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

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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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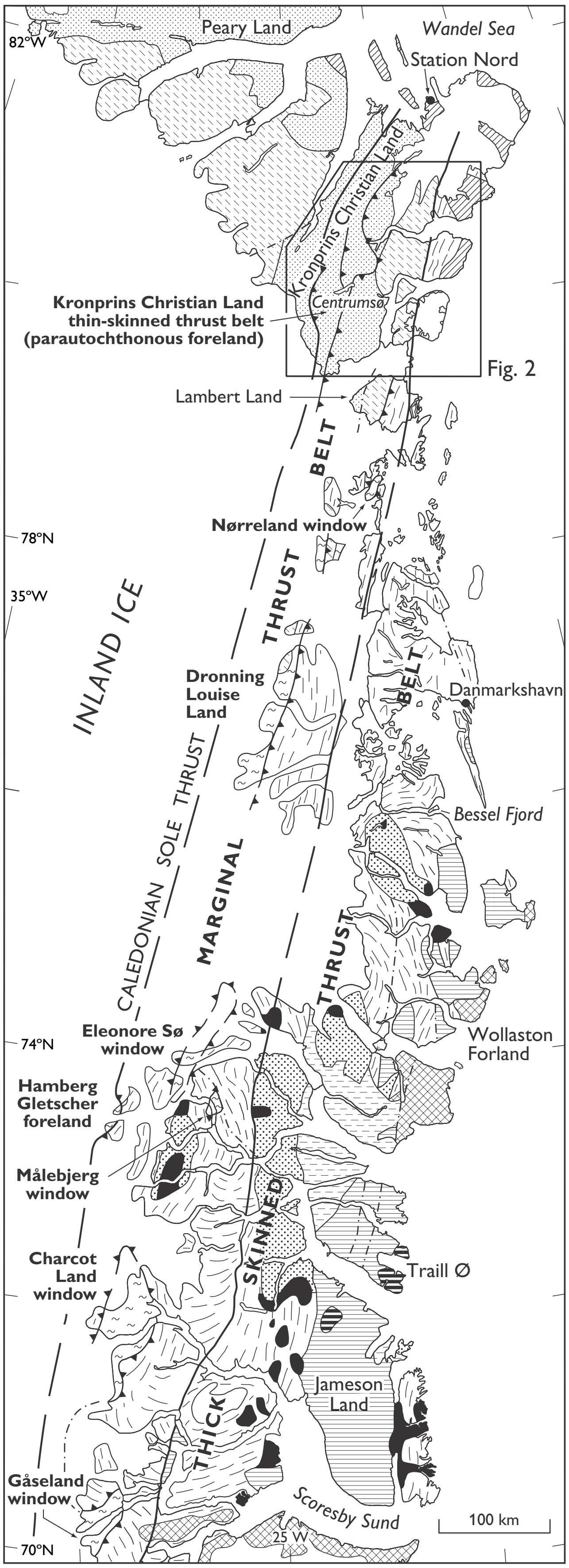
The East Greenland Caledonides extend for 1300 km along the coastal region of East Greenland between latitudes 70° and 82°N, in a belt up to 300 km wide. It can be broadly divided into an eastern thick-skinned thrust belt, and a western marginal thrust belt that in places is thin-skinned (Fig. 1). The 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.



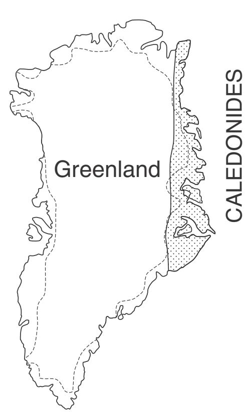


Fig. 1. General geological map of the East Greenland Caledonides, illustrating the division into western marginal and eastern thick-skinned thrust belts (modified from Higgins *et al.* 2001a). The main foreland windows along the length of the fold belt are shown, with the Kronprins Christian Land area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

