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The Ellesmerian and Caledonian Orogenic Belts of Greenland

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THEME 7: Problems of the Caledonian/Ellesmerian Junction

Summary: The 1300 km long N–S trending East Greenland Caledonides comprises a western thin-skinned fold and thrust belt characterised by a pile of flat lying thrust sheets displaced to the west or north-west, and an eastern thick-skinned zone dominated by crystalline basement rocks. Erosion of the emergent Caledonian thrust sheets commenced in mid-Llandovery time and produced the thick Silurian flysch deposits which filled the deep marine trough of the Franklinian Basin which extended westwards across North Greenland into the Canadian Arctic Islands. Deposition in the Franklinian Basin was brought to a close in the latest Devonian by the Ellesmerian orogeny, which produced the 600 km long E–W trending North Greenland fold belt. The sediments of the deep water trough were displaced southwards against the former platform margin producing a southern thin-skinned fold and thrust belt. Deformation and metamorphism increase in intensity northwards, and on the northern seaboard of Greenland there is a north-vergent Paleogene (Eurekan) overprint. Extensional faults which controlled development of the Franklinian Basin were reactivated by thrusting during the Ellesmerian orogeny, but in contrast to the Caledonides no basement lithologies were brought to present exposure levels in North Greenland, and there was no apparent associated magmatism.

INTRODUCTION

Two major Palaeozoic orogenic belts are well preserved in Greenland (Fig. 1). The 600 km long E–W trending North Greenland fold belt developed on the site of the Lower Palaeozoic Franklinian Basin during the end-Devonian Ellesmerian orogeny; its continuation is seen to the west in Ellesmere Island in Arctic Canada. The earlier, N–S trending and 1300 km long East Greenland Caledonides comprises the northern segment of the Caledonian-Appalachian orogen, and formed by the collision of Baltica and Laurentia during the mid-Silurian Scandian orogeny. The intersection of these two belts is obscured beneath the Mesozoic Wandel Sea Basin offshore eastern North Greenland. The following description of the East Greenland Caledonides concentrates on the northern segment exposed in Kronprins Christian Land (Fig. 2).

This paper gives a brief review of the two Palaeozoic orogenic belts in Greenland which border on the Arctic Ocean, and in respect of North Greenland is largely based on existing published papers. Description of the East Greenland Caledonides incorporates the results of recent Survey mapping expeditions.

EAST GREENLAND CALEDONIDES

Survey mapping of the East Greenland Caledonides has demonstrated a straightforward essentially conventional architecture. The western marginal zone of the fold belt throughout its length comprises a marginal thin-skinned fold and thrust belt in which autochthonous or parautochthonous windows are intermittently exposed along the margin of the Inland Ice (Fig. 2); these windows are distinguished by the presence of a thin, low grade, Proterozoic–Palaeozoic succession comparable to that in the foreland, and are overlain by a pile of higher grade thrust sheets. The broad eastern segment of the Caledonian fold belt appears to be essentially a thick-skinned thrust belt, dominated by deep-seated crystalline basement rocks of Palaeoproterozoic origin reworked during the Caledonian orogeny, but also involving very thick Neoproterozoic to Lower Palaeozoic sedimentary sequences. The boundaries between the various lithostructural units in the thick-skinned zone are frequently steeply inclined thrusts or shear zones. Top-to-the west or north-west displacement on the thrusts in both the thin- and thick-skinned thrust belts probably amounts to two or three hundred kilometres (HIGGINS & LESLIE 2000). Some thrusts in the thick-skinned thrust belt were subsequently reactivated in extension associated with orogenic collapse (LARSEN & BENGAARD 1991, ANDRESEN et al. 1998).

