the uppermost Caledonian thrust sheet (Higgins *et al.* 2004).

In 1968, the southern part of the Charcot Land area was mapped by the Geological Survey of Greenland (Henriksen & Higgins 1969, 1976; Steck 1971), during a systematic regional mapping project in the Scoresby Sund region (70°–72°N). During the 1997 and 1998 Survey expeditions to the Kong Oscar Fjord region (72°–75°N), the northern part of Charcot Land was mapped by Friderichsen & Thrane (1998). Sample collections were made for ion microprobe zircon studies, the results of which are reported here.

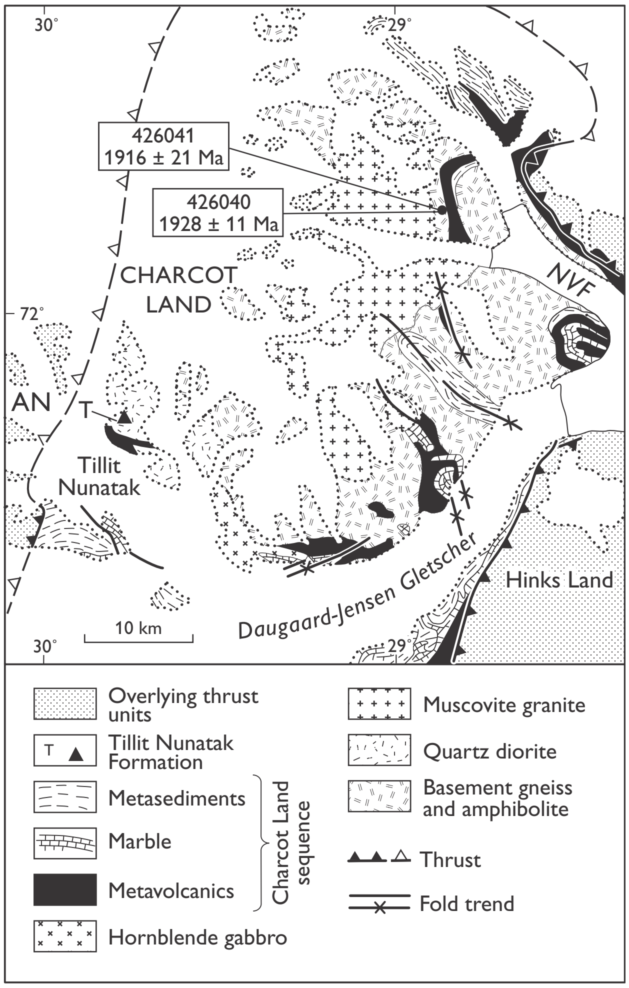


Fig. 2. Geological map of the Charcot Land window, showing major lithological divisions and sample locations. Modified from Henriksen & Higgins (1976). The rock types of the overlying thrust sheets are undifferentiated, and include gneisses of the Flyverfjord infracrustal complex and the Krummedal supracrustal sequence. **AN**, Alfabet Nunatakker; **NVF**, Nordvestfjord.

Geological setting

The foreland rock units exposed within the Charcot Land window include crystalline basement orthogneisses with interleaved amphibolite bands, that are overlain by a *c.* 2000 m thick succession of various metasedimentary rocks (including white marble) and metamorphosed basic extrusive and intrusive rocks (Charcot Land supracrustal sequence). These units are cut by two major granitoid intrusions which crop out widely in central Charcot Land (Fig. 2); one is a hornblende-biotite quartz diorite to granodiorite body and the other a pegmatitic muscovite granite. In southernmost Charcot Land a hornblende gabbro body intrudes the basement gneisses.

Tillit Nunatak in south-west Charcot Land takes its name from a sheared tillite resting unconformably on the granodiorite intrusion. This tillite has been correlated with the Vendian tillites of the fjord zone (Moncrieff 1989), as has a similar tillite in the Gåseland window. The Charcot Land tillite is very little deformed but does contain a planar cleavage.

The Charcot Land supracrustal sequence of southernmost Charcot Land is characterised by greenschist facies metamorphism. Metamorphic grade increases towards the north-east and reaches upper amphibolite facies at ~ 72°N latitude (Steck 1971). Further to the north, the metamorphic grade again decreases (Friderichsen & Thrane 1998).

The eastern and western boundaries of the Charcot Land window are marked by major Caledonian thrusts (Fig. 2). The western thrust dips gently to the

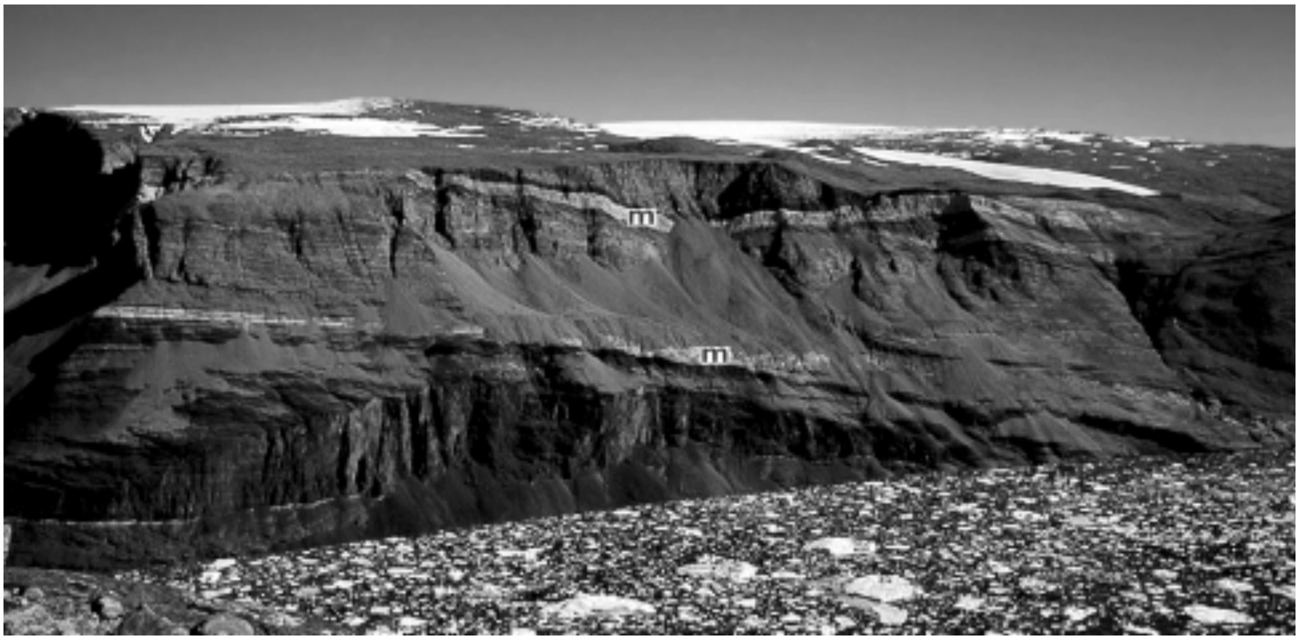


Fig. 3. Part of the major, recumbent, west-verging isoclinal fold that defines the eastern boundary of the Charcot Land window (hanging wall). The isocline is outlined by the two white marble bands (**m**) which form a closure just beyond the left side of the photograph. The black units are amphibolite. North-east of innermost Nordvestfjord (see Fig. 2); profile height about 1000 m.

west and is only exposed on the Alfabet Nunatakker, while the eastern thrust dips to the east and can be traced for more than 25 km in western Hinks Land (Higgins 1982).

North-east of Charcot Land, on the north-east side of innermost Nordvestfjord, a very large-scale, recumbent, west-vergent isoclinal anticline makes up the eastern boundary of the window (Fig. 3). This fold nappe is sitting in the hanging wall and is made up by the cover rocks from outside of the window. The nappe, first recognised by Eduard Wenk and Helge Backlund in 1934 (Backlund in Koch 1955; Wenk 1956), is outlined by a conspicuous white marble unit that has an isoclinal fold closure some 25 km north-west of its first appearance opposite the front of Daugaard-Jensen Gletscher. However, the narrow closure that Wenk and Backlund observed from fjord level accounts for less than half of the magnitude of this fold nappe. Over its entire length, the structure could easily accommodate a translative movement of the proportions necessary to form the Charcot Land window, a minimum of 40 km displacement (Friderichsen & Thrane 1998).

Structures

The broad structure of the Charcot Land window is an elongate N–S-trending dome (Fig. 2). Within the window, foliation trends have a general NW–SE strike and dip at shallow angles to the east. Lineations plunge at moderate angles eastwards, between north-east and south-east. Major folds have trends between E–W and NW–SE, while minor folds have more variable trends and plunge directions.

The crystalline basement terrain east and north-east of Charcot Land, that forms part of the structurally overlying thrust sheet, exhibits a different pattern of structures. Friderichsen & Thrane (1998) mapped a broad area of the allochthonous gneisses north-east of Charcot Land. They record the general foliation trends in eastern parts of their area as NE–SW to N–S with an eastwards dip, with linear elements plunging at moderate to shallow angles to the east or south-east; these were interpreted as Caledonian structures. The presence of major, recumbent, NW-verging folds suggests the NE–SW trends might be a response to Caledonian compression, while the N–S trends may relate to Caledonian extension, mainly seen as ductile top-down-to-the-east faults. In the western part of their area, Friderichsen & Thrane (1998) noted the structural pattern as more diffuse, perhaps due to a less intense Caledonian overprinting of older and more complex pre-Caledonian structures. In general the foliation trends are NE–SW, with NW-plunging lineations.

Although the general foliation trends within the Charcot Land window are also broadly NW–SE, like those in the eastern areas of the overlying thrust sheets, the structures in Charcot Land are not interpreted as Caledonian. Lineations in Charcot Land also have much steeper eastward dips than in the thrust sheets. Further evidence that the Caledonian overprint within the window was generally weak is that the large Palaeoproterozoic granite intrusions cutting the basement gneisses in Charcot Land show no evidence of deformation. The only certain Caledonian structures are the planar cleavage in the diamictites of the Vendian Tillit Nunatak formation.

The major thrust along the east side of the Charcot Land window is well-defined in north-west Hinks Land (Fig. 2), but its northward continuation on the north-east side of Nordvestfjord was previously uncertain (Henriksen & Higgins 1976). On the basis of their 1997 studies, Friderichsen & Thrane (1998) proposed that the movement might have been taken up by the major nappe-like fold on the north-east side of the Charcot Land window (Fig. 3). The trend and westward sense of overturning of this nappe-like fold support the viewpoint that it is a Caledonian structure, although no other comparable structures were observed within the window. A thick low-grade succession of dark phyllitic shales observed in the crest of the fold has also been traced in the western nunataks of Charcot Land, substantially increasing the possible extent of the structure. In addition a thrust associated with this nappe-like major fold suggests that the total displacement was probably significantly more than the 40 km proposed by Henriksen & Higgins (1976) and Henriksen (1986).

Previous geochronological studies

Hansen *et al.* (1981) analysed hornblende from amphibolite bands within the Charcot Land basement gneisses, and obtained K-Ar ages of 2097 ± 105 Ma and 2855 ± 145 Ma. These were regarded as minimum ages for the amphibolite units of the crystalline complex. Rb-Sr whole rock analyses on samples of the gneisses were undertaken by Hansen (1976), but while the results did not yield any exact ages, there were indications that the gneisses might be more than 2200 Ma old. Based on lithology and age an Archaean origin comparable to that of the Flyverfjord basement gneisses was thought likely. Rb-Sr whole rock analyses were also undertaken on samples of the widespread pegmatitic muscovite granite body, that intrudes both the basement gneisses and the supracrustal rocks in Charcot Land (Hansen *et al.* 1981); an age of *c.* 1850 Ma was considered to indicate the approximate time of intrusion. K-Ar analyses on large muscovite crystals from the same granite yielded ages of 1760 ± 60 and 1870 ± 60 Ma, interpreted as a minimum age of emplacement (Hansen *et al.* 1981). Based on field observations, Steck (1971) argued that the granite was intruded after the main metamorphism of the supracrustal rocks, which was suggested to have taken place about 1900–1850 Ma ago (Hansen *et al.* 1981).

A young Rb-Sr biotite age of 402 ± 10 Ma from an amphibolite, together with a biotite-feldspar-whole-rock isochron age of 402 ± 8 Ma for samples of the pegmatitic granite, were considered to reflect a Caledonian greenschist facies metamorphic overprint (Hansen *et al.* 1981).

Isotopic data from orthogneiss units in some of the other foreland areas exposed along the margin of the Caledonian orogen in East Greenland have yielded Palaeoproterozoic protolith ages, e.g. Kalsbeek *et al.* (1993) and Tucker *et al.* (1993) obtained Palaeoproterozoic ages for basement gneisses from the western part of Dronning Louise Land (77°N, 25°W) and quartz porphyry bodies and grey granites within the Eleonore Sø window have yielded similar ages (Higgins & Leslie 2004, this volume). None of the so far dated foreland rock units have yielded convincing Archaean ages.

Geochronology

Samples

Two representative samples from the basement gneiss complex were studied. Sample 426040 is a fine-grained, light grey, granodioritic orthogneiss, and sample 426041 a dark grey, coarse-grained, granodioritic orthogneiss (Fig. 4). Both rock units exhibit a penetrative gneissosity and mineral lineation, and are cut by deformed light-coloured granite veins and undeformed pegmatitic muscovite granite veins. In the field, the age relationships between the two orthogneisses are very clear; the fine-grained orthogneiss (426040) intrudes and cuts the coarse-grained orthogneiss (426041). The limited field work undertaken in Charcot Land in 1997, and that undertaken earlier during the 1968–

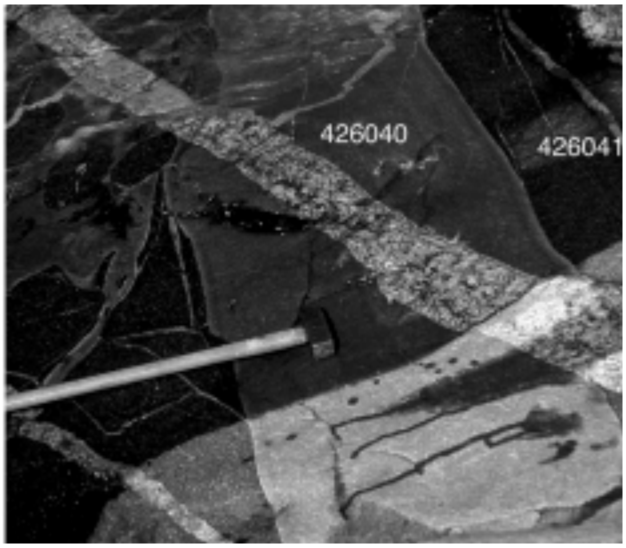


Fig. 4. Dark grey orthogneiss (426041) cut by a broad dyke of light grey orthogneiss (426040). Both are cut by later pegmatitic granite veins. Water flowing from right to left produces the colour differences between wet and dry rocks.

1972 Scoresby Sund expeditions (Henriksen 1986), indicate both gneiss types to be part of the regional basement gneiss complex, the oldest rocks exposed in Charcot Land.

Analytical methods for the ion microprobe study

U-Pb dating of zircons was undertaken using the Cameca IMS 1270 ion probe at the NORDSIM laboratory, Swedish Museum of Natural History, Stockholm. Approximately 50 zircon grains from each sample were hand-picked, and mounted in a transparent epoxy resin together with reference zircons 91500 (from Ontario, Canada, with a weighted average $^{207}Pb/^{206}Pb$ age of 1065 Ma; Wiedenbeck *et al.* 1995). The zircon grains were polished sufficiently to expose any potentially older cores. The mounts were examined by reflected light microscopy and by backscatter imaging in a scanning electron microscope and then coated with *c.* 30 nm of gold. Analytical procedures are similar to those described by Schuhmacher *et al.* (1994) and Whitehouse *et al.* (1997). Calibration of Pb/U ratios follows procedures similar to those used by the ion probe group at the Australian National University (Williams 1998), and is based on observed relationships between Pb/U and UO_2/U, during the same analytical run. Results are given as discordia line intercept ages. The ages were calculated using Isoplot/Ex (Ludwig 1999).