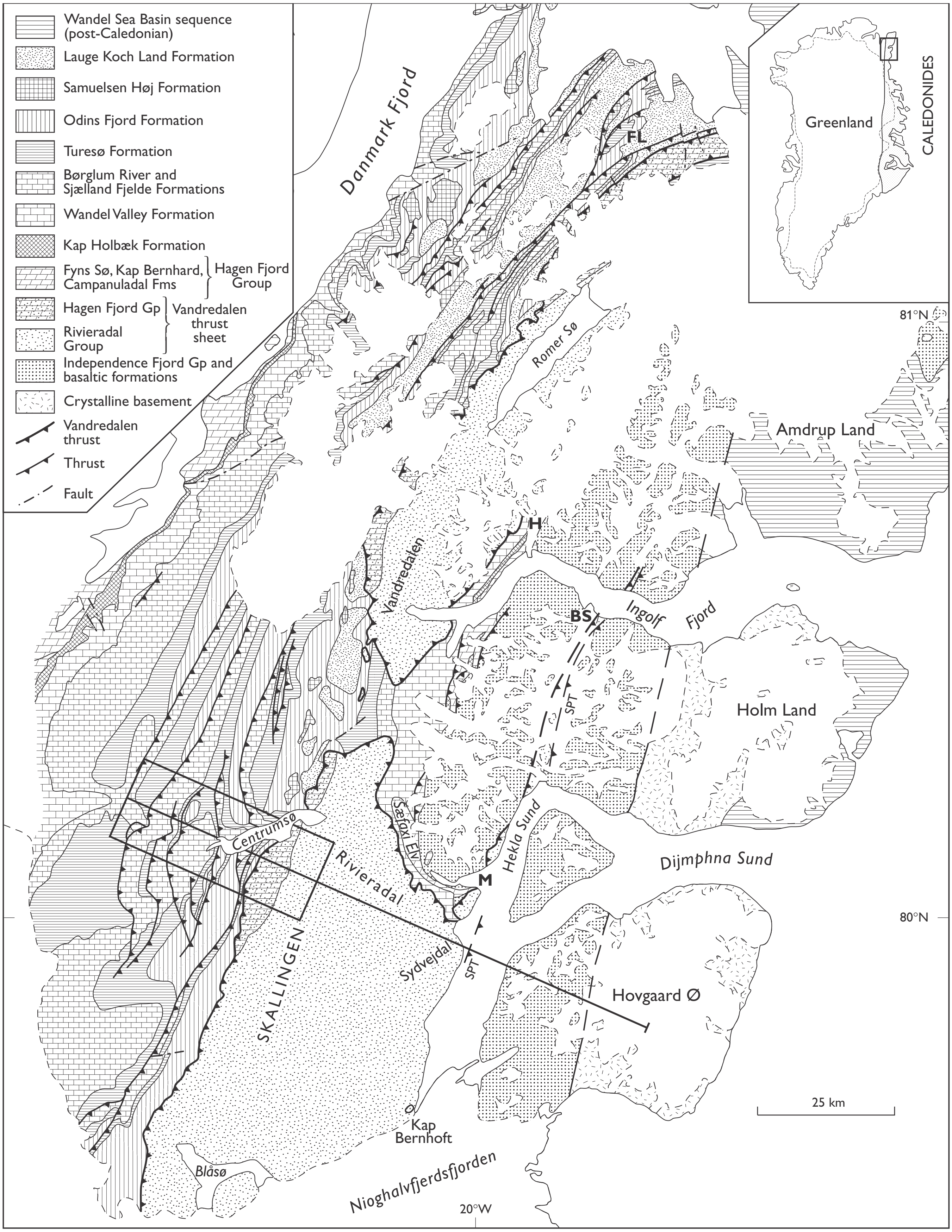
Proterozoic sedimentary successions overlying the crystalline gneiss complexes are widespread in the southern half of the Caledonides. An older late Mesoproterozoic to early Neoproterozoic succession (Krummedal supracrustal sequence and equivalents; Higgins 1988) preserves isotopic evidence of a pre-Caledonian (~ 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
Greenland
CALEDONIDES
Danmark Fjord
FL
Romer Sø
Amdrup Land
H
Vandredalen
BS
Ingolf Fjord
Holm Land
SPT
Centrumsø
Sæfaxi Elv
Hekla Sund
Dijmphna Sund
M
Rivieradal
Sydvejdal
SKALLINGEN
Hovgaard Ø
Kap Bernhoft
Blåsø
Nioghalvfjerdsfjorden
81°N
80°N
20°W
25 km