The Caledonian foreland areas fortuitously exposed in windows along the margin of the Inland Ice include from south to north (Fig. 2): the Gåseland window, Charcot Land window, Niggli Spids window, Målebjerg window, Eleonore Sø window, western Dronning Louise Land and the Nørreland window. Recognition that the rock successions in the window areas were all affected to some degree by Caledonian deformation indicates that they should strictly be regarded as parautochthonous rather than autochthonous, with a floor thrust at depth; the limit of Caledonian deformation, or Caledonian sole thrust, is thus now placed slightly west of the traditional position, and is largely concealed by the Inland Ice (cf. Figs 1 and 2). The sequences exposed in the windows show broad similarities from area to area. Tillites of presumed Varanger age occur in the Gåseland, Charcot Land and Målebjerg windows (MONCRIEFF 1989, LESLIE & HIGGINS 1998), quartzites with *Skolithos* trace fossils are found in the Målebjerg and Eleonore Sø windows and in Dronning Louise Land (LESLIE & HIGGINS 1998, STRACHAN et al. 1994), and in nearly all windows the highest rock unit underlying the Caledonian thrusts comprises a variable thickness of carbonates of Lower Palaeozoic age (LESLIE & HIGGINS 1998, SMITH &

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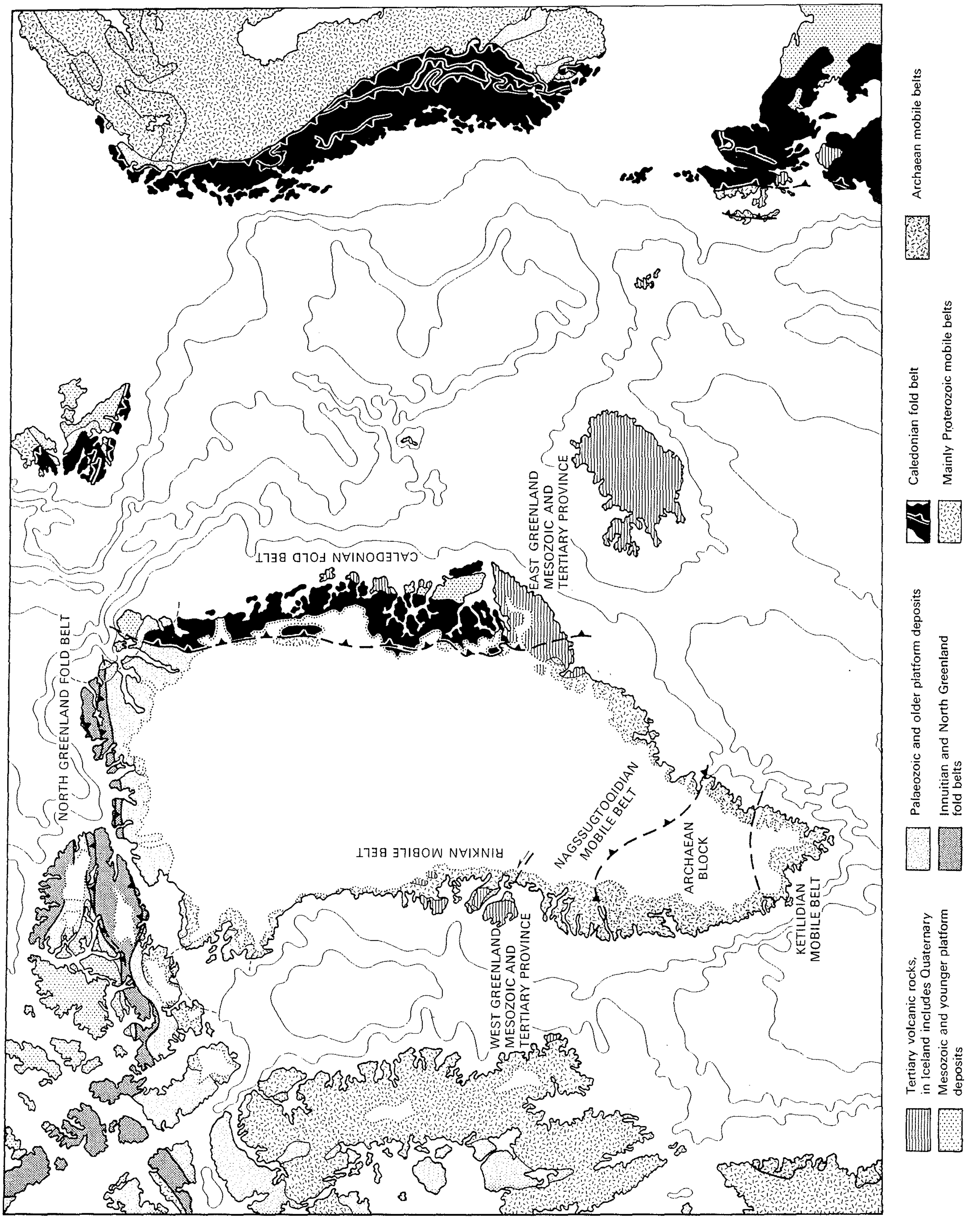