Analytical results

The U-Pb zircon data (Table 1) are presented in conventional concordia diagrams (Fig. 6; 1 σ error ellipses).

Sample 426041

Most of the zircons in sample 426041 are elongate, prismatic and clear, with sizes ranging from 100 to 400 mm, most commonly between 200 and 250 mm. They contain solid homogenous cores, some of which show oscillatory zonation. The rims are broad, metamict and show zonation. From the backscatter images, it is not clear whether the rims are metamorphic or simply alteration rims (Fig. 5). However, there is a clear chemical variation, with the rims having much lower Th/U ratios (0.02–0.07) than the cores (0.19–0.36), and also containing more common lead (Table 1). The variation in the Th/U ratios indicates that the rims may have a metamorphic origin, while the higher common lead content may be a result of alteration of the rims. In the concordia diagram (Fig. 6A), all the analyses (rims as well as cores) fall on the same discordia line. The upper intercept age is 1916 ± 21 Ma and the lower intercept date of 443 ± 25 Ma (MSWD = 10.9), where the upper intercept is interpreted as the best approximation of the crystallisation age of the gneiss protolith. Most of the rims plot on the discordia line, indicating that they must have a Palaeoproterozoic origin very close in age to the protolith, e.g. the rock must have been exposed to metamor-

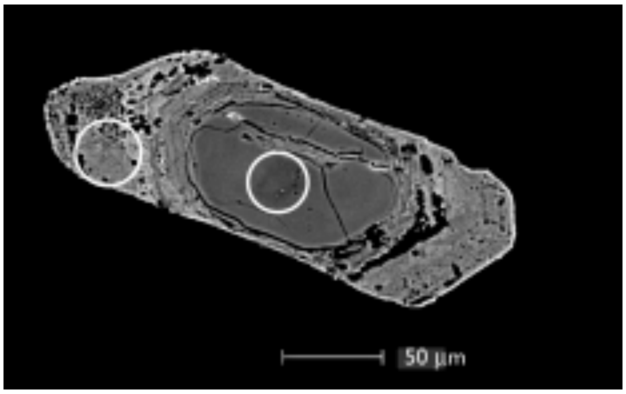


Fig. 5. Backscatter image of zircon number 7 from sample 426041. The circles indicate the ion probe analysis sites.

Table 1. SIMS U-Th-Pb analytical data and derived ages

Sample/ spot#	U ppm	Pb ppm	Th ppm	Th/U meas.	f % common	$^{207}Pb/^{206}Pb$	± σ %	$^{207}Pb/^{235}U$	± σ %	$^{206}Pb/^{238}U$	± σ %	Disc. %	Ages (Ma) $^{207}Pb/^{206}Pb$	± σ	Ages (Ma) $^{207}Pb/^{235}U$	± σ	Ages (Ma) $^{206}Pb/^{238}U$	± σ
426040																		
9c	351	137	86	0.25	0.08	0.1170	0.29	5.275	0.82	0.327	0.77	–5.3	1911	5	1865	7	1824	12
6c	473	148	134	0.28	0.07	0.1125	0.33	4.041	0.82	0.261	0.75	–21.1	1840	6	1642	7	1493	10
5c	717	192	279	0.39	1.10	0.1034	0.46	2.713	0.92	0.190	0.79	–36.3	1686	8	1332	7	1123	8
1c	1583	245	727	0.46	1.29	0.0998	0.55	1.739	1.00	0.126	0.83	–55.8	1620	10	1023	6	767	6
3c	628	122	190	0.30	1.14	0.0996	0.92	2.243	1.26	0.163	0.87	–42.7	1616	17	1195	9	975	8
4c	856	158	362	0.42	0.18	0.0971	0.42	2.062	1.14	0.154	1.06	–44.1	1569	8	1136	8	923	9
2c	752	134	194	0.26	1.49	0.0958	0.59	2.007	1.12	0.152	0.96	–43.8	1543	11	1118	8	912	8
7r	7482	463	250	0.03	4.80	0.0527	5.96	0.425	6.01	0.058	0.77	15.9	317	130	359	18	366	3
426041																		
2c	302	110	83	0.27	0.09	0.1165	0.40	4.883	0.93	0304	0.83	–11.6	1904	7	1799	8	1711	13
13c	247	93	88	0.36	0.11	0.1143	0.49	4.857	1.19	0.308	1.09	–8.3	1869	9	1795	10	1732	17
14c	503	138	94	0.19	0.40	0.1115	0.42	3.635	0.93	0.236	0.83	–27.7	1824	8	1557	7	1368	10
4c	364	107	123	0.34	0.21	0.1107	0.41	3.707	0.97	0.243	0.87	–25.1	1810	7	1573	8	1402	11
2r	475	127	106	0.22	0.24	0.1086	0.39	3.424	0.95	0.229	0.87	–27.9	1775	7	1510	8	1328	10
7c	780	212	162	0.21	0.16	0.1067	0.25	3.415	0.96	0.232	0.93	–25.3	1745	5	1508	8	1345	11
9c	618	136	175	0.28	0.53	0.1057	0.45	2.711	1.15	0.186	1.06	–39.4	1727	8	1332	9	1100	11
1c	683	134	192	0.28	0.36	0.0999	0.41	2.288	0.93	0.166	0.84	–41.9	1621	8	1208	7	991	8
7r	3705	594	95	0.03	0.40	0.0935	0.29	1.827	0.88	0.142	0.83	–45.8	1498	5	1055	6	854	7
8r	3445	514	73	0.02	0.83	0.0924	0.33	1.727	0.90	0.136	0.83	–47.3	1475	6	1019	6	820	6
9r	2780	289	132	0.05	0.69	0.0750	0.58	0.992	1.09	0.096	0.92	–46.7	1068	12	700	6	591	5
15r	3761	349	159	0.04	1.59	0.0732	0.63	0.867	1.05	0.086	0.84	–49.8	1019	13	634	5	531	4
3r	3824	354	93	0.02	0.80	0.0693	0.52	0.823	0.98	0.086	0.83	–43.2	909	11	609	5	532	4
11r	3622	294	108	0.03	1.67	0.0598	0.80	0.630	1.16	0.076	0.85	–21.2	597	17	496	5	475	4
5r	3622	280	255	0.07	2.27	0.0548	0.87	0.542	1.22	0.072	0.86	–11.4	403	19	440	4	447	4

Errors on ratios and ages are quoted at 1 σ level.
f % common is the fraction of common ^{206}Pb estimated from the measured ^{204}Pb.
Disc. % refers to the degree of discordance of the zircon analysis.

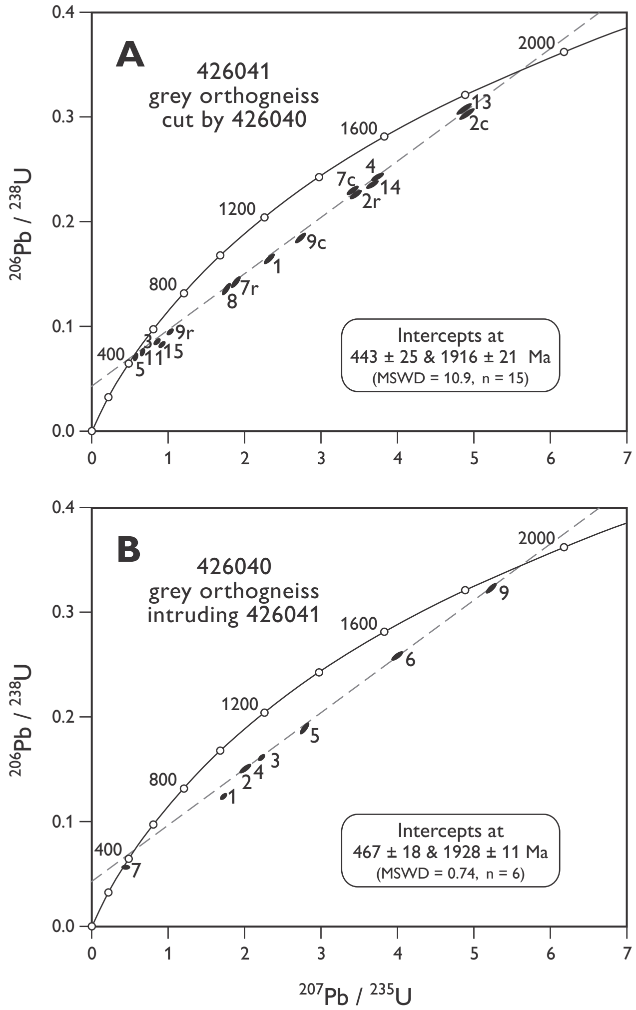


Fig. 6. U-Pb concordia diagrams for the two samples of orthogneiss from Charcot Land. **A**: Sample 426041. **B**: Sample 426040. Error ellipses show 1 σ errors and errors on the intercept ages are 2 σ.

phism soon after crystallisation of the protolith, and these rims have later suffered Pb loss. Only a few rims cluster around the lower intercept and could reflect the time when the gneiss suffered Caledonian metamorphism.

Sample 426040

The morphologies of the zircons in 426040 are very similar to those in sample 426041. Most have long prismatic shapes, but stubby grains also occur. The zircons are clear and range in size from 100 to 250 mm. Both homogenous and oscillatory zoned cores are present, while the rims are often metamict. In this study mostly cores were analysed. They plot on a discordia line (Fig. 6B) yielding intercept ages of 1928 ± 11 Ma and 467 ± 18 Ma (MSWD = 0.74). Two rims were analysed; these do not plot on the discordia line, but one of them plots on the concordia line, yielding a $^{206}Pb/^{238}U$ age of 366 ± 3 Ma.

Discussion

The two analysed samples of basement gneisses from the Charcot Land window yield identical upper intercept ages for the protolith within error, 1928 ± 11 and 1916 ± 21 Ma. The fact that the two orthogneisses yield the same age demonstrates that several distinct magma pulses were emplaced during this time period. If the Rb-Sr whole-rock age of *c.* 1850 Ma reported by Hansen *et al.* (1981) for the undeformed muscovite granite is valid, then the time of deformation and gneissification is bracketed between *c.* 1920 and 1850 Ma. The Palaeoproterozoic metamorphic effect seen in the growth of rims on zircons in sample 426041 might have been caused by the Palaeoproterozoic intrusive activity. The lower concordia intercepts suggesting Caledonian ages are indicative of some Pb loss and alteration of the zircons (Fig. 6), and can be linked to burial of the foreland beneath a several kilometre thick pile of Caledonian thrust sheets. Within the Charcot Land window limited Caledonian deformation is recorded, e.g. development of a planar cleavage in the diamictites of the Vendian Tillit Nunatak Formation, and associated folding in the underlying basement gneisses (Moncrieff 1989). However, Caledonian deformation was not pervasive and, as noted above, the Palaeoproterozoic muscovite granite body has no internal fabric.

The new age determinations reported here indicate that the protolith of the basement gneiss complex in Charcot Land is Palaeoproterozoic, rather than Archaean as suggested by Hansen (1976) and Hansen *et al.* (1981). At the current state of knowledge there is, in fact, no convincing isotopic evidence of the presence of Archaean basement rocks in any of the foreland windows along the western margin of the Caledonian orogen.

Volcano-sedimentary sequences of Palaeoproterozoic age are known in the Charcot Land and Eleonore Sø windows (Higgins *et al.* 2001), but are not known in the allochthonous thrust sheets that overlie the foreland windows. Similarly, the late Mesoproterozoic – early Neoproterozoic Krummedal supracrustal sequence that is widely represented in the thrust sheets structurally above these windows is not present within them. It could, therefore, be argued that the known Archaean rock units, such as the allochthonous Flyverfjord infracrustal complex south of latitude 72°50′N, represent a terrain that was accreted onto the Palaeoproterozoic foreland.

There remain many uncertainties in making regional assessments. For example, modern isotopic age data are still lacking for the crystalline basement rocks of the southern Gåseland window, while metasedimentary rocks found as infolded layers within the allochthonous crystalline basement gneisses north of latitude 72°N (Friderichsen & Thrane 1998; Thrane & Friderichsen 1999) are of uncertain age. The assumption that these infolded metasedimentary layers are related to the thick developments of the late Mesoproterozoic – early Neoproterozoic Krummedal sequence is not proven, and it cannot be excluded that they are equivalents of the Palaeoproterozoic Charcot Land supracrustal sequence. The absence of representatives of the Krummedal supracrustal sequence in the foreland windows could be considered as support for the view that this sequence was deposited far away from the Flyverfjord crystalline basement and that these units were juxtaposed during the Caledonian orogeny (Watt & Thrane 2001).

The ages obtained from the basement gneiss complex in the Charcot Land foreland window are not dissimilar from the ages obtained on the allochthonous crystalline basement complexes north of 72°50′N (Rex & Gledhill 1981; Kalsbeek *et al.* 1993; Thrane 2002), although the lithological make-up of the two basement complexes is different. Characteristic features of Charcot Land include the spectacular Palaeoproterozoic granitoid intrusions, which occur both as netveining dykes and as major undeformed plutons. Such characteristic features are uncommon in the allochthonous Palaeoproterozoic crystalline basement rocks to the north. It is the author's opinion that the grey orthogneisses in the allochthonous crystalline basement north of 72°50′N originally had much the same appearance as the Charcot Land orthogneisses, but that the former suffered much more intense deformation during the Caledonian orogeny. Thus, the Charcot Land basement gneisses and the allochthonous basement gneiss complexes north of 72°50′N could once have been parts of the same terrain prior to separation by Caledonian thrusting, with the major nappe-like structure on the north-east side of the Charcot Land window taking up the thrust movement. Alternatively, the two Palaeoproterozoic basement terrains may originally have been unrelated, and with different histories, but have been brought into close proximity by thrusting during the Caledonian orogeny.

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Reconnaissance Pb-Pb dating of single mineral phases by the step-leaching method: results from the Caledonides of East Greenland

Kristine Thrane

Reconnaissance Pb-Pb step-leaching analyses have been carried out on garnet and kyanite from the Krummedal supracrustal sequence in East Greenland, yielding respectively Neoproterozoic and Caledonian ages. These data support previous analyses suggesting that the Krummedal supracrustal sequence, widespread in southern parts of the East Greenland Caledonides, was affected by both an early Neoproterozoic and a Caledonian thermal event. Titanite and apatite fractions from the underlying crystalline basement rocks were analysed in order to obtain metamorphic ages, as a contrast and supplement to the numerous existing protolith ages on orthogneisses. The titanite yielded a date of 486 ± 15 Ma which, if interpreted as a true age, is older than the usual range of Caledonian ages in East Greenland. The significance of this date is uncertain, but one possibility is that it reflects extension and subsidence taking place prior to Caledonian collision. The apatite, in contrast, yielded a very young Caledonian date of 392 ± 24 Ma that may reflect the cooling of the basement gneisses to < 500°C subsequent to collision.

Keywords: Caledonian, East Greenland, geochronology, Neoproterozoic, step-leaching

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The Pb-Pb step-leaching (PbSL) method of Frei & Kamber (1995) makes it possible to date a range of rock-forming minerals that are normally difficult to date due to the low parent to daughter isotope ratios. Stepwise leaching of the mineral phases increases the data spread in uranogenic ($^{207}Pb/^{204}Pb$ – $^{206}Pb/^{204}Pb$) and thorogenic vs. uranogenic ($^{208}Pb/^{204}Pb$ – $^{206}Pb/^{204}Pb$) diagrams, and as a consequence the precision of Pb/Pb isochrons is improved (Frei *et al.* 1997). Another advantage of the method is that the corresponding uranogenic and thorogenic Pb ratios of the different leach solutions can be observed, and a signature of Pb-containing microscopic mineral inclusions revealed. Leach solutions that do not follow a linear pattern in the $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram reveal sources with different Th/U ratio from that of the host mineral. If all the analyses fall on a linear trend in the uranogenic diagram then the mineral inclusions are in isotopic equilibrium with the host mineral.