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).

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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

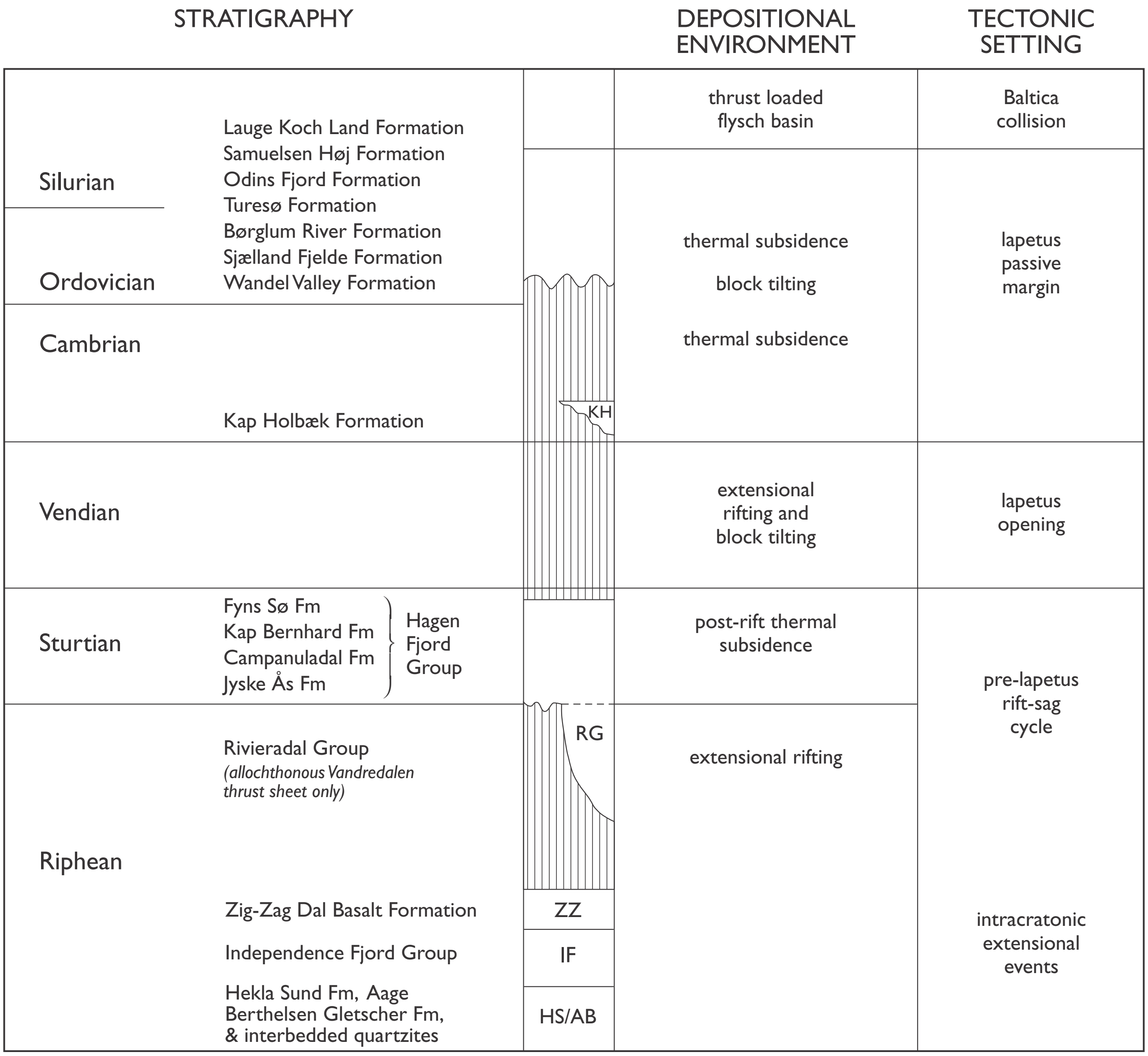

Fig. 3. Summary stratigraphic scheme of Proterozoic and Palaeozoic units depicted on the maps, and their relationships to Iapetus opening (modified from Smith *et al.* 1999). Non-deposition or erosion is depicted by vertical ruling.

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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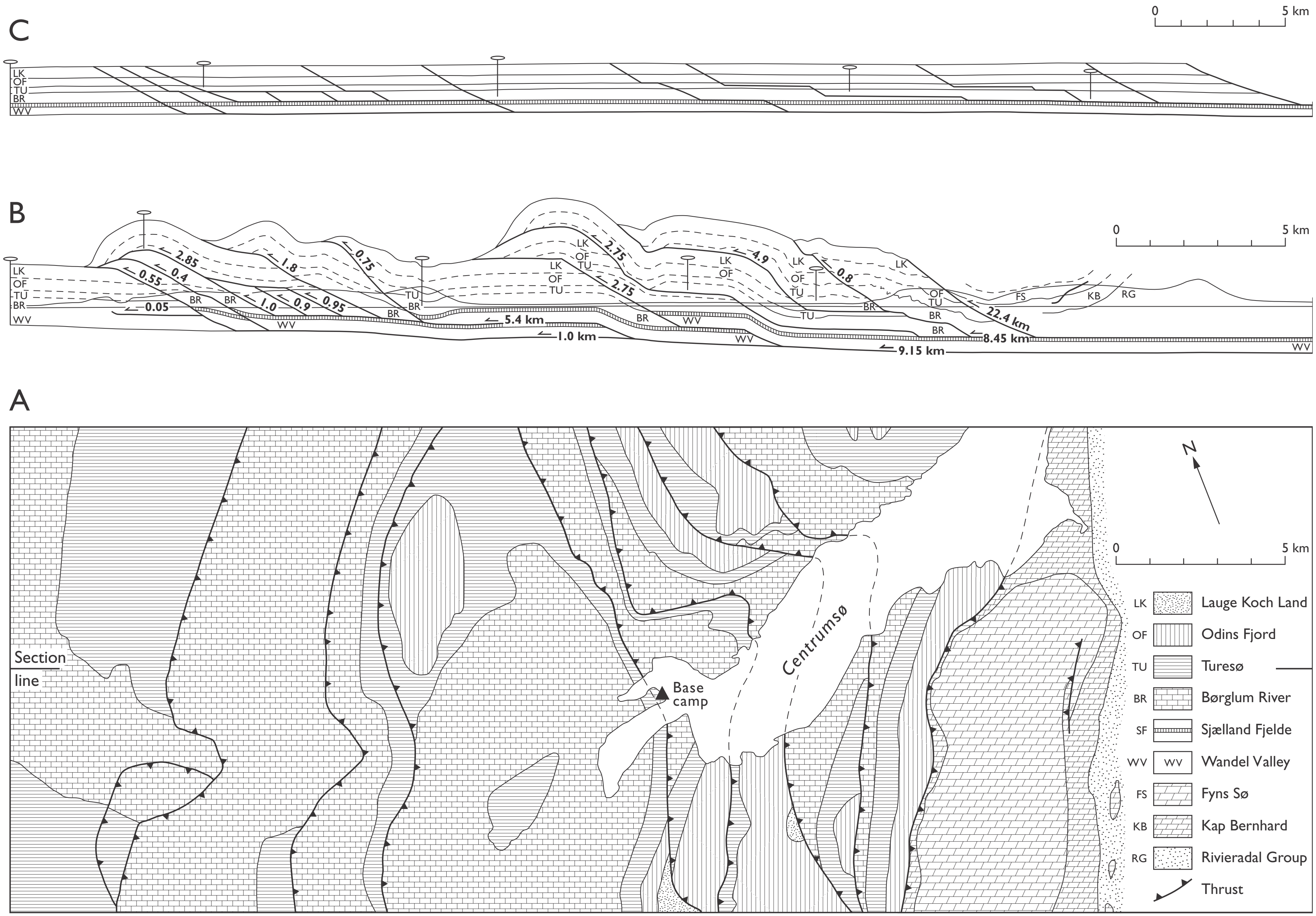
Fig. 4. Geological map and restored cross-section of the thin-skinned thrust belt in the Centrumsø region. **A**: Geological map and location of section line; see also frame in Fig. 2. Base camp indicated by filled triangle. **B**: Cross-section with calculated displacements on individual thrusts in 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.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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