Fig. 1: Structural divisions of Greenland, showing the North Greenland (Ellesmerian) fold belt extending into arctic Canada and the circum-Atlantic Caledonian fold belts (after ESCHER & WATT 1976, Fig. 1). The traditional west boundary of the Caledonian fold belt in East Greenland shown here follows the allochthonous thrust front (cf. Fig. 2).

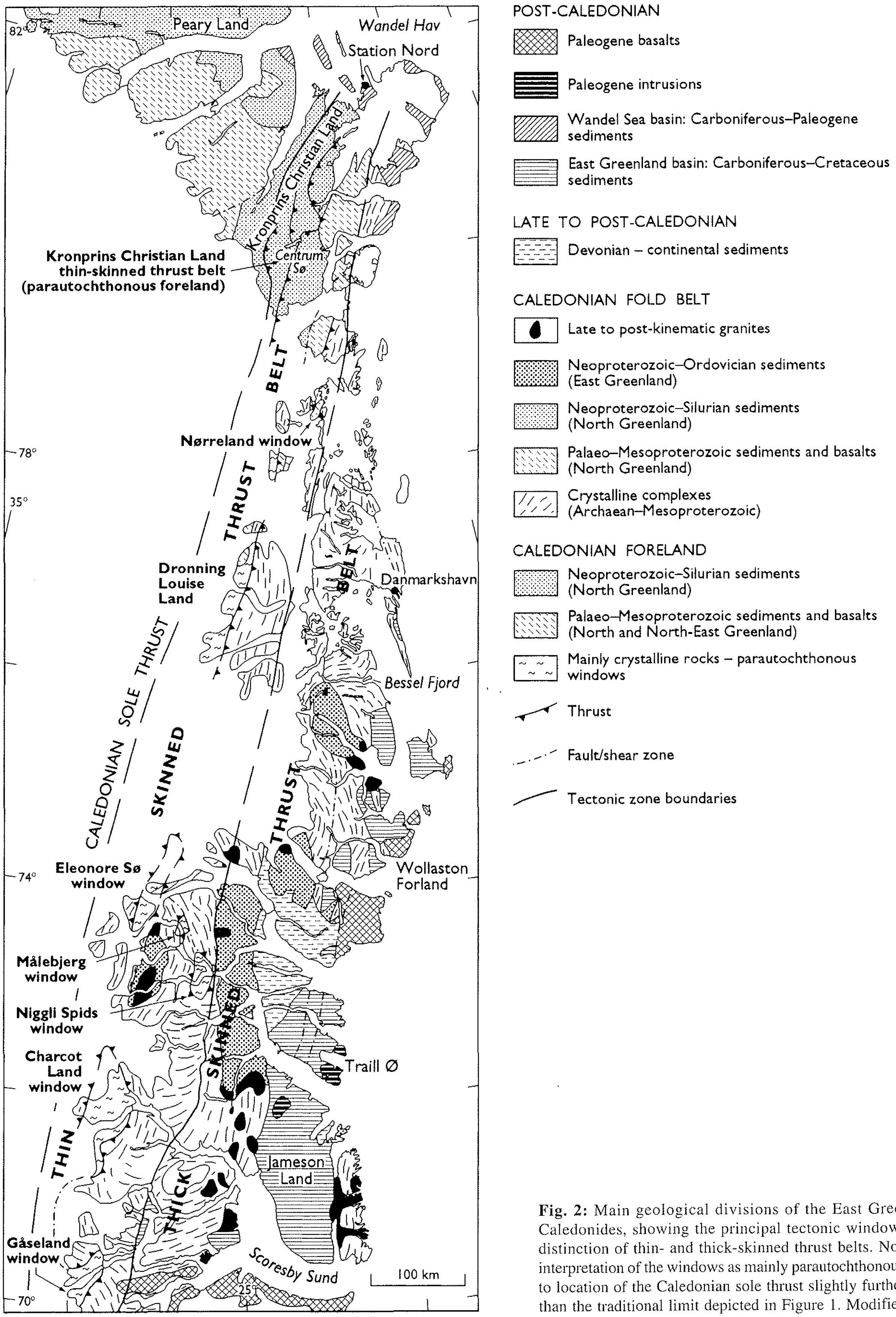


Fig. 2: Main geological divisions of the East Greenland Caledonides, showing the principal tectonic windows, and distinction of thin- and thick-skinned thrust belts. Note that interpretation of the windows as mainly parautochthonous leads to location of the Caledonian sole thrust slightly further west than the traditional limit depicted in Figure 1. Modified after Higgins & Leslie (2000).