Investigations by the PbSL method were undertaken on selected samples collected during the 1997 and 1998 Geological Survey of Denmark and Greenland expeditions to the Kong Oscar Fjord region (72°–75°N) of the East Greenland Caledonides (Henriksen 1998, 1999). The study area (Fig. 1) is made up of major Caledonian thrust sheets displaced westwards across foreland windows (see also Higgins & Leslie 2004, this volume; Thrane 2004, this volume). The thrust sheets incorporate Archaean and Palaeoproterozoic orthogneiss complexes overlain by a thick late Mesoproterozoic – early Neoproterozoic metasedimentary succession known as the Krummedal supracrustal sequence; the latter is structurally overlain by the Neoproterozoic Eleonore Bay Supergroup and Tillite

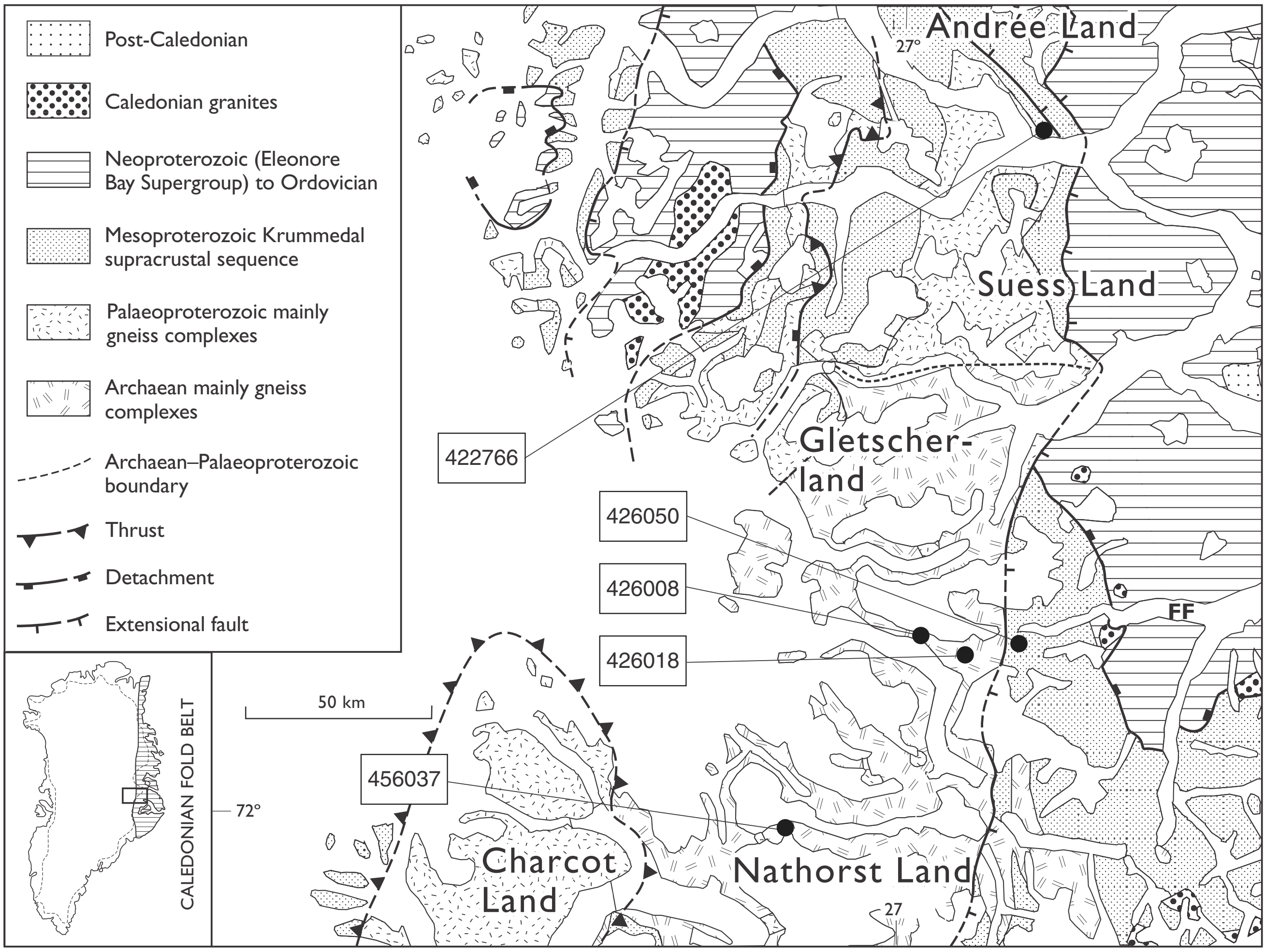

Fig. 1. Simplified geological map of the study area in the East Greenland Caledonides, with sample localities discussed in the text. Supracrustal rocks of Palaeoproterozoic age in Charcot Land are included with the Palaeoproterozoic gneiss complexes. **FF**, Forsblad Fjord.

Group, and Lower Palaeozoic rocks. These rock units have been variably reworked during the Caledonian orogeny.

Samples

In this study, PbSL analyses were carried out on garnet and kyanite from samples 426050 and 422766 of the late Mesoproterozoic – early Neoproterozoic Krummedal supracrustal sequence (Kalsbeek *et al.* 2000), with the objective of constraining the age of metamorphism which produced these minerals. In addition, PbSL analyses were undertaken on titanite from a garnet amphibolite (426037) and a gabbroic gneiss (426018), and on an apatite fraction from a tonalitic basement gneiss (426008). The latter three samples all derive from the crystalline basement complex underlying the Krummedal supracrustal sequence (Fig. 1), and the aim was to determine metamorphic ages for the mineral phases in the samples. Whole-rock Pb analyses were also carried out on samples 426008, 426018 and 426050.

Zircon grains from the crystalline basement complex in the study area analysed by ion microprobe have hitherto only yielded Archaean and Palaeoproterozoic magmatic ages. Although the rocks form parts of Caledonian thrust sheets and have undergone extensive Caledonian deformation and metamorphism, so far not a single Caledonian age has been obtained from zircon (Thrane 2002). While Caledonian K-Ar mineral ages have previously been recorded from all rock types in the study area (e.g. Rex & Higgins 1985), the spread in ages and uncertainties inherent in the method is indicative only of a metamorphic overprint of approximately Caledonian age.

Table 1. Sample data stepwise dissolution procedures

Sample	Weight mg	Step 1	Time min.	Step 2	Time min.	Step 3	Time hrs	Step 4	Time hrs	Step 5	Time hrs	Step 6	Time hrs	Step 7	Time hrs
426050 Garnet	236	Mix	10	4.4N HBr	45	8.8N HBr	3	8.8N HBr	24	conc. HF	48	conc. HF	260	8.8N HBr	290
426050 Kyanite	97	Mix	10	4.4N HBr	45	8.8N HBr	3	8.8N HBr	24	conc. HF	48	conc. HF	260		
422766 Kyanite	719	Mix	30	1.0N HBr	60	4.0N HBr	3	8.8N HBr	6	8.8N HBr	12	conc. HF	24	conc. HF	340
426018 Titanite	195	Mix	10	4.4N HBr	45	8.8N HBr	3	8.8N HBr	24	conc. HF	48	conc. HF	260		
426037 Titanite	71	Mix	10	4.4N HBr	90	8.8N HBr	3	8.8N HBr	24	conc. HF	50	conc. HF	340		
426008 Apatite	139	50% mix + 50% H_2O	10	50% mix + 50% H_2O	60	1.0N HBr	3	1.5N HBr	3	8.8N HBr	3	7N HNO_3	9		

Mix = 1.5N HBr – 2N HCl 12:1 mixture. All steps except number 1 were left on the hotplate during the dissolution time.

Methods

For the samples analysed in the present study, a 200 mm sieve fraction of each mineral separate was purified by hand-picking. The samples were digested in a series of steps using procedures documented in Table 1; the method used was modified after that of Berger & Braun (1997) and Frei *et al.* (1997). The purified Pb was loaded on Re filaments with silica gel and H_3PO_4, and the isotopic ratios analysed on the VG sector 54-IT instrument at the University of Copenhagen. Most analyses were performed using the Faraday multi-collector; a few steps that contained very little Pb were analysed with the single collector (ion counting Daly detector). Fractionation of Pb was monitored by repeated analyses of the NBS 981 standard (values of Todt *et al.* 1993) and amounted to 0.103 ± 0.016 %/amu. The calculations of regression lines follow the method of Ludwig (1999). Errors quoted are 2 σ.

Five to seven acid-leach steps were undertaken on each mineral separate. Whole-rock Pb and PbSL isotope data are listed in Table 2 and plotted in Figs 2–5.

PbSL results

Krummedal supracrustal sequence

The late Mesoproterozoic – early Neoproterozoic Krummedal supracrustal sequence is widely distributed in the southern part of the East Greenland Caledonides between 70° and 74°N (Fig. 1; Higgins 1988).

Sample 426050 was collected from the Krummedal supracrustal sequence south of innermost Forsblad Fjord, close to the faulted contact with the crystalline basement complexes (Fig. 1). The general metamorphic grade of the Krummedal supracrustal sequence is amphibolite facies, and the sample consists of quartz + plagioclase + K-feldspar + garnet + biotite + kyanite + sillimanite + amphibole + muscovite + titanite. The garnet and biotite represent early phases, while kyanite is a later phase that overgrows the deformation fabric of the biotite. Kyanite and K-feldspar crystallised at the same time, demonstrating that the rock has been exposed to high *P–T* conditions; during cooling, sillimanite, titanite and secondary biotite crystallised, and part of the kyanite was consumed during formation of muscovite.

Garnet and kyanite were analysed by PbSL (Fig. 2). Seven steps were performed on the garnet; all the steps, together with the whole-rock analysis, fall on a linear array in the $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram

Table 2. Pb-Pb step leaching (PbSL) data

Sample	Phase	Step	$^{206}Pb/^{204}Pb$	$\pm 2\sigma$*	$^{207}Pb/^{204}Pb$	$\pm 2\sigma$*	$^{208}Pb/^{204}Pb$	$\pm 2\sigma$*	r_1	r_2
426050	Wr		19.39	0.01	15.65	0.01	38.91	0.03	0.96	0.93
426008	Wr		14.32	0.01	14.61	0.01	38.51	0.03	0.93	0.92
426018	Wr		17.10	0.04	15.13	0.04	37.76	0.09	0.99	0.98
426050	Grt	1	23.34	0.64	16.01	0.44	39.09	1.08	1.00	1.00
426050	Grt	2	29.02	0.75	16.34	0.43	43.66	1.14	0.97	0.98
426050	Grt	3	69.99	1.99	18.74	0.53	116.25	3.30	1.00	1.00
426050	Grt	4	272.79	6.53	32.93	0.79	436.00	10.43	1.00	1.00
426050	Grt	5	99.56	1.31	20.49	0.27	44.90	0.59	1.00	1.00
426050	Grt	6	139.41	0.74	23.99	0.13	57.17	0.31	1.00	1.00
426050	Grt	7	152.05	4.39	24.48	0.71	87.67	2.53	1.00	1.00
426050	Ky	1	19.53	0.06	15.66	0.05	38.17	0.11	0.99	0.98
426050	Ky	2	20.45	0.14	15.70	0.11	38.52	0.27	0.99	1.00
426050	Ky	3	24.26	0.23	15.82	0.15	47.05	0.44	0.99	0.99
426050	Ky	4	34.83	0.16	16.42	0.08	65.68	0.31	0.99	0.99
426050	Ky	5	20.00	0.02	15.70	0.02	38.09	0.05	0.95	0.94
426050	Ky	6	33.13	0.19	16.49	0.10	38.81	0.22	0.99	0.99
422766	Ky	1	18.23	0.05	15.49	0.04	37.96	0.10	0.99	0.98
422766	Ky	2	19.92	0.16	15.64	0.12	40.81	0.32	0.99	1.00
422766	Ky	3	42.22	0.52	16.75	0.21	82.30	1.03	0.97	0.98
422766	Ky	4	171.43	19.09	24.12	2.69	326.96	36.41	1.00	1.00
422766	Ky	5	137.46	5.87	22.08	0.95	258.40	11.04	1.00	1.00
422766	Ky	6	20.59	0.04	15.70	0.03	38.60	0.07	0.98	0.97
422766	Ky	7	27.19	1.02	16.16	0.61	39.21	1.48	1.00	1.00
426018	Tit	1	16.50	0.02	15.09	0.02	37.40	0.04	0.95	0.95
426018	Tit	2	19.47	0.05	15.27	0.04	38.22	0.11	0.99	0.99
426018	Tit	3	104.74	1.13	20.29	0.22	56.20	0.61	1.00	1.00
426018	Tit	4	152.44	0.53	22.89	0.08	65.29	0.23	0.99	0.99
426018	Tit	5	120.05	0.35	20.97	0.06	56.99	0.17	0.99	0.99
426018	Tit	6	122.84	0.92	21.14	0.16	57.72	0.43	1.00	1.00
426037	Tit	1	16.53	0.22	15.11	0.20	37.11	0.50	1.00	1.00
426037	Tit	2	20.87	0.09	15.30	0.07	40.03	0.18	0.99	0.99
426037	Tit	3	76.66	1.92	18.21	0.46	46.56	1.17	1.00	1.00
426037	Tit	4	69.70	1.09	17.90	0.28	48.30	0.76	1.00	1.00
426037	Tit	5	36.53	0.18	16.15	0.08	41.79	0.21	0.99	0.99
426037	Tit	6	36.78	0.27	16.18	0.12	41.76	0.31	1.00	1.00
426008	Apa	1	27.93	0.06	15.36	0.04	40.96	0.09	0.99	0.99
426008	Apa	2	37.36	0.04	15.95	0.02	39.13	0.05	0.97	0.96
426008	Apa	3	38.28	0.03	15.91	0.01	38.70	0.04	0.93	0.85
426008	Apa	4	38.68	0.08	16.08	0.03	38.73	0.08	0.99	0.98
426008	Apa	5	64.84	0.94	21.41	0.31	35.92	0.52	1.00	1.00

Wr = whole-rock, Grt = garnet, Ky = kyanite, Tit = titanite, Apa = apatite.
r_1 = $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ error correlation (Ludwig 1988).
r_2 = $^{206}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$ error correlation (Ludwig 1988).

* Errors are two standard deviations absolute (Ludwig 1988).