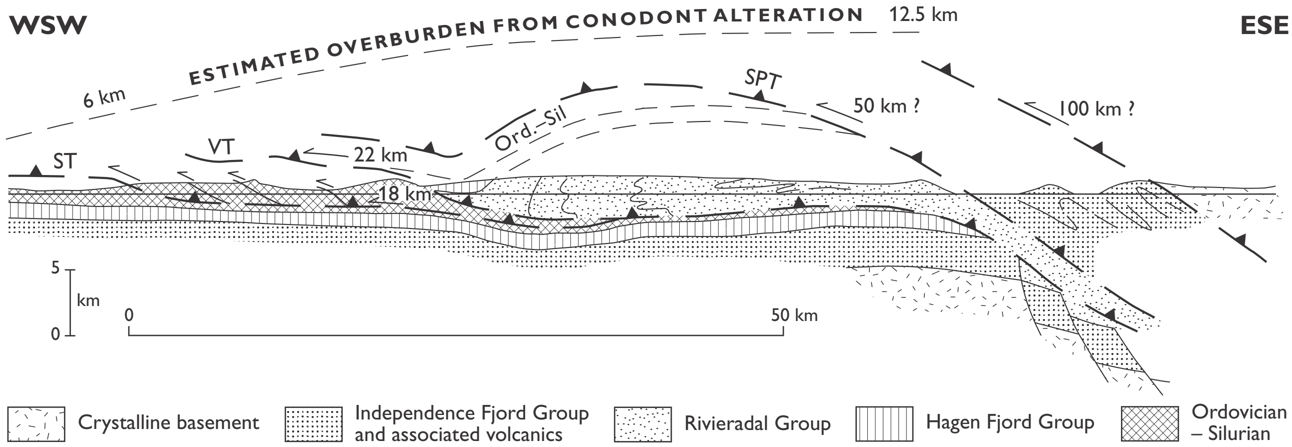

Fig. 5. Simplified cross-section through the Caledonian fold belt in Kronprins Christian Land, from Higgins *et al*. (2001b); for section line see Fig. 2. The maximum overburden deduced from conodont alteration indices (indicative of eastward increase in temperature) is also shown. **SPT**, Spærregletscher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