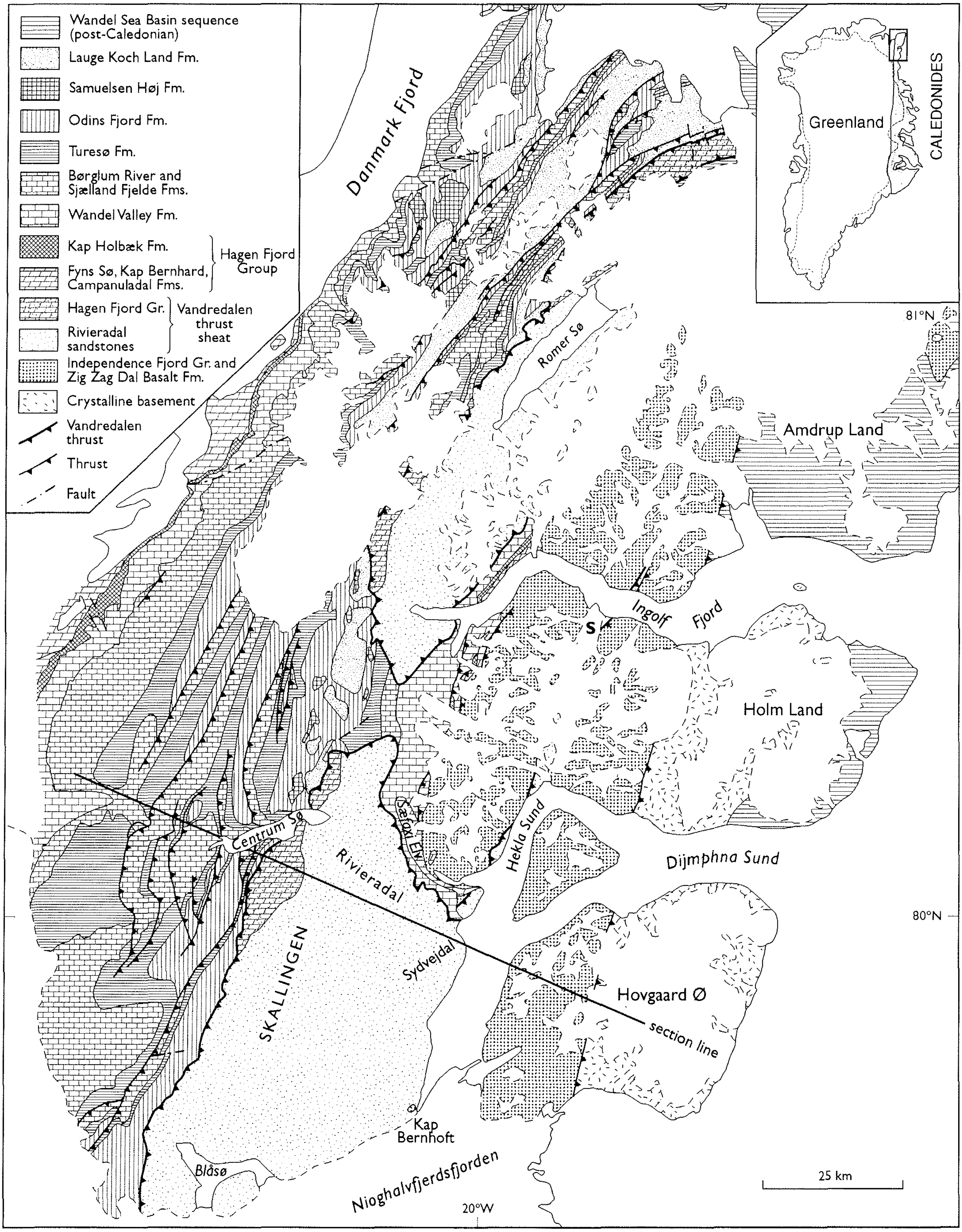


Fig. 3: Geological map of Kronprins Christian Land, eastern North Greenland, the northernmost segment of the East Greenland Caledonides. S: Spærregletscher. For age of formations see Table 1. Cross-section line of Figure 4 is also shown. Modified after Higgins & Leslie (2000).

Robertson 1999, Higgins et al. in press).

The western marginal zone of the East Greenland Caledonides is only completely exposed in Kronprins Christian Land in eastern North Greenland (Fig. 3; see e.g. Henriksen 1995, 1996, Rasmussen & Smith 1996). Here the western foreland, undisturbed by Caledonian deformation, preserves a Mesoproterozoic to Early Palaeozoic sedimentary sequence that has been related to pre-Iapetan extension, Iapetan rifting and passive margin sedimentation (Table 1; Smith et al. 1999). In an up to 40 km wide parautochthonous fold and thrust belt these same sequences are disrupted by numerous thrusts with generally limited displacements (Fig. 3; Higgins & Soper 1994, 1995); total displacement on these thrusts in a cross-section through this parautochthonous belt along Centrum Sø has been estimated by the authors at about 18 km, assuming the thrusts to root in flat floor thrusts in Ordovician carbonates. The main nappe front throughout Kronprins Christian Land is formed by the Vandredalen thrust, which transports the Neoproterozoic siliciclastic rocks known as the Rivieradal sandstones across its rift shoulders (Higgins & Soper 1994, 1995); this Neoproterozoic rift sequence is only found in the Vandredalen thrust sheet, and is represented by a hiatus in the foreland. Uppermost Proterozoic sequences (Hagen Fjord Group) overlying the Rivieradal sandstones in the front of the Vandredalen thrust sheet are also preserved in the footwall to the Vandredalen thrust and demonstrate a total westward displacement of about 40 km for the nappe front (22 km on the Vandredalen thrust and 18 km on the thrusts in the parautochthonous belt to the west; Fig. 4). The allochthonous Vandredalen thrust sheet forms the eastern half of the thin-skinned thrust belt in Kronprins Christian Land; the flat trajectory of the Vandredalen thrust intersecting with the topography produces intricate outcrop patterns on the geological map (Fig. 3).