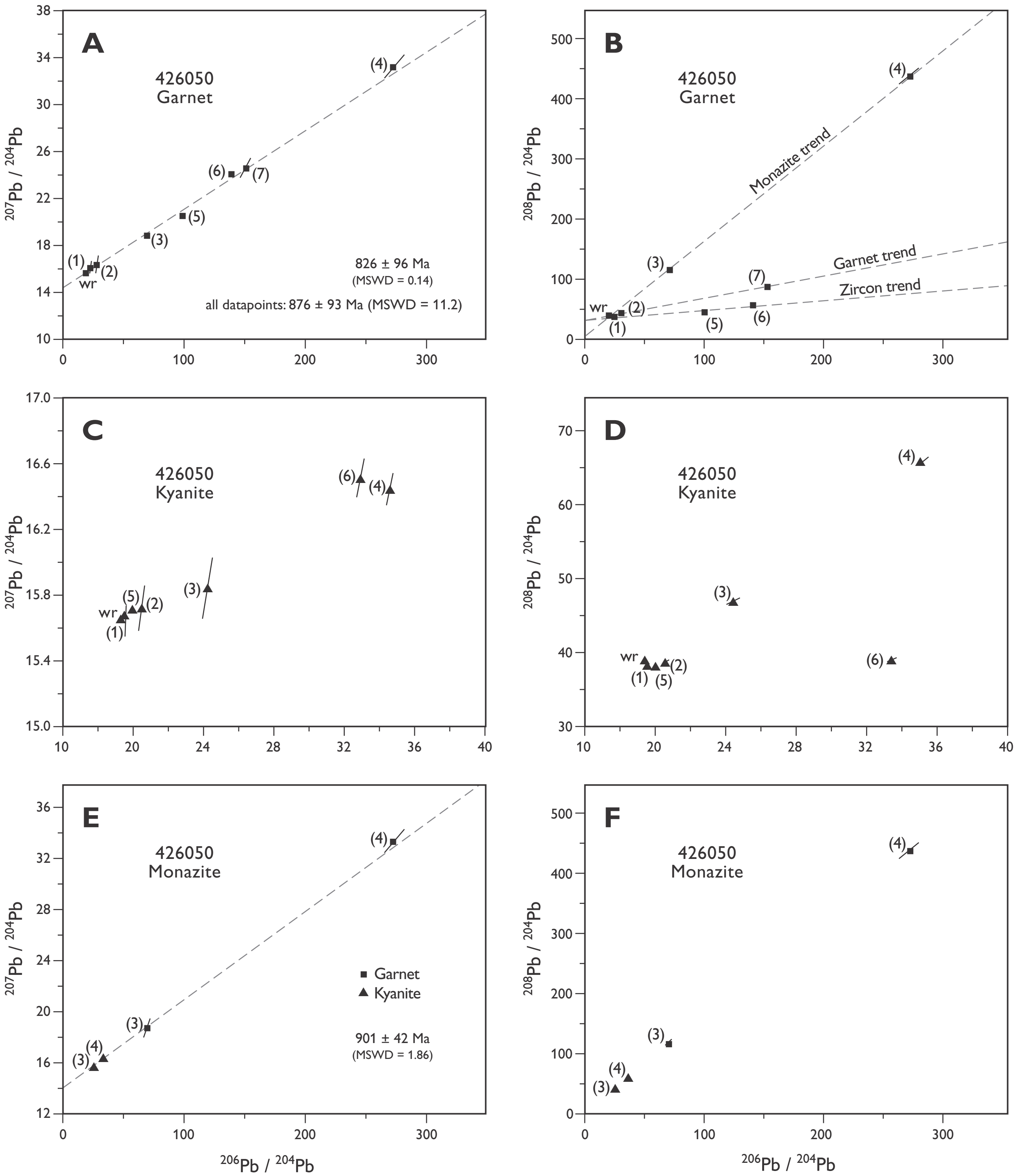

Fig. 2. Uranogenic ($^{207}Pb/^{204}Pb$ – $^{206}Pb/^{204}Pb$) and thorogenic vs. uranogenic ($^{208}Pb/^{204}Pb$ – $^{206}Pb/^{204}Pb$) Pb isotope diagrams with PbSL data from step-leaching experiments on garnet (**A**, **B**) and kyanite (**C**, **D**), from mica schist sample 426050 (Krummedal supracrustal sequence). **E** and **F** are steps representing monazite inclusions within the garnet and kyanite.

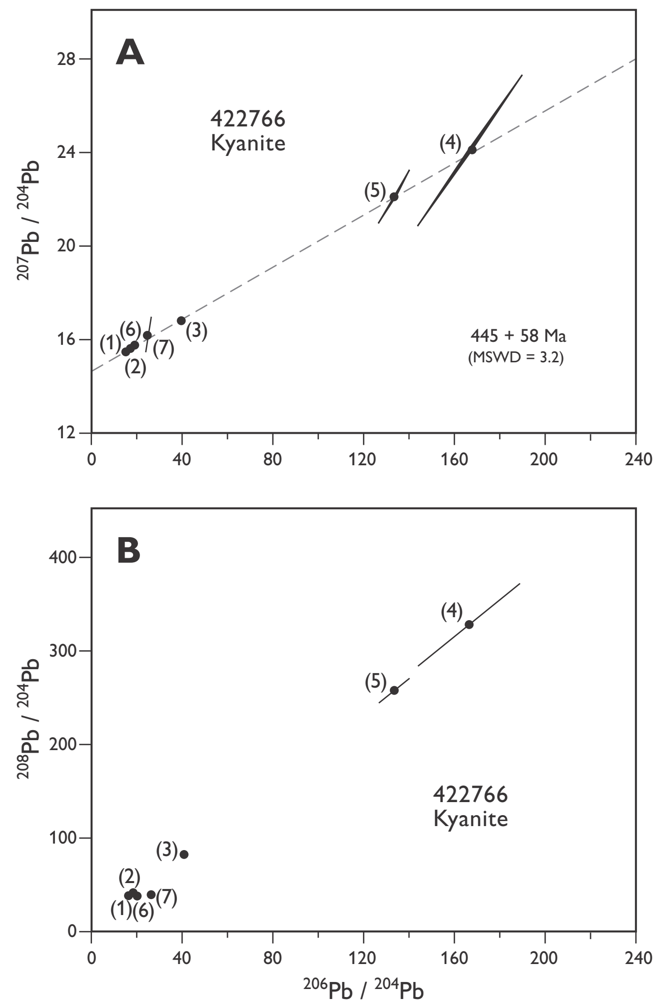

Fig. 3. Uranogenic ($^{207}Pb/^{204}Pb$ – $^{206}Pb/^{204}Pb$) and thorogenic vs. uranogenic ($^{208}Pb/^{204}Pb$ – $^{206}Pb/^{204}Pb$) Pb isotope diagrams with PbSL data from step-leaching experiments on kyanite, from mica schist sample 422766 (Krummedal supracrustal sequence).

(Fig. 2A) yielding a $^{207}Pb/^{206}Pb$ date of 876 ± 93 Ma (MSWD = 11.2). The $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram (Fig. 2B) reveals the presence of mineral inclusions in the garnet. The different Th/U ratios of the host mineral and the inclusions may explain the large MSWD value of the errorchron. Steps 3 and 4 have very high Th/U ratios, interpreted as representing monazite inclusions (Th/U > 3; DeWolf *et al.* 1996). All the monazite is leached out in step 4, causing the observed drop in the Th/U ratio. The very low Th/U ratio in steps 5 and 6 is characteristic of zircon leach steps (Th/U < 1; DeWolf *et al.* 1996). All the zircon is dissolved in step 6. Step 7 was undertaken because of the red colour of the residue after step 6, showing that garnet was still present.

The only leach steps dominated by garnet are the two first, where all the most primitive Pb is extracted, and step 7. These three steps together with the whole-rock analysis yield an isochron date of 826 ± 96 Ma (MSWD = 0.14). The large error of the date is due to the low precision of step 7.

The same procedure was carried out on kyanite, and again there is evidence for the presence of both monazite and zircon inclusions (Fig. 2D). Steps 3 and 4 are dominated by monazite, and step 6 by zircon. Three steps (1, 2 and 5) are interpreted as representing kyanite, but while the individual analyses are very precise they do not form a sufficiently wide spread in the Pb ratios to yield a precise date. The Pb whole-rock analysis and the kyanite-dominated steps define a slope which yields an isochron date of 1219 ± 790 Ma (MSWD = 0.24). Given the large uncertainty, this date does not yield any useful chronological information. The monazite-dominated steps from the garnet (3 and 4) and the kyanite (3 and 4) plot on a linear trend in both the $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagrams (Fig. 2E, F). The four monazite steps yield an isochron date of 901 ± 42 Ma (MSWD = 1.86).

The monazite and garnet dates are in general accordance with the ion microprobe analyses of metamorphic zircon rims from the Krummedal supracrustal sequence that have yielded Neoproterozoic ages around 940 Ma (Thrane *et al.* 1999a, b; Kalsbeek *et al.* 2000). The cores of detrital zircons from the same study yielded ages ranging from *c.* 1100 to 1900 Ma, and it therefore serves no practical purpose to calculate an age from the zircon steps, as these will represent a mixture of ages.

Sample 422766, also derived from the Krummedal supracrustal sequence, was collected by J.C. Escher and K.A. Jones in the southern part of Andrée Land, very close to the contact with the structurally underlying crystalline basement (Fig. 1). The sample contains garnet and kyanite crystals up to 5 cm in diameter.

The kyanite was analysed by PbSL, while the garnet was considered too altered to justify analysis. Seven steps were undertaken on the kyanite, and the analyses represent an almost perfect leaching pattern (Fig. 3); all fall on a linear array in both the $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagrams, except for step 7 which has a lower $^{208}Pb/^{204}Pb$ ratio that probably indicates the presence of zircon inclusions. A $^{207}Pb/^{206}Pb$ date of 437 ± 62 Ma (MSWD = 2.6) is obtained using all the steps, while if step 7 is excluded a date of 445 ± 58 Ma (MSWD = 3.2) is obtained. The large error is due to the analytical error of steps 4 and 5.

Crystalline basement

The East Greenland Caledonian orogen is dominated by major thrust sheets of reworked orthogneiss complexes. The crystalline basement is divided into an Archaean terrain to the south of 72°50′N and a Palaeoproterozoic terrain to the north (Fig.1; Thrane 2002).

PbSL analyses on titanite from a metagabbroic gneiss (426018) in the Archaean crystalline basement complex west of innermost Forsblad Fjord (Fig. 1) were undertaken. This gabbroic gneiss has yielded a Sm-Nd model age (t_{DM}) of 3.25 Ga (Thrane 2002). The whole-rock analysis has the same Pb ratios as step 1, indicating that the whole-rock and titanite are in equilibrium. The six leach steps together with the whole-rock analysis yield an isochron date of 504 ± 48 Ma (MSWD = 1.81). However, the $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram (Fig. 4B) suggests that the titanite contains small amounts of monazite inclusions, which result in slightly elevated Th/U ratios for steps 3 and 4 compared with the titanite trend. If steps 3 and 4 are excluded, an isochron date of 486 ± 15 Ma (MSWD = 0.16) is obtained (Fig. 4A).

Titanite from a sheared garnet amphibolite (426037) cutting the basement gneisses of Nathorst Land (Fig. 1) was also analysed. All six data points define an isochron date of 335 ± 140 Ma (MSWD = 0.11; Fig. 4C); the large error of the date is due to the limited spread in the data points, as well as the large analytical errors of steps 3 and 4. In the $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram (Fig. 4D) the analyses show an unusual

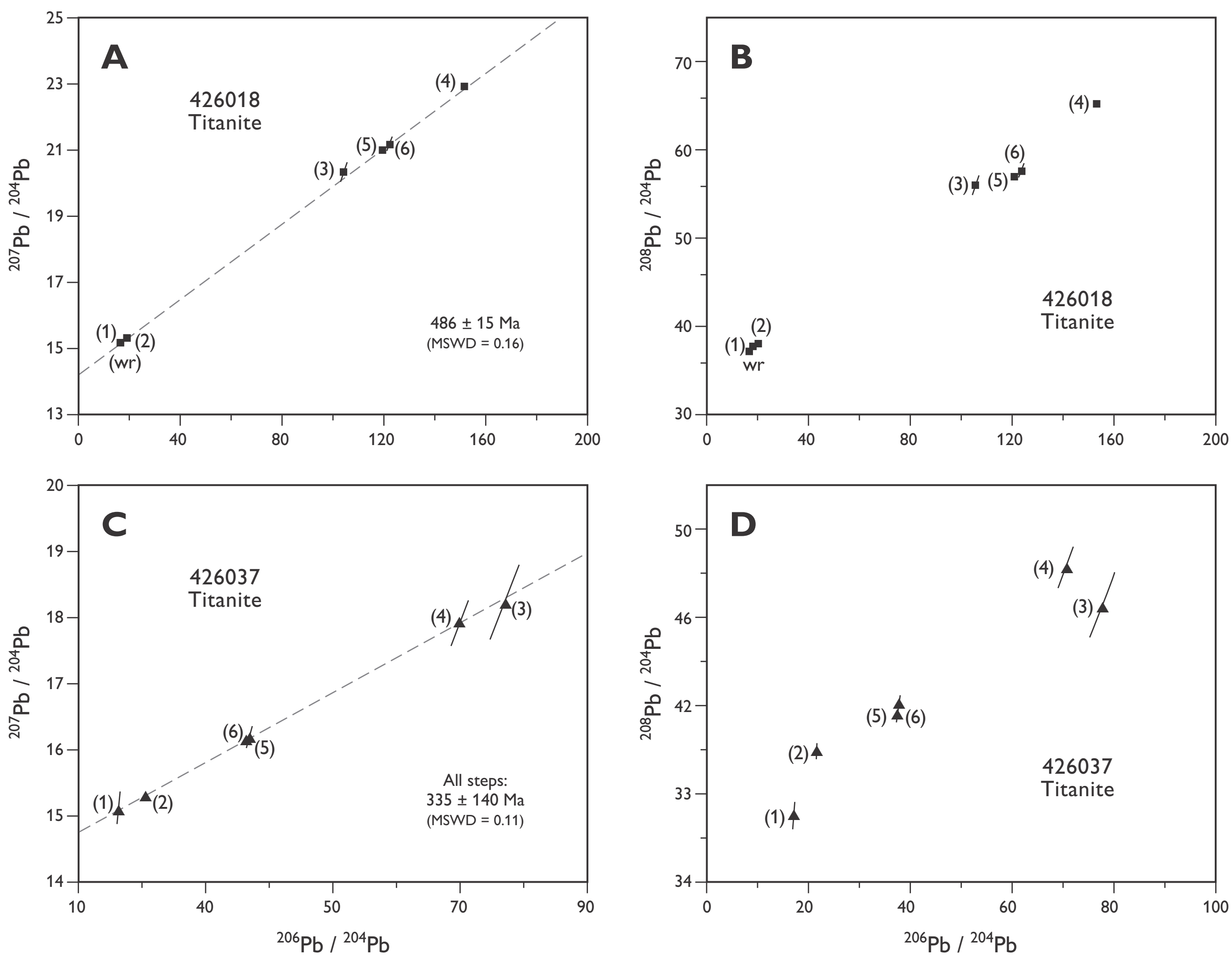

Fig. 4. Uranogenic ($^{207}Pb/^{204}Pb$ – $^{206}Pb/^{204}Pb$) and thorogenic vs. uranogenic ($^{208}Pb/^{204}Pb$ – $^{206}Pb/^{204}Pb$) Pb isotope diagrams with PbSL data from step-leaching experiments on titanite from a gabbroic gneiss in the basement (**A**, **B**; sample 426018) and a garnet amphibolite (**C**, **D**; sample 426037).

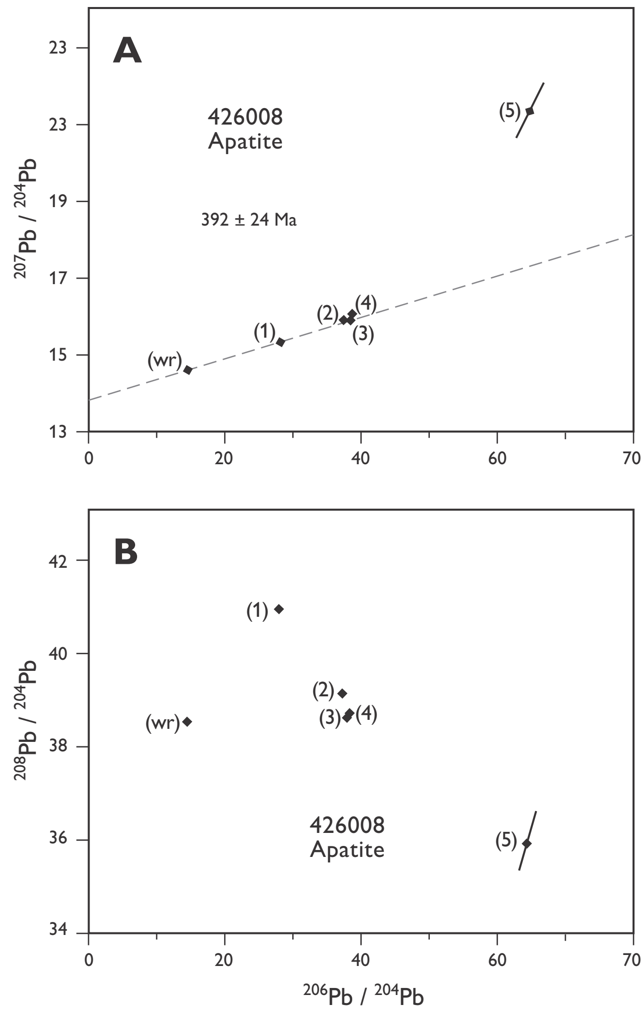

Fig. 5. Uranogenic (^{207}Pb/^{204}Pb – ^{206}Pb /^{204}Pb) and thorogenic vs. uranogenic (^{208}Pb/^{204}Pb – ^{206}Pb /^{204}Pb) Pb isotope diagrams with PbSL data from step-leaching experiments on apatite from a tonalitic basement gneiss (sample 426008).

pattern: step 2 has an elevated Th/U ratio compared to the general trend while step 3 has a lower Th/U ratio. These features cannot be explained by the presence of monazite and zircon inclusions. If steps 2 and 3 are excluded from the isochron an even less precise date of 309 ± 230 Ma (MSWD = 0.03) is obtained.