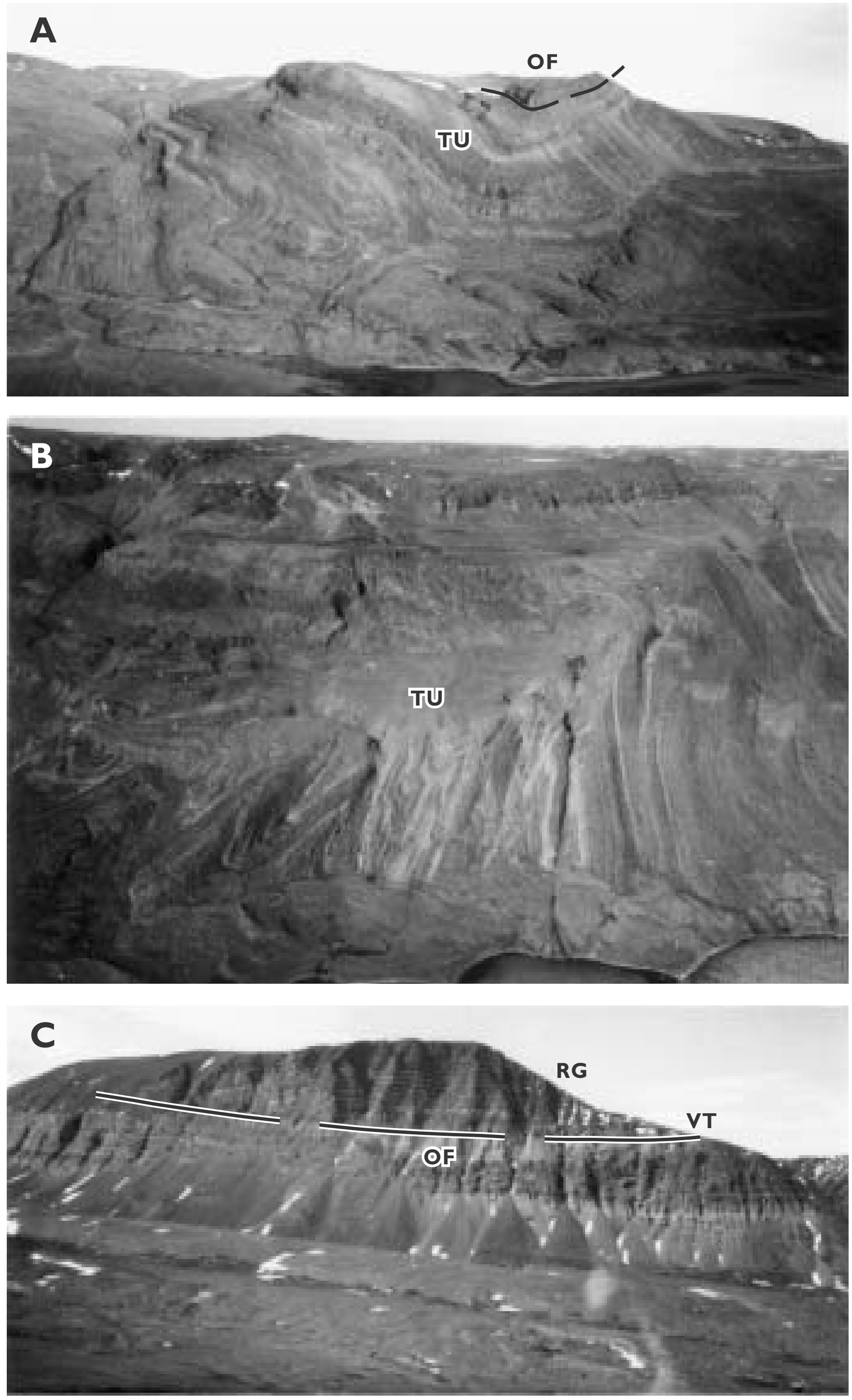

Fig. 6. **A**: Syncline in line of cross-section looking north, 7 km west of the Centrumsø base camp. **OF**, Odins Fjord Formation; **TU**, Turesø Formation. Cono-donts have CAI values of 4, indicative of a former overburden of about 6.8 km. Summit at centre is 500 m above the valley floor. Photo: J. 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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