The simplified cross-section of Figure 4 illustrates the main structure. Eastwards the Vandredalen thrust abruptly steepens, and disappears below exposure level along Hekla Sund (Fig. 3). Farther east a broad zone of highly deformed Proterozoic quartzites and dykes (probably Independence Fjord Group and Midsommersø dolerites; Sønderholm & Jepsen 1991; see also Jepsen & Kalsbeek 2000, this vol.) extends as far as another steep N–S trending lineament which approximately marks the transition between thin-skinned and thick-skinned thrust geometry. Crystalline basement rocks east of this lineament and extending to the outer Greenland coast can be interpreted to represent the cores of thick-skinned nappes whose frontal parts would formerly have extended westwards over the thin-skinned thrust belt. Displacement of the Independence Fjord Group and associated rocks on the Spærregletscher thrust (Fig. 4), is probably more than 50 km, while the displacement of crystalline basement rocks on the next thrust to the east may be as much as 100 km (Fig. 4).

Figure 4 also shows the thickness of overburden deduced from characteristic colour alteration indices in conodonts extracted from the Lower Palaeozoic carbonates in the parautochthonous thin-skinned belt (J.A. Rasmussen and M.P. Smith personal communications 1998). The calculated overburden increases systematically from west to east, reaching approximately 8–10 km at the position of the Vandredalen nappe front. It can be argued that this substantial overburden cannot be due to the thickness of the Vandredalen nappe alone, and that higher nappe sheets derived from the thick-skinned zone of the Caledonides must once have been present, as surmised above. The timing of the thrusting in the East Caledonian Caledonides that produced uplift of the Caledonian mountains is well documented (Hurst et al. 1983, Higgins et al. 1991a, 1991b), since it was the erosion of the rising mountains that produced the enormous quantities of sediments which from early Late Llandovery times until the Lower Devonian flowed as turbidity currents into the deep-water trough of the Franklinian Basin. Throughout the 600 km length of the Franklinian Basin in North Greenland the commencement of Silurian flysch sedimentation can be dated as Late Llandovery.