Apatite from a tonalitic basement gneiss (426008) collected west of innermost Forsblad Fjord (Fig. 1) was also analysed. Zircon crystals from this sample have yielded U-Pb ages of *c.* 2800 Ma (Thrane 2002). Apatite dissolves much more easily than silicate phases, so a weaker acid and shorter leaching times were used in this experiment. The analyses form a complex pattern (Fig. 5). Step 1 is too thorogenic to derive from apatite, and it is interpreted instead as influenced by allanite since this is very easily dissolved and has a higher Th/U ratio than apatite. Step 2 is less thorogenic than step 1, but more so than step 3, and is therefore interpreted as a mixture between allanite and apatite. Step 3 is the only step dominated by apatite. The only possible way to obtain a date is thus by combining the whole-rock analysis and step 3, which yields a date of 392 ± 24 Ma (Fig. 5A). Step 1 falls on the isochron, while step 2 falls slightly above, demonstrating that the two mineral phases were almost in equilibrium, with the presumed allanite being slightly older corresponding to its higher closure temperature. In the ^{208}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb diagram it seems that both steps 3 and 4 are apatite steps, but in the ^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb diagram it is clear that step 4 is older and must be influenced by zircon inclusions which were leached out in the strong acid of step 5. The whole-rock analysis and step 5 yield a date of 2159 ± 46 Ma.

Summary and discussion

The analyses reported in this paper are the first PbSL analyses reported on rocks from the Caledonian orogen of East Greenland. All the samples have been analysed only once. Several of the dates obtained are not consistent with existing ages from the area, and some of the new dates are also somewhat controversial; replicate analyses should therefore be made for all the samples, to confirm that the dates are consistent, before any definite interpretations can be made. Thus different interpretations are presented in the discussion that follows.

The reliability of the PbSL method is still an open question. The main concern is the importance of the micro-inclusions contained in the mineral being analysed, and whether it is possible to be certain which combination of minerals is dissolved and affect the individual steps. This important point has not yet been resolved, and must be kept in mind when evaluating the new dates.

Supracrustal rocks

The PbSL study demonstrates that Neoproterozoic monazite and garnet are present in the Krummedal supracrustal sequence; evidence of Caledonian monazite has previously been reported (Kalsbeek *et al.* 2000). Zoned garnets have often been recorded (Elvevold & Gilotti 1999; Thrane *et al.* 1999b), of which the outer rims are interpreted to be Caledonian whereas there has previously been doubt as to whether the cores were Neoproterozoic or early Caledonian. In contrast, the presence of Neoproterozoic kyanite has not been demonstrated in this study. Petrographically it is often difficult to determine to which mineral paragenesis the kyanite belongs, and thus it cannot be ruled out that some of the kyanite in parts of the Krummedal supracrustal sequence may be Neoproterozoic (Elvevold & Spears 2000).

Evidence of early Caledonian metamorphism in the crystalline basement?

The closure temperature for titanite is estimated by Dahl (1997, and references therein) to be in the range of 620–680°C, and by Cherniak (1993) in the range of 575–707°C, depending on the grain size. The titanite date of 486 ± 15 Ma for sample 426018, together with the date of the monazite inclusions, suggest that the crystalline basement did experience Caledonian medium to high-grade metamorphism.

No other ages of *c*. 486 Ma have yet been obtained in East Greenland. The age of the Caledonian collision in East Greenland is usually referred to the interval 430–425 Ma, on the basis of zircon ages from granite intrusions and the time of migmatite formation in the Krummedal supracrustal sequence (Watt *et al.* 2000; Kalsbeek *et al.* 2000, 2001). No comparable zircon ages have been recorded in the crystalline basement rocks in the study area, where evidence of the Caledonian overprint is restricted to imprecise lower concordia intercept ages ranging from 467 ± 18 Ma to 443 ± 25 (Thrane *et al.* 1999a). It is not possible to determine whether these lower intercept ages correspond to the 'traditional' East Greenland Caledonian range of events, or to a potential earlier event. In North-East Greenland Caledonian zircons have been recorded in some Palaeoproterozoic gneisses (Kalsbeek *et al.* 1993), which is in line with the assumption that the crystalline basement complexes of this northern region were more strongly reworked during the Caledonian orogeny.

It might be speculated that the titanite date of 486 ± 15 Ma is a cooling age, while the slightly older monazite micro-inclusions in the titanites could represent the peak of a collision event – comparable to the early Caledonian event in Scandinavia (Mørk *et al.* 1988; Andréasson 1994, 2000). However, this is not possible in East Greenland, since Ordovician carbonates were still being deposited in the Iapetus-margin basin that lay east of the Laurentian crystalline basement at this time; there is no associated clastic input that would be expected if a collision had taken place nearby. The exceptionally thick Ordovician carbonate succession in East Greenland (Smith 1991) is indicative of a significant increase in the rate of subsidence, and it is possible that the *c*. 500 and 486 Ma dates are instead related to extension. The *c*. 430 Ma ages are thus still the best indication of the main Caledonian collision phase in East Greenland. Apatite, yielding the youngest Caledonian date of 392 ± 24, could be interpreted to represent the time where the basement gneisses cooled to < 500°C (Dahl 1997).

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The Eleonore Sø and Målebjerg foreland windows, East Greenland Caledonides, and the demise of the 'stockwerke' concept

A.K. Higgins and A. Graham Leslie

Recognition of the Eleonore Sø and Målebjerg foreland windows during the 1997–1998 regional mapping expeditions to the East Greenland Caledonides provided critical evidence for large-scale, westward-directed thrusting in the Kong Oscar Fjord region (72°–75°N), a revelation that dealt a final blow to the 'stockwerke' concept of an *in situ* highly mobile infrastructure characterised by rising fronts of Caledonian migmatisation and metasomatism. This paper reviews earlier investigations in both the Eleonore Sø and Målebjerg areas, and the misinterpretations of rock units that initially obscured recognition of their foreland affinity. The Eleonore Sø and Målebjerg windows can now be placed in context, as part of the lowest structural level of the foreland-propagating thrust pile of the Kong Oscar Fjord region.

Keywords: Caledonides, East Greenland, tectonic windows

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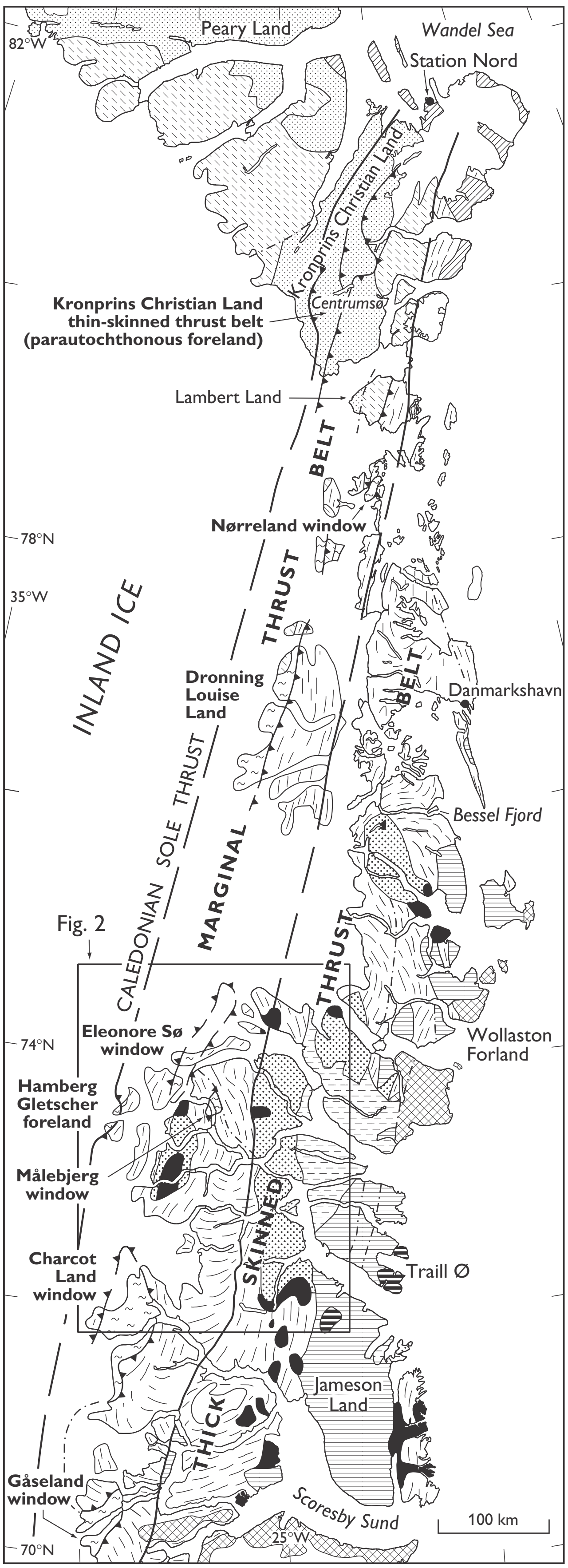
The 1300 km long East Greenland Caledonides (70°–81°30′N) can be broadly divided into western marginal and eastern thick-skinned thrust belts (Fig. 1; Higgins & Leslie 2000; Higgins *et al.* 2001, 2004). The western thrust margin of the orogen against the Caledonian foreland is largely obscured by the Greenland Inland Ice, with the most continuous foreland exposures west of Kronprins Christian Land in the extreme north. Elsewhere foreland areas are locally preserved in the westernmost nunataks and in scattered tectonic windows exposed along the length of the marginal thrust belt (Fig. 1). While the foreland windows all exhibit some disturbance due to Caledonian deformation, and have therefore been classified as para-utochthonous, the similarities of the successions preserved within the various windows and that in the undisturbed foreland, suggest they are only slightly displaced from their original locations (Higgins *et al.* 2001). Prior to the Survey's 1997–1998 regional mapping programme, large-scale thrusting had not been demonstrated in the Kong Oscar Fjord region (Fig. 2; 72°–75°N). Indeed, new investigations in this region (Hartz & Andresen 1995; Andresen & Hartz 1998; Andresen *et al.* 1998), had led to interpretations of Caledonian orogenesis in terms of upward and lateral movement of light, low viscosity, lower crustal material towards the region of maximum crustal extension, a process compared to Haller's (1953, 1970, 1971) 'stockwerke' concept, and that carried the implication that orogenic contraction was negligible.

The recognition of the Målebjerg and Eleonore Sø foreland windows during the Survey's 1997–1998 regional mapping provided incontrovertible evidence for large-scale westward-directed Caledonian thrusting in the Kong Oscar Fjord region (Figs 2, 3). This discovery completely undermined arguments for explaining orogenic development in terms of the *in situ* 'stockwerke' concept or similar processes, and at the same time resolved a number of outstanding problems of East Greenland geology. The areas of both



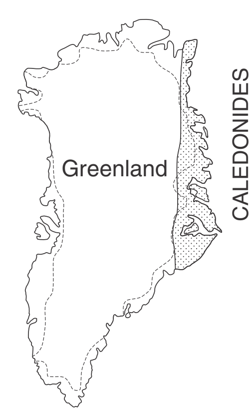
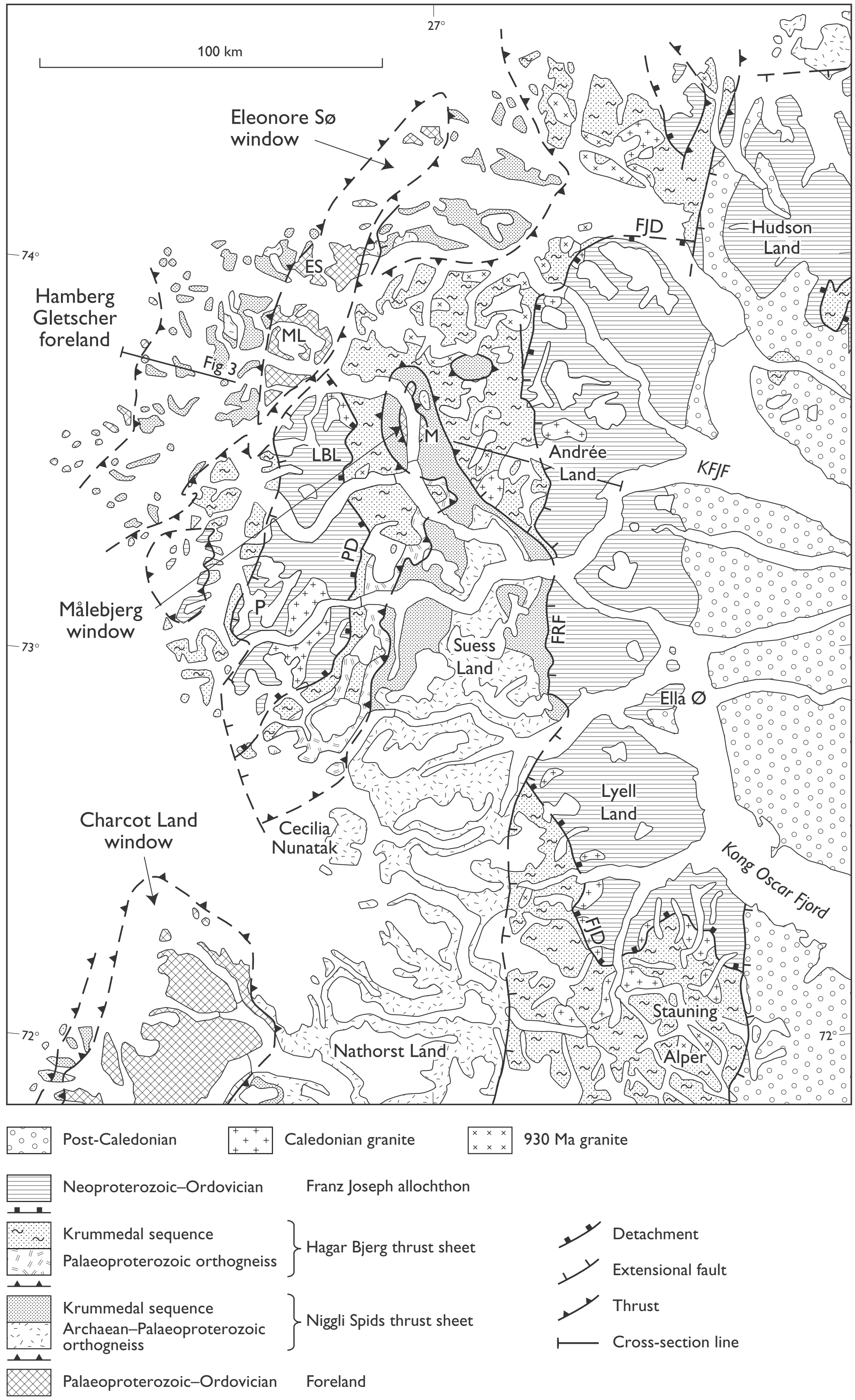


Fig. 1. Geological map of the East Greenland Caledonides, showing location of the foreland windows in the western marginal thrust belt. The frame indicates the region between 71°50′ and 74°30′N, shown at a larger scale in Fig. 2, which includes the Målebjerg and Eleonore Sø windows. Modified from Higgins & Leslie (2000).