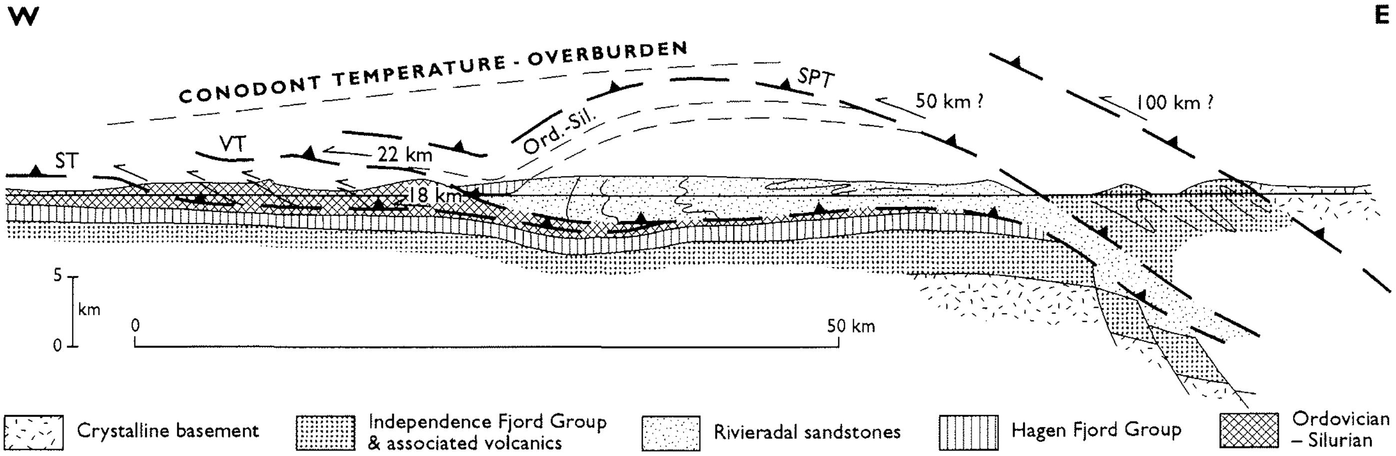
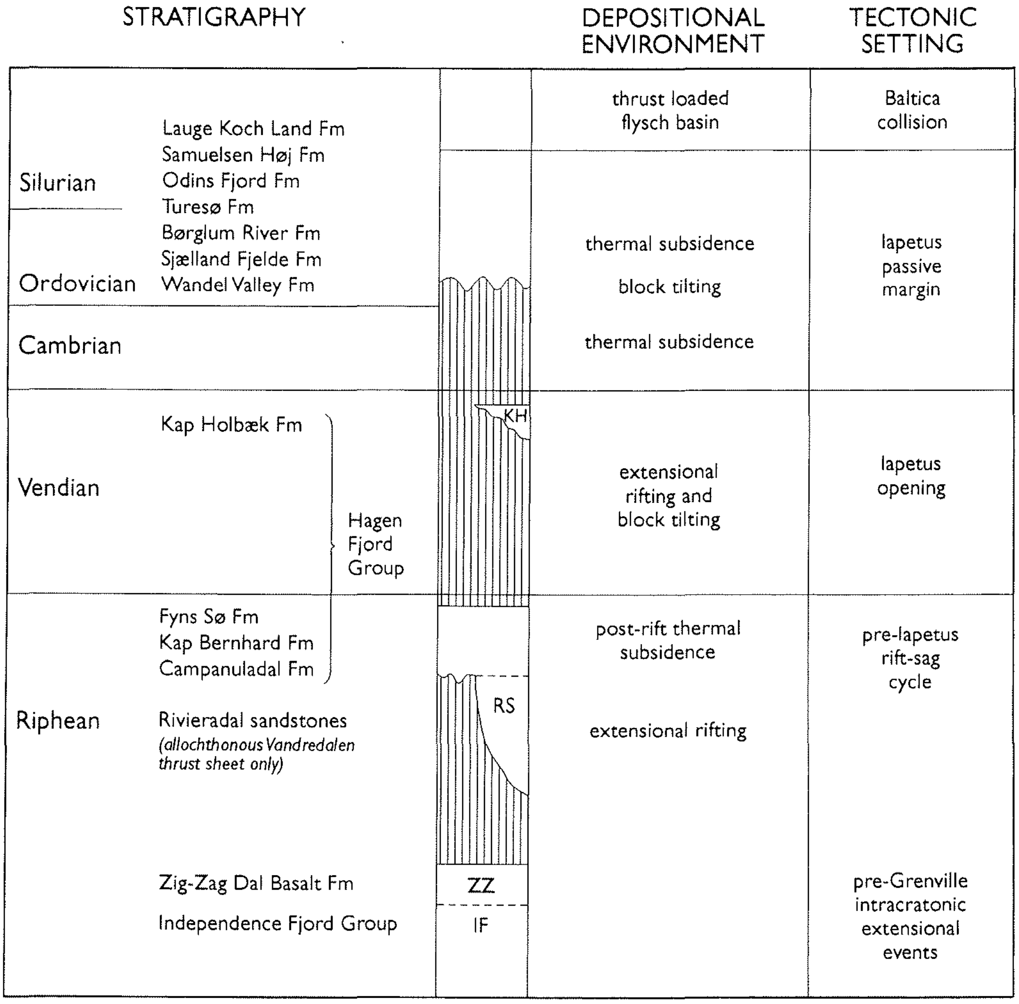


Fig. 4: Schematic E–W cross-section of the thin-skinned thrust belt in Kronprins Christian Land. The parautochthonous thrust belt referred to in the text is the zone between the sole thrust (ST) and the Vandredalen thrust (VT). SPT is the Spærregletscher thrust. Estimated maximum overburden is from conodont alteration indices (M.P. Smith & J.A. Rasmussen, personal communications 1998). See Figure 3 for line of cross-section. Modified after Higgins et al. (in press).