Fig. 2. Geological map of North-East Greenland 71°50′–74°30′N, showing location of the Eleonore Sø, Målebjerg and Charcot Land windows, and the Hamberg Gletscher foreland. The legend depicts the units contained in the two thrust sheets and Franz Joseph allochthon overlying the windows. The Målebjerg and Eleonore Sø areas are shown in more detail in Figs 5 and 6. **ES**, Eleonore Sø; **FJD**, Franz Joseph detachment; **FRF**, Fjord region fault; **KFJF**, Kejser Franz Joseph Fjord; **LBL**, Louise Boyd Land; **M**, Målebjerg; **ML**, J.L. Mowinckel Land; **P**, Petermann Bjerg; **PD**, Petermann detachment. The line of the cross-section shown in Fig. 3 is indicated.



windows had been investigated prior to the Survey's regional mapping, the Eleonore Sø area by Katz (1952) and the Målebjerg area in Andrée Land by Haller (1953). However, while Haller (1971) had speculated that the Eleonore Sø region might be a window (see below), neither Katz nor Haller identified the Lower Palaeozoic rock units whose presence clarifies the structural setting beyond any doubt.

This paper reviews the history of investigations in the Eleonore Sø and Målebjerg areas, and the early misinterpretations of rock units that obscured their recognition as parts of the Caledonian foreland. These misinterpretations were closely linked to the evolution of ideas to explain orogenic developments in East Greenland, that culminated in the 'stockwerke' concept as elaborated by Haller (1970, 1971).

Haller's 'stockwerke' model was a development of the earlier ideas of Backlund (1930, 1933) and Wegmann (1935). The crystalline gneiss complexes constituting the central metamorphic complex that underlie, and appear to be interleaved with high grade metasediments, were envisaged by Haller as elements of a highly mobile infrastructure formed by the rise of Caledonian fronts of migmatisation and metasomatism. Associated mechanical and chemical changes were thought to have led to *in situ* transformation of a succession of sedimentary rocks into the gneissic and granitic rocks of the infrastructure, which was considered 'entirely rejuvenated'. The mobile migmatite domes of the infrastructure were bordered by and overlain by the more rigid sedimentary suprastructure, with the two levels separated by a thick, often strongly folded, 'zone of detachment'. The term 'stockwerke' refers to the different levels of the growing orogenic belt; in German 'stockwerke' refers to the floors or stories of a house. In Haller's map compilations the infrastructure of the central metamorphic complex is depicted as Caledonian synorogenic granite (Koch & Haller 1971), and he remarks that regional thrusting was probably of "no importance in their formation" (Haller 1971, p. 179). The spectacular 'stockwerke' structures in East Greenland, and Haller's drawings, are still presented in modern textbooks (e.g. Best 2003) as classic examples of mantled gneiss domes, and metamorphic core complexes.

The Målebjerg and Eleonore Sø windows can now be placed in their correct context as parts of the lowest structural level of the foreland-propagating thrust pile in the southern half of the Caledonian orogen (70°–75°N; Elvevold *et al.* 2000; Higgins *et al.* 2004). These foreland windows are structurally overlain by a lower Niggli Spids thrust sheet and an upper Hagar Bjerg thrust sheet, both with substantial westward displacements (Fig. 3). The very thick Neoproterozoic to Lower Palaeozoic succession (Eleonore Bay Supergroup, Tillite Group, Kong Oscar Fjord Group) is distinguished as the Franz Joseph allochthon, and viewed as an upper detached part of the Hagar Bjerg thrust sheet.

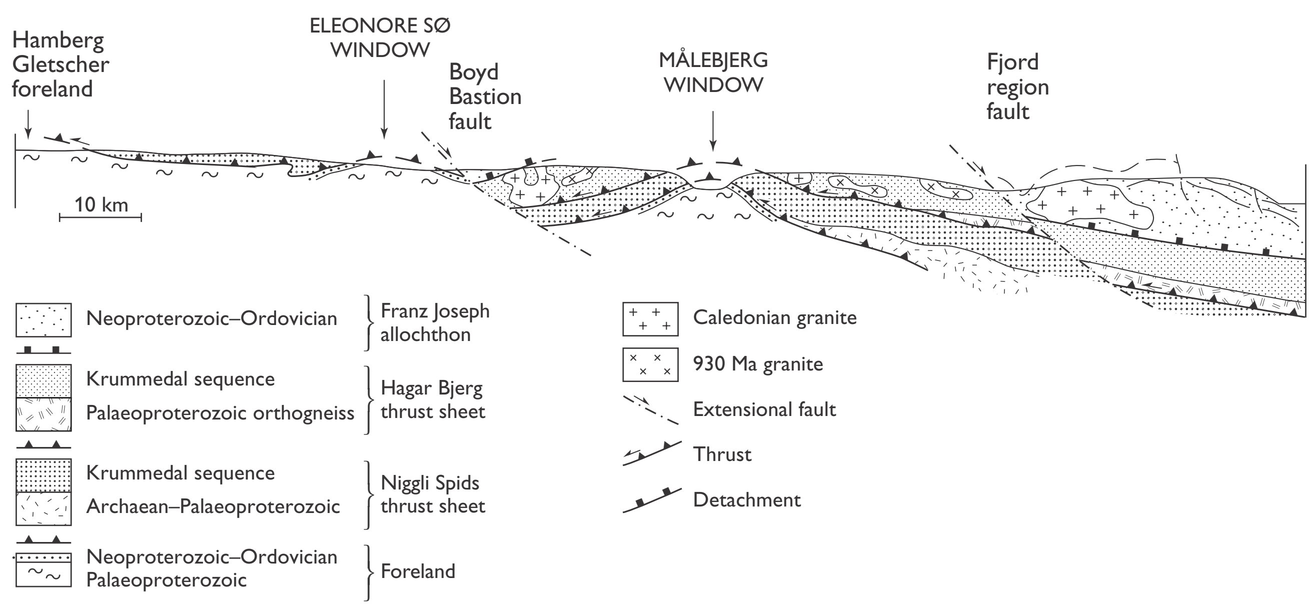


Fig. 3. Cross-section through the Eleonore Sø and Målebjerg windows showing the foreland windows overlain by two thrust sheets and the Franz Joseph allochthon. Section line is indicated on Fig. 2.

Geological setting

The Eleonore Sø and Målebjerg windows (Figs 2, 3) are characterised by thin (< 400 m) Neoproterozoic – Lower Palaeozoic sedimentary successions. The latter comprise a lens-like 31 m thick diamictite in the Målebjerg window correlated with the Vendian Tillite Group, a 143–350 m thick quartzite sequence with *Skolithos* ichnofossils of Early Cambrian age defined as the Slottet Formation, and a 32–45 m thick dolomite sequence of Cambrian–Ordovician age defined as the Målebjerg Formation (Smith *et al.* 2004, this volume). This thin Vendian–Ordovician foreland succession is in great contrast to the 18.5 km thick, partly equivalent succession, preserved in the structurally overlying Franz Joseph allochthon. In the Eleonore Sø window the Slottet Formation overlies a Palaeoproterozoic sedimentary-volcanic assemblage with profound unconformity, and in the Målebjerg window unconformably overlies gneisses of presumed Palaeoproterozoic age.

The Niggli Spids thrust sheet structurally overlying both windows (Fig. 3) incorporates crystalline gneiss complexes and high-grade metasedimentary successions, which were reworked to varying degrees during Caledonian orogenesis. Ion microprobe studies on zircons from the orthogneisses have yielded Archaean and Palaeoproterozoic protolith ages (Thrane 2002; unpublished data 2004, F. Kalsbeek and A.P. Nutman), that confirm earlier less precise isotopic ages by other methods (e.g. Rex & Gledhill 1981). The high-grade metasedimentary rocks of both the Niggli Spids thrust sheet and the higher Hagar Bjerg thrust sheets are correlated with the Krummedal supracrustal sequence (Higgins 1988). The Krummedal sequence metasedimentary rocks in the Hagar Bjerg thrust sheet host a suite of 940–910 Ma augen granites generated during an early Neoproterozoic thermal event (Kalsbeek *et al.* 2000; Watt *et al.* 2000; Watt & Thrane 2001). Ion microprobe studies of detrital zircons from the Krummedal sequence show the youngest detrital zircons are about 1050 Ma old, and deposition of the sediments must therefore have taken place in the period *c.* 1050–940 Ma ago (late Mesoproterozoic – early Neoproterozoic). High-grade regional metamorphism and associated anatexis during the Caledonian orogeny led to generation of a new suite of 440–425 Ma granites (Watt *et al.* 2000; Hartz *et al.* 2001; Kalsbeek *et al.* 2001a, b).

The Franz Joseph allochthon is made up of the *c.* 13 km thick Neoproterozoic Eleonore Bay Supergroup (Riphean–Sturtian; post-900 to *c.* 590 Ma), the 800–1000 m thick Vendian Tillite Group (Hambrey & Spencer 1987), and the *c.* 4 km thick Cambrian–Ordovician Kong Oscar Fjord Group (Cowie & Adams 1957; Smith & Bjerreskov 1994; Smith *et al.* 2004, this volume). This succession is widely exposed in the central fjord system of the Kong Oscar Fjord region, and also occurs in a more restricted area to the west in Louise Boyd Land and around Petermann Bjerg (Fig. 2). The contact between the Eleonore Bay Supergroup and underlying high-grade Krummedal metasediments of the Hagar Bjerg thrust sheet is a shear zone, in which both extensional and contractional strain have been recorded. In the west the shear zone is known as the Petermann detachment (PD, Fig. 2; Escher & Jones 1998, 1999), and in the east the Franz Joseph detachment (FJD, Fig. 2). The latter is only well exposed between northern Andrée Land and Hudson Land (Leslie & Higgins 1998, 1999), and between Lyell Land and the Stauning Alper (cf. Tindern detachment of White *et al.* 2002). In most of the fjord region the present-day west limit of the Eleonore Bay Supergroup outcrop is a late-orogenic extensional fault, the 'fjord region fault' of this paper (FRF, Fig. 2). This corresponds to the 'fjord zone fault' of Larsen & Bengaard (1991) and to part of the 'fjord region detachment' system of Hartz & Andresen (1995) and co-workers (Andresen *et al.* 1998; Hartz *et al.* 2000; White *et al.* 2002). Conodonts extracted from the uppermost levels of the Ordovician succession exhibit very low conodont alteration indices (Smith 1991; Stouge *et al.* 2002), which demonstrate that the Franz Joseph allochthon in this region cannot have been over-ridden by higher thrust sheets.

Historical review: the Målebjerg and Eleonore Sø areas

The investigations of John Haller and others working with Lauge Koch's long series of East Greenland geological expeditions (1926–1958) more than 40 years ago, essentially predated the era of isotopic age determinations. The first, very few, K-Ar ages from East Greenland only became available in 1961 (Haller & Kulp 1962), after the cessation of field work in 1958. The evolution of ideas and the conclusions of their studies were thus almost entirely based on field observations and interpretations. The revolutionary concept of plate tectonics did not make its mark until the late 1960s, and while it was widely accepted by many geologists, John Haller considered that its enthusiastic reception had obscured its shortcomings (see Haller 1979).

Lauge Koch's sledge journeys along the length of the Caledonian orogen led him to propose that the greater part of the gneisses that previous expeditions assumed to be Archaean were "in reality the nucleus of a Caledonian folding range" (Koch 1929, p. 60, fig. 20). However, at this time the gneisses of the inner fjords between Scoresby Sund and Kejser Franz Joseph Fjord were still considered to be Archaean. Meanwhile, British geologists working in the inner part of the Kong Oscar Fjord region compared the gneisses and metasedimentary rocks of the so called 'Central Metamorphic Complex' to the Lewisian and Dalradian of Scotland, and concluded that the Caledonian orogeny was 'superficial' (Wordie 1930; Parkinson & Whittard 1931). Helge Backlund investigated the same region, but reached a different interpretation (Backlund 1930, 1932). He proposed that Wordie's 'Archaean' granites and gneisses were the result of Caledonian granitisation and migmatisation of a varied sedimentary succession, similar to the processes of gneiss formation in Fennoscandia. Backlund's views were largely supported by Wegmann's (1935) report on the 'Caledonian orogeny', in which Wegmann speculated that any former basement to the Caledonian geosyncline (Greenlandian) would have been transformed to such a degree as to be unrecognisable (see also reviews of early work in Haller 1971, pp. 6–35).

Up to 1950 no outcrops of the Caledonian foreland had been recognised in East Greenland. However, the period 1952–1961 saw the discovery and description of foreland areas in Kronprins Christian Land in the north (Fränkl 1954, 1955), in Dronning Louise Land (Peacock 1956, 1958), and in western Gåseland in the south (Wenk 1961; see Fig. 1). All of these discoveries were incorporated into Haller's major reviews and map compilations of the East Greenland Caledonides (Haller 1970, 1971, 1983; Koch & Haller 1971).

The area around Målebjerg (73°27′N) was first mapped by John Haller in 1949–1950 as part of a regional investigation of western Andrée Land (Haller 1953): it was a key area for his development of the 'stockwerke' models of the Caledonian orogeny. On the basis of his studies in Andrée Land, Haller reached wide-ranging conclusions as to the nature of the Caledonian orogeny, elaborating on the earlier interpretations of Backlund (1930, 1932) and Wegmann (1935). Thus Haller (1953) stated in his English summary (p. 190) that: "The dispute as to the age of the 'Central Metamorphic Complex' is, as far as the region of Kejser Franz Josephs Fjord is concerned, finally resolved by the present study, which shows that several stratigraphic subdivisions, recognised in the Eleonore Bay Formation, can be traced also in the gneisses, schists and marbles of the 'Central Metamorphic Complex'. The crystalline rocks of sedimentary origin represent members of the Groenlandium, metamorphosed and metasomatically altered during the Caledonian Orogeny." With respect to the area around Målebjerg, he correlated the distinctive quartzites and dolomites found there with Fränkl's (1951) 'Alpefjord Series', i.e. the lower levels of the Eleonore Bay 'Formation' (Haller 1953).

The 'Groenlandium' (also spelt Grönlandium, Groenlandian or Greenlandian) is a now obsolete term that originally encompassed all Proterozoic sedimentary (and metasedimentary) rocks of North and East Greenland (Koch 1930). Within the Caledonides of East Greenland it was considered to be made up entirely of the Eleonore Bay 'Formation' and equivalents. Thus, Haller envisaged the sedimentary rocks of the present-day Målebjerg window, together with those of the structurally overlying Niggli Spids and Hagar Bjerg thrust sheets and Franz Joseph allochthon, to form parts of a single stratigraphical succession. The gneisses, which he viewed originally as synorogenic granites, formed parts of the mobilised infrastructure (see below). This basic interpretation remained essentially unchanged in Haller's detailed studies of nearby areas (Wenk & Haller 1953; Haller 1955), and was only slightly modified in his later regional descriptions (Haller 1970, 1971, 1983; Koch & Haller 1971).

Haller's early observations in the crystalline rocks of the inner fjords and nunatak region (Haller 1953, 1955, 1956; Wenk & Haller 1953), and those of his coworkers, were all interpreted within the context of the 'stockwerke' concept. A series of categorical statements in their published descriptions appear to be aimed particularly at countering the interpretations of British geologists. Thus they stated: "The Archaean basement of the Upper Algonkian-Ordovician series of deposits has hitherto not been found anywhere in Central East Greenland" (Haller 1956, p. 160); "the geologists participating in the investigations agree that the base of the Eleonore Bay Group is *not* to be found within the central zone of the Caledonides" (Wenk 1961, p. 8); "The granitic and migmatitic infrastructure, in its present state of preservation, is not older, but younger, than the pre-Cambrian sedimentary cover.

The ascent of the granitic solutions, and associated thermal fronts, represented the most important act of the East Greenland orogeny" (Wenk & Haller 1953, p. 32–33). However, within a few years these early interpretations were modified significantly, with recognition that a 'basement' to the metasedimentary rocks was in fact recognisable: "Inside the Caledonian domain, rock units which were originally from the ancient basement, represent substantial ingredients of the fold belt" (Haller & Kulp 1962, p. 18).

The basement gneiss complexes were, nevertheless, considered to have been petrogenetically rejuvenated over large areas, and were assigned a Caledonian age. A sketch map by Haller (Haller & Kulp 1962, fig. 3b; Haller 1971, fig. 15b) shows that the 'Niggli Spids dome' and 'Gletscherland migmatite complex' (two of the units of the 'Central Metamorphic Complex'), were now to be considered Caledonian reworked Precambrian basement rocks. However, in respect of the nappe-like convolutions of the so called 'Hagar migmatite sheet', an entirely Caledonian origin was still envisaged. In his description of these nappe-like migmatite sheets Haller 1971 (p. 179) writes: "They are asymmetrical and have considerable overlaps of up to 25 km. Regional thrusting is probably of no importance in their formation." This is essentially a re-statement of the earlier conclusion of Wenk & Haller (1953, p. 32): "We cannot believe that these structures are due to far-reaching tectonic transport, produced by tangential compression. Their mode of occurrence, especially their diapir-like character, indicates that we are here dealing with mobile masses of the infrastructure, which have ascended and intruded into the covering sedimentary series." Many of the essential principles of the 'stockwerke' interpretation of the East Greenland Caledonides were maintained in Haller's later publications (Haller 1971, 1983). Haller does express regret, however, that the term 'synorogenic granite' had been retained on his maps for the central metamorphic complex gneisses (Koch & Haller 1971), because it was at variance with the modified views given by Haller & Kulp (1962) and had thus been misunderstood by many workers.

The assumption that all metasedimentary rocks in the southern part of the Caledonides were parts of the Eleonore Bay 'Formation' or 'Group' (promoted to a 'Supergroup' by Sønderholm & Tirsgaard 1993) was retained in Haller's latest publications (1971, 1983). It was not until the 1968–1972 expeditions by the former Geological Survey of Greenland (GGU) to the Scoresby Sund region that suspicions grew that the widespread high-grade and often migmatitic metasedimentary rocks might be significantly older than the distinctive succession now known as the Eleonore Bay Supergroup. Rb-Sr whole rock isochrons and U-Pb bulk zircon determinations indicated that some granites emplaced into the metasediments were approximately 1000 Ma old (Hansen *et al.* 1978; Steiger *et al.* 1979; Rex & Gledhill 1981). These presumed older metasedimentary rocks, cut by the *c.* 1000 Ma granite suite, were therefore distinguished as the Krummedal supracrustal sequence (e.g. Henriksen & Higgins 1969; Higgins 1974, 1988). Convincing proof that the Krummedal sequence metasedimentary rocks had experienced an early Neoproterozoic thermal event (940–910 Ma) not seen in the Eleonore Bay Supergroup had to await the advent of sophisticated modern geochronology, notably ion microprobe age determinations on individual zircon grains (Strachan *et al.* 1995; Jepsen & Kalsbeek 1998; Kalsbeek *et al.* 2000; Watt *et al.* 2000; Leslie & Nutman 2000, 2003).

In the mid-1970s a number of reconnaissance investigations were carried out in the general Kong Oscar Fjord region. These extended the general conclusions of the 1968–1972 investigations in the Scoresby Sund region northwards. The widespread medium- to high-grade metasedimentary successions in the Kong Oscar Fjord region were correlated with the Krummedal supracrustal sequence (Higgins 1988), and Rb-Sr whole rock isochrons on the underlying gneisses yielded Palaeoproterozoic ages (Rex & Gledhill 1981). Two further important observations were made: (1) the distinctive quartzite in the Målebjerg window was mapped in 1976 as resting unconformably on the gneissic basement (Tage Thyrsted *in* Higgins *et al.* 1981, fig. 8), and (2) during a Survey reconnaissance helicopter flight to the Eleonore Sø region, it was recorded that the base of the 'Slottet quartzite' at one locality was an unconformity with a basal conglomerate, rather than the supposed thrust. Unfortunately, the regional significance of these observations was not appreciated at the time.

Målebjerg

The Målebjerg area was a significant location for Haller's 'stockwerke' interpretation, in particular for the magnificent exposures of what was described as the 'zone of detachment' between the mobile granitic infrastructure and the more rigid metasedimentary superstructure (Haller 1971, photograph 47, p. 138;

Fig. 4. The west face of Målebjerg in western Andrée Land (for location see Fig. 5). Light coloured folded quartzites (< 200 m thick) of the Slottet Formation (**SF**) unconformably overlie grey gneisses (**G**) that are probably of Palaeoproterozoic age. The unconformity is strongly folded. A few metres of grey dolomite (Målebjerg Formation) occur immediately beneath the Niggli Spids thrust (**NST**). Overlying units of the Niggli Spids thrust sheet are dominated by massive mica schists with pale coloured carbonate-rich units (Krummedal supracrustal sequence). The summit of Målebjerg at right is 1873 m high, about 1500 m above the glacier surface in the foreground.

see also Fig. 4). Haller mapped the main lithological units in the Målebjerg area including the white quartzite now distinguished as the Slottet Formation, and recognised that they occupied an anticlinal structure (Haller 1953, 1970). He observed that the intensity of metamorphism was weaker than elsewhere and that the stratigraphy was well preserved, but he referred this quartzite and nearby marble units to the 'Basal Series' of the Eleonore Bay 'Group' (Haller 1971, p. 86).

Haller's geological and structural maps of the area around Målebjerg show several features marked with thrust symbols, some of which have no obvious significance and appear to be photogeological interpretations, while others can be identified with major structures. The most prominent structure on his maps corresponds to the NW–SE-trending, NE-dipping thrust that crosses Gemmedal (Fig. 5), a major feature now identified as the Hagar Bjerg thrust at the base of the Hagar Bjerg thrust sheet. Haller's 'zone of detachment' in the cliff of Målebjerg is not marked with a thrust symbol on his maps, but the folded quartzites of his 'zone of detachment' lie immediately beneath the Niggli Spids thrust of current usage (NST in Fig. 4).

There is no evidence that Haller considered the Målebjerg area to be a foreland window or that he suspected the presence of Lower Palaeozoic sediments. However, he was aware that a "detailed exploration of this key locality is still lacking" (Haller 1971, p. 86), and there is reason to believe that such exploration would have been carried out if Lauge Koch's expeditions had not been brought to an unexpected close after 1958.

As noted above, reconnaissance investigations in the Målebjerg area in 1976 led to recognition of an unconformity at the base of the *c*. 200 m thick quartzite, with a distinctly diverging foliation in the underlying basement gneisses (T. Thyrsted *in* Higgins *et al.* 1981, fig. 8). Detailed studies in 1997–1998 by Leslie & Higgins (1998) established the presence of a significant foreland window (Fig. 5). Key observations included: (1) the presence of a local diamictite in depressions in the peneplained gneiss surface, now correlated with the diamictites of the Vendian Tillite Group; (2) a *Skolithos*-bearing quartzite (the early Cambrian Slottet Formation) unconformably overlying the gneisses and the diamictite; (3) a Lower Palaeozoic dolomite unit (Målebjerg Formation) above the Slottet Formation quartzite; (4) a major thrust at the top of the Målebjerg Formation (Niggli Spids thrust). These observations were confirmed by Smith & Robertson (1999), who made additional detailed observations and measured sections in the diamictite unit (interpreted as a tillite), and in the Slottet and Målebjerg Formations (Smith *et al.* 2004, this volume).

Eleonore Sø

Investigation of the western nunatak region between 72° and 75°N was for many years limited to the traverse of the Eleonore Sø area by Hans Katz in 1951 (Katz 1952, 1953), traverses by Eduard Wenk and John Haller west and south of Petermann Bjerg in 1951 and 1953 (Wenk & Haller 1953; Haller 1956), and extensive aerial reconnaissance by John Haller. Cautious statements about what might be present in this vast nunatak area thus amounted to speculation on the basis of very limited ground information. Reviewing the possibilities subsequent to the discovery of the Caledonian foreland areas in Dronning Louise Land (76°N; Peacock 1956, 1958) and in Gåseland (70°N; Wenk 1961), Haller (1971, p. 195–196) suggested that the thrusts around the Gåseland window (70°N) and near Charcot Land (72°N; Vogt 1965) had only modest displacements (20 km and < 1 km, respectively). Recording that no further outcrops of the foreland were known, he further speculated (Haller 1971, p. 218): "Considering the structure pattern hitherto obtained from this poorly exposed and little known nunatak region, I would not be surprised if future investigators were able to trace relics of early Caledonian overthrust tectonics, on which the present pattern of main folding was then superimposed." He continues: "However, the main Caledonian structures displayed in the well-explored fjord region are definitely not far travelled; on the contrary, they appear to be autochthonous, initiated and caused by the rise of the migmatite front resulting in a 'stockwerk' folded belt."

On the basis of his 1951 traverse of the Eleonore Sø region, Katz had observed that the low grade sedimentary rocks at Eleonore Sø "are of the same type as those of the Eleonore Bay Formation of the fjord zone"

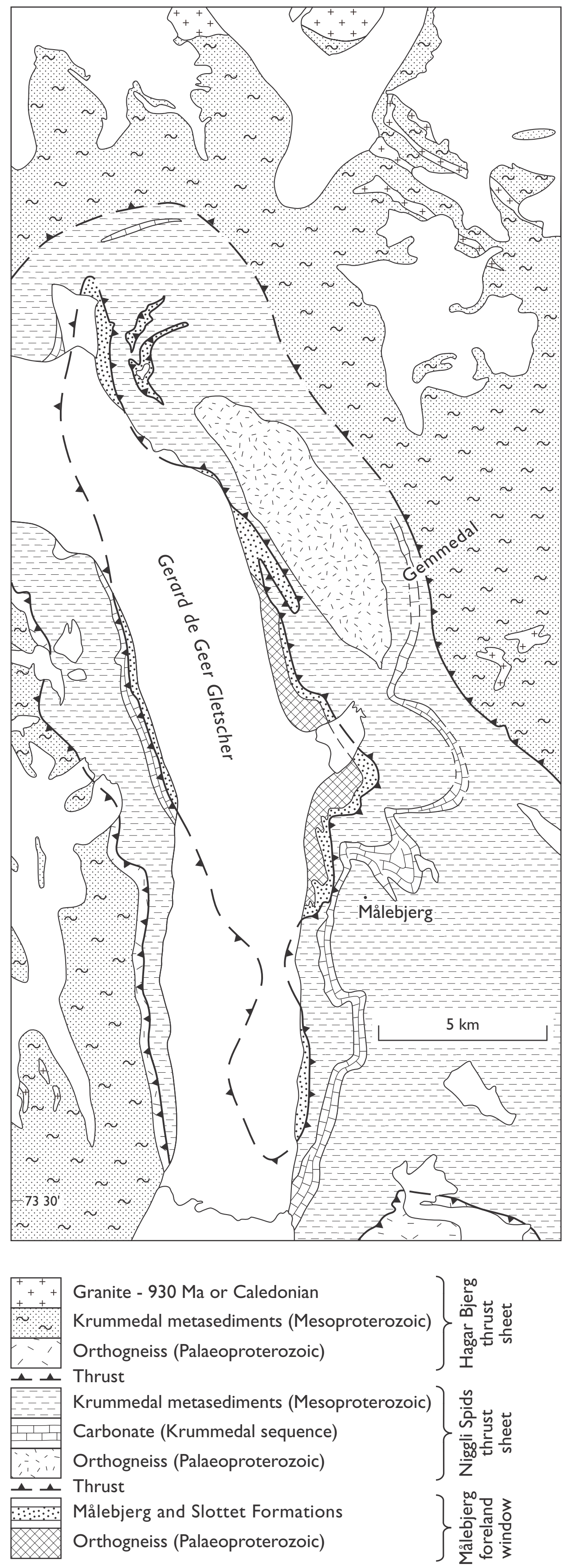


Fig. 5. Geological map of the Målebjerg area, after maps and interpretations of Leslie & Higgins (1998, 1999). Legend below figure illustrates the new thrust terminology.

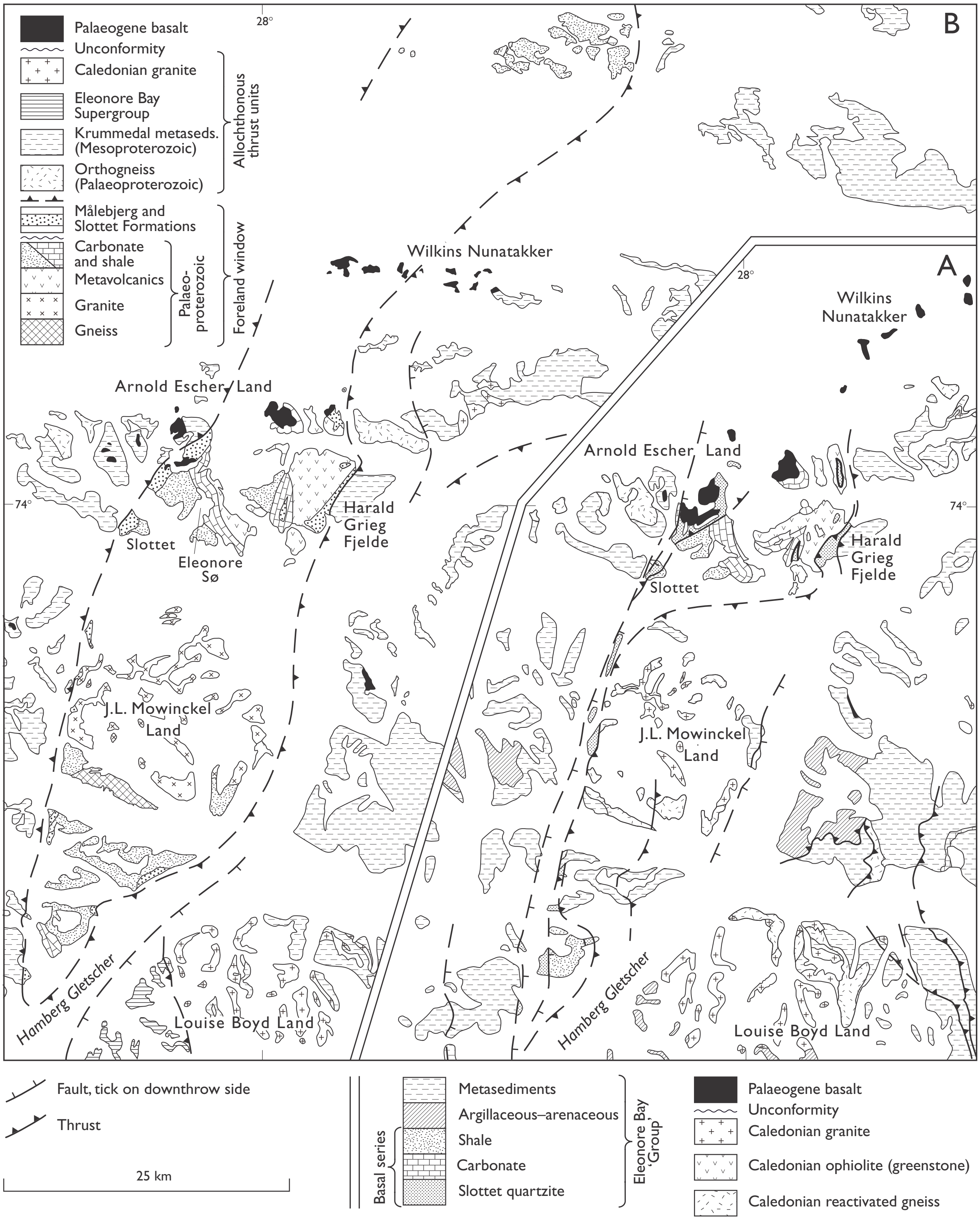


Fig. 6. Geological maps of the Eleonore Sø area, at the same scale but with slightly different topographic bases. **A**: Redrawn after maps and interpretations of Katz (1952), Haller (1970, 1971) and Koch & Haller (1971). Note legend below figure assigns all sediments and metasedimentary rocks to the Eleonore Bay 'Group'. **B**: Redrawn after maps and interpretations of Leslie & Higgins (1998, 1999), using a modern topographic base. Legend at top left distinguishes foreland lithologies from allochthonous thrust units.