STRATIGRAPHY			DEPOSITIONAL ENVIRONMENT	TECTONIC SETTING
Silurian	Lauge Koch Land Fm Samuelsen Høj Fm Odins Fjord Fm Turesø Fm		thrust loaded flysch basin	Baltica collision
Ordovician	Børglum River Fm Sjælland Fjelde Fm Wandel Valley Fm		thermal subsidence block tilting	Iapetus passive margin
Cambrian			thermal subsidence	
Vendian	Kap Holbæk Fm Hagen Fjord Group	KH	extensional rifting and block tilting	Iapetus opening
Riphean	Fyns Sø Fm Kap Bernhard Fm Campanuladal Fm		post-rift thermal subsidence	pre-Iapetus rift-sag cycle
	Rivieradal sandstones *(allochthonous Vandredalen thrust sheet only)*	RS	extensional rifting	
	Zig-Zag Dal Basalt Fm	ZZ		pre-Grenville intracratonic extensional events
	Independence Fjord Group	IF		

Tab. 1: Proterozoic to Early Palaeozoic stratigraphy of eastern North Greenland and geotectonic interpretation (modified after Smith et al. 1999).

Caledonian orogenesis and regional metamorphism were extensive, and Caledonian eclogites are recorded emplaced into crystalline basement gneisses of North-East Greenland (e.g. Brueckner et al. 1998). Caledonian granites are abundant in the southern half of the East Greenland Caledonides, notably towards the base of the Neoproterozoic Eleonore Bay Supergroup, but are not known north of latitude 76 °N; emplacement ages of many of the granites, recently determined by SHRIMP work on zircons and other methods, cluster around 430–420 Ma (e.g. Andresen et al. 1998, Kalsbeek et al. 1998). Ar-Ar mineral cooling ages following the Caledonian metamorphism are in the range 438–370 Ma (Early Silurian – Middle Devonian; e.g. Dallmeyer et al. 1994, Dallmeyer & Strachan 1994).

NORTH GREENLAND FOLD BELT

Sedimentation in the Franklinian Basin was brought to a close in both Greenland and Arctic Canada by the Ellesmerian orogeny, which was the consequence of collision along the north margin of the Franklinian Basin with an unknown continent in the Devonian. In Greenland the Ellesmerian orogenic deformation produced the E–W trending 600 km long North Greenland fold belt (Fig. 5). This fold belt is characterised by E–W to ENE–WSW trending fold structures, with deformation increasing northwards such that in the extreme north metamorphic grade reaches low amphibolite facies (Soper & Higgins 1987, 1990). In the extreme north there is a north-vergent Paleogene overprint associated with the Kap Cannon thrust zone (Eurekan orogeny), but swarms of late Cretaceous dykes (not shown on Fig. 5) provide an easy means of distinguishing Ellesmerian and Eurekan structures. Three distinct (Ellesmerian) tectonic zones can be recognised, all of which appear spatially related to the geometry of the Franklinian Basin, and are described below.

From earliest Cambrian to early Silurian time a distinction existed in the Franklinian Basin between the trough, in which more than 8 km of turbiditic and hemipelagic sediments were deposited, and the shelf to the south on which accumulated a thinner carbonate-dominated succession (see also Henriksen & Higgins this volume). The evolution of the basin has been outlined by Surlyk & Hurst (1983, 1984), and is presented in more detail together with the trough and platform stratigraphy by Higgins et al. (1991a, 1991b). In summary three stages in the evolution of the trough can be distinguished (Soper & Higgins