(Katz 1953, p. 12). The associated volcanic rocks were interpreted as ophiolitic intrusions and of the same age as the tillites of the fjord zone. While Katz correctly depicted a thrust at the west side of Harald Grieg Fjelde (Fig. 6A), he considered it to be of Devonian age (this thrust corresponds to the major thrust contact on the east side of the window above the Målebjerg Formation dolomites; Fig. 6B). The map in Katz (1953) also shows a continuous thrust contact at the base of his 'Slottet Quartzite' (Fig. 6A), with the internal structure of the quartzite depicted on his cross-sections (Katz 1953, tafel 4) as discordant to the 'thrust' at the base. It was Katz's interpretation of this prominent quartzite unit as equivalent to the lower part of the Eleonore Bay 'Formation' that led him to introduce the basal thrust, because the quartzite lay structurally above the sedimentary rocks he viewed as correlateable with the upper part of the Eleonore Bay 'Formation'. Katz's cross-section of the Eleonore Sø region (1953, tafel 4) does indicate tectonic contacts at both margins of the present window, but his preferred interpretation was that the rock units occupied a graben.

Based on the work of Katz, Haller initially agreed with Katz's interpretation that the Eleonore Sø sediments, which from aerial observations he had traced southwards through J.L. Mowinckel Land to Hamberg Gletscher, occupied a large post-Caledonian graben structure (Haller 1956, p. 161). Most geologists that have worked in East Greenland have come across the widespread and often large erratic blocks of *Skolithos*-bearing quartzites, and Haller (1971, fig. 48) had plotted observations of these quartzites, and inferred that the source areas lay beneath the Inland Ice. However, he clearly did not make any link between the *Skolithos* erratic boulders and the 'Slottet Quartzite' of Katz (1952, 1953), since he placed this latter unit in his 'Basal Series' of the Eleonore Bay 'Formation'. Summarising the situation at Eleonore Sø, Haller writes of the non-metamorphic dolomites and quartzites at Eleonore Sø as being associated with greenschists that Katz had interpreted as Caledonian ophiolites. He notes that the region in which the outcrops are found is bounded on both sides by tectonic lineaments, and he writes (Haller 1971, p. 86–87) "it is open to question whether we are concerned here with parts of the overridden Caledonian foreland, similar to the Gaaseland 'window', or not."

The structures distinguished by Haller (1970, 1971) in the vicinity of Eleonore Sø compared to those mapped by Leslie & Higgins (1998, 1999) are shown in Fig. 6. The only thrust correctly depicted by Haller, who here followed the usage of Katz (1952), is the east-dipping structure on the east side of the window at Harald Grieg Fjelde. At this locality, high-grade metasedimentary rocks in the hanging wall lie structurally above low-grade carbonates and quartzites in the foot wall. In view of the difficulties of access to the region in the 1950s, and the lack of isotopic age determinations, it is not surprising that the ages attributed to the rock units in the Eleonore Sø region by Katz and Haller have since proved to be incorrect. However, the thrust that marks the west side of the window is depicted on Haller's maps as a major normal fault, whereas the other thrusts shown on Haller's interpretation (Fig. 6A) correspond to the unconformity at the base of the 'Slottet Quartzite', the present-day Slottet Formation. It is, perhaps, surprising that Katz did not apparently examine the base of the quartzite unit, which is an obvious unconformity in the field, and often has a basal conglomerate. His erroneous interpretation of this unconformity as a thrust contact does give the impression of an arched thrust on Haller's structural maps (e.g. Haller 1971, fig. 58), and has been taken by some authors as evidence that Haller 'discovered' the window (cf. Hartz *et al.* 2001). However, as noted above, Haller (1971) considered it "open to question".

Only a few geologists have visited the Eleonore Sø region since Katz's 1951 visit, but it was not until the Survey's 1997–1998 regional mapping expedition that detailed field studies led to the regional delineation of the basal unconformity of the 'Slottet Quartzite'. The authors of this article retraced one of Katz's traverses eastwards towards Harald Grieg Fjelde, and observed that the basal contact of the quartzite was in fact conformable to the bedding within the quartzite rather than discordant as in Katz's profiles (Katz 1952). The quartzites were observed to contain well-preserved sedimentary structures, and the first *in situ* finds of *Skolithos* were found just west of the thrust at Harald Grieg Fjelde. The unconformity surface, subsequently studied at several localities, proved to be a clean undisturbed contact (Fig. 7) with a basal conglomerate up to 1.5 m thick often present. In nearly every section of the quartzites examined, *in situ* long *Skolithos* burrows were observed, and these demonstrate that the sequence now termed the Slottet Formation (Smith *et al.* 2004, this volume) is of Lower Cambrian age (Crimes 1992). A Cambrian–Ordovician age can therefore be assumed for the thin dolomite sequence of the Målebjerg Formation, which conformably overlies

Fig. 7. The nunatak Slottet in the Eleonore Sø window, looking northwards. The white (lower) and dark (upper) quartzites of the Lower Cambrian Slottet Formation (**SF**: 350 m thick) rest unconformably on dark coloured Palaeoproterozoic clastic sediments of the Eleonore Sø volcano-sedimentary complex (**ES**). The highest summit of Slottet is 1933 m high, about 600 m above the glacier surface.

the Slottet Formation and immediately underlies the thrust (Leslie & Higgins 1998, 1999; Smith *et al.* 2004, this volume). On the west side of the window, the west-dipping thrust contact is well exposed and associated with thick developments of mylonites. A clear definition of the entire thrust system bordering the window was established for the first time during the 1997–1998 mapping (Fig. 6B). Finds of low grade volcanic rocks in eastern J.L. Mowinckel Land have extended the known distribution of their occurrence considerably, such that the eastern marginal thrust of the window can now be placed parallel to the glacier to the east of J.L. Mowinckel Land. Exposures of characteristic rock types (low-grade volcanic rocks and *Skolithos*-bearing quartzites) observed as far north as nunataks at 74°25′N (Fig. 6B) show that the NNE–SSW extent of the Eleonore Sø window is at least 125 km. The volcanic succession (pillow lavas and tuffs) and associated sedimentary rocks (thick dolomites and dolomite breccias, sandstones and shales) that are unconformably overlain by the Slottet Formation quartzites are intruded locally by quartz porphyry bodies, dated by SHRIMP analyses of zircon to *c.* 1950 Ma (F. Kalsbeek, personal communication 2000). The Eleonore Sø volcano-sedimentary rocks are thus Palaeoproterozoic or older in age, and can be broadly compared with the volcano-sedimentary rocks of the Charcot Land window at *c.* 72°N and the foreland exposures of the Hamberg Gletscher complex (volcanic rocks and associated gabbros) at *c.* 73°N (Fig. 1; Higgins *et al.* 2001).

Discussion

The exceptional exposures in the extensive fjord system and nunataks of the Kong Oscar Fjord region (72°–75°N), and the long series of geological expeditions led by Lauge Koch (1926–1958), have deservedly led to recognition of the East Greenland Caledonides as a spectacular example of an orogenic belt. This is in large part a tribute to the superb compilations of data presented by John Haller (Haller 1970, 1971; Koch & Haller 1971). Development of new models for the East Greenland Caledonides, to replace the 'stockwerke' concept, has been a gradual process extending over a period of some 30 years (1968–1998), during which the entire 1300 km length of the orogen has been remapped as part of the Survey's regional 1:500 000 mapping project. During this extended period of research, most of the assumptions built into Haller's (1970, 1971) 'stockwerke' concept of an *in situ* Caledonian orogenic belt have been queried or refuted, and the new interpretations confirmed by increasingly sophisticated isotopic age determinations.

Prior to the Survey's 1997–98 expeditions the existence of far-travelled thrust sheets had not been demonstrated in the Kong Oscar Fjord region. With discovery of the Eleonore Sø and Målebjerg windows, and distinction of a thrust pile with hundreds of kilometres of west-north-west thrust displacement (Henriksen 1998, 1999; Leslie & Higgins 1998, 1999; Elvevold *et al.* 2000; Higgins *et al.* 2004), the 'stockwerke' concept of *in situ* Caledonian orogenesis can finally be pronounced dead and laid to rest. Restoration of the thrust sheets to their approximate original locations implies that the focus of Caledonian orogenesis, i.e. the collision of Laurentia with Baltica, took place several hundred kilometres east-south-east of the orogenic belt now preserved onshore in East Greenland.

Wordie (1930) and Parkinson & Whittard (1931) were, in fact, partly correct when they compared the crystalline gneisses of the inner fjord region of East Greenland to the Archaean Lewisian gneisses of Scotland. The former have yielded Archaean and Proterozoic protolith ages, with Archaean gneiss complexes extending throughout the inner part of the Scoresby Sund region and northwards to southern Suess Land (72°50′N). Farther north the orthogneisses have yielded Palaeoproterozoic protolith ages which relate to an important episode of regional Palaeoproterozoic crust-formation well documented throughout the northern half of the East Greenland Caledonides (Kalsbeek *et al.* 1993, 1999). It follows that Haller (1953) was wrong in attributing the formation of the orthogneisses to rising fronts of Caledonian migmatisation that transformed metasedimentary rocks of the Eleonore Bay 'Formation'. Haller's later re-interpretation of these gneisses as Caledonian reworked basement rocks was close to the present-day interpretation (Haller & Kulp 1962; Haller 1971).

John Haller was of Swiss nationality, educated in Switzerland, and obviously familiar with the major thrusts and fold nappes of the Alpine orogenic belt. His earliest 1949–1951 studies in East Greenland were in Andrée Land (Haller 1953), and his main conclusions were presented as a confirmation and elaboration of the interpretations of H.G. Backlund and C.E. Wegmann. He was already committed to the idea of widespread transformation of a single metasedimentary succession (Eleonore Bay 'Group') by the vertical rise of mobile migmatitic bodies, a view that was developed during his subsequent field work, and elegantly presented as the 'stockwerke' concept (Haller 1970, 1971). Haller's wide-ranging observations on the ground and from the air, and Katz's observations around Eleonore Sø, were all interpreted within the context of the basic 'stockwerke' model. Thus the Palaeoproterozoic volcano-sedimentary succession of the Eleonore Sø window and the thin Lower Palaeozoic successions of the Målebjerg and Eleonore Sø windows were referred to the Eleonore Bay 'Group'. An unconformity at the base of the 'Slottet quartzite' in the Eleonore Sø window, presumably not examined very closely, was interpreted as a major thrust in order to force the stratigraphy to fit into the model. The displacements on the major thrusts that were recognised were grossly underestimated, perhaps in order not to upset the assumption that "the main Caledonian structures displayed in the well-explored fjord region are definitely not far travelled; on the contrary, they appear to be autochthonous" (Haller 1971, p. 218).

While the 'stockwerke' model of intense *in situ* granitisation is no longer tenable, the Caledonian orogeny in East Greenland was certainly not the 'superficial' orogeny envisaged by the early British geologists. The Precambrian orthogneiss complexes, together with the overlying metasedimentary successions, have experienced high-grade Caledonian metamorphism and intense reworking during the regional Caledonian compressive deformation that produced major westward propagating thrust sheets. Caledonian granites generated by melting of Mesoproterozoic sediments are widespread in the Hagar Bjerg thrust sheet, but absent in the lower Niggli Spids thrust sheet. The dominant fabric in the Archaean and Palaeoproterozoic orthogneisses of the thrust sheets is today interpreted in many areas to be essentially Caledonian, which as a concept is not greatly different from the 'Caledonian petrogenetic rejuvenation' envisaged by Haller & Kulp (1962, p. 18). However, despite Caledonian reworking, the orthogneisses of the crystalline complexes still yield Archaean and Palaeoproterozoic protolith ages, and in low strain areas relicts of the Precambrian foliation cut by discordant amphibolite dykes are preserved (Higgins *et al.* 1981, p. 37–38).

The assumption that all metasedimentary rocks in the southern half of the East Greenland Caledonides were variably transformed parts of the Eleonore Bay 'Group', was not questioned until GGU's work in the Scoresby Sund region in 1968–1972. Although then based on imprecise Rb-Sr and U-Pb ages (Rex & Gledhill 1974; Hansen *et al.* 1978; Steiger *et al.* 1979), GGU's investigations led to distinction of two sedimentary successions (Henriksen & Higgins 1969, 1976; Higgins 1974, 1988). The widespread high-grade metasedimentary rocks that hosted *c.* 1000 Ma augen granites were ascribed to the Krummedal supracrustal sequence, whereas the high-grade to non-metamorphic Eleonore Bay Supergroup appeared to be affected only by Caledonian metamorphism and deformation. This viewpoint did not go unchallenged, and diverging interpretations have continued to be expressed (Peucat *et al.* 1985; Hartz & Andresen 1995; Andresen & Hartz 1998; Hartz *et al.* 2000).

Recent ion microprobe zircon studies have now confirmed the widespread distribution of a distinctive 940–910 Ma granite suite hosted by the high-grade, commonly migmatitic, Krummedal sequence of the Hagar Bjerg thrust sheet (Jepsen & Kalsbeek 1998; Kalsbeek *et al.* 2000; Leslie & Nutman 2000; Watt *et al.* 2000; Watt & Thrane 2001). A later granite suite, hosted by both the Krummedal sequence and the lowest part of the Eleonore Bay Supergroup, is Caledonian in age (Rex & Gledhill 1981; Hartz *et al.* 2001; Kalsbeek *et al.* 2001a, b; White *et al.* 2002).

The most dramatic revelation of the recent Survey mapping is that the 18.5 km thick Neoproterozoic–Ordovician succession preserved in the Franz Joseph allochthon of the Hagar Bjerg thrust sheet structurally overlies a partly equivalent < 400 m thick sequence preserved in the Målebjerg window (Fig. 4). Higgins *et al.* (2001, fig. 8) demonstrated the similarities of the restricted foreland succession of the Målebjerg window with that in the Eleonore Sø window and other foreland areas preserved along the western margin of the East Greenland Caledonides. It follows that the allochthonous and very thick Eleonore Bay Supergroup – Tillite Group – Kong Oscar Fjord Group succession must have been laid down in a completely different sedimentary environment a substantial distance to the east of the restricted sequence deposited on the foreland craton. The succession preserved in the Franz Joseph allochthon of East Greenland exhibits broad similarities with the major Neoproterozoic – Lower Palaeozoic sedimentary successions of Svalbard, NW Scotland and Newfoundland that were deposited along the western passive margin of the Iapetus ocean (e.g. Swett & Smit 1972; Soper 1994). In East Greenland the preserved remnants of this basin were displaced at least 200 km, and possibly as much as 400 km, west-north-west across the Laurentian margin to structurally overlie their thin foreland equivalents, a Caledonian shortening across the orogenic belt estimated at 40–60% (Higgins & Leslie 2000; Higgins *et al.* 2001, 2004). As noted above, restoration of the thrust sheets to their approximate original locations implies that the collision of Laurentia with Baltica took place several hundred kilometres east-south-east of the orogenic belt now preserved onshore in East Greenland.

The models of the Caledonian orogen presented by Hartz & Andresen (1995) and Andresen *et al.* (1998), which invoked upward and lateral movement of light, low viscosity, lower crustal material towards the region of maximum crustal extension, a process compared to Haller's 'stockwerke' concept, neglect the significance of Caledonian thrusting. Following the Survey's demonstration of the existence of the foreland windows and the presence of major thrusts at Caledonian symposiums held in Copenhagen (Frederiksen & Thrane 1998, 1999), a considerably revised model for the orogen was presented by Hartz *et al.* (2001). While the thrust terminology employed by Hartz *et al.* (2001) has similarities with that of Elvevold *et al.* (2000), there are many differences in interpretation. Some boundaries on their map (Hartz *et al.* 2001, fig.1) appear to have been adopted from Koch & Haller's (1971) obsolete maps, and, for example, the west-dipping thrust of the Eleonore Sø window is incorrectly indicated as an east-dipping extensional fault (cf. Fig. 6).

John Haller's contributions to the understanding of the East Greenland Caledonides are considerable (see e.g. Henriksen & Higgins 1993; Schwarzenbach 1993). However, although he did not discover the Målebjerg and Eleonore Sø windows or identify the Lower Palaeozoic rock units, many of his observations, in retrospect, support such an interpretation. Unfortunately, Haller's emphasis on the autochthonous *in situ* origin of the crystalline complexes led him to deny that significant thrusting was involved in the central fjord zone, and to underestimate displacements on the thrusts that were observed in Gåseland, near Charcot Land, around Eleonore Sø, and around Målebjerg in Andrée Land.

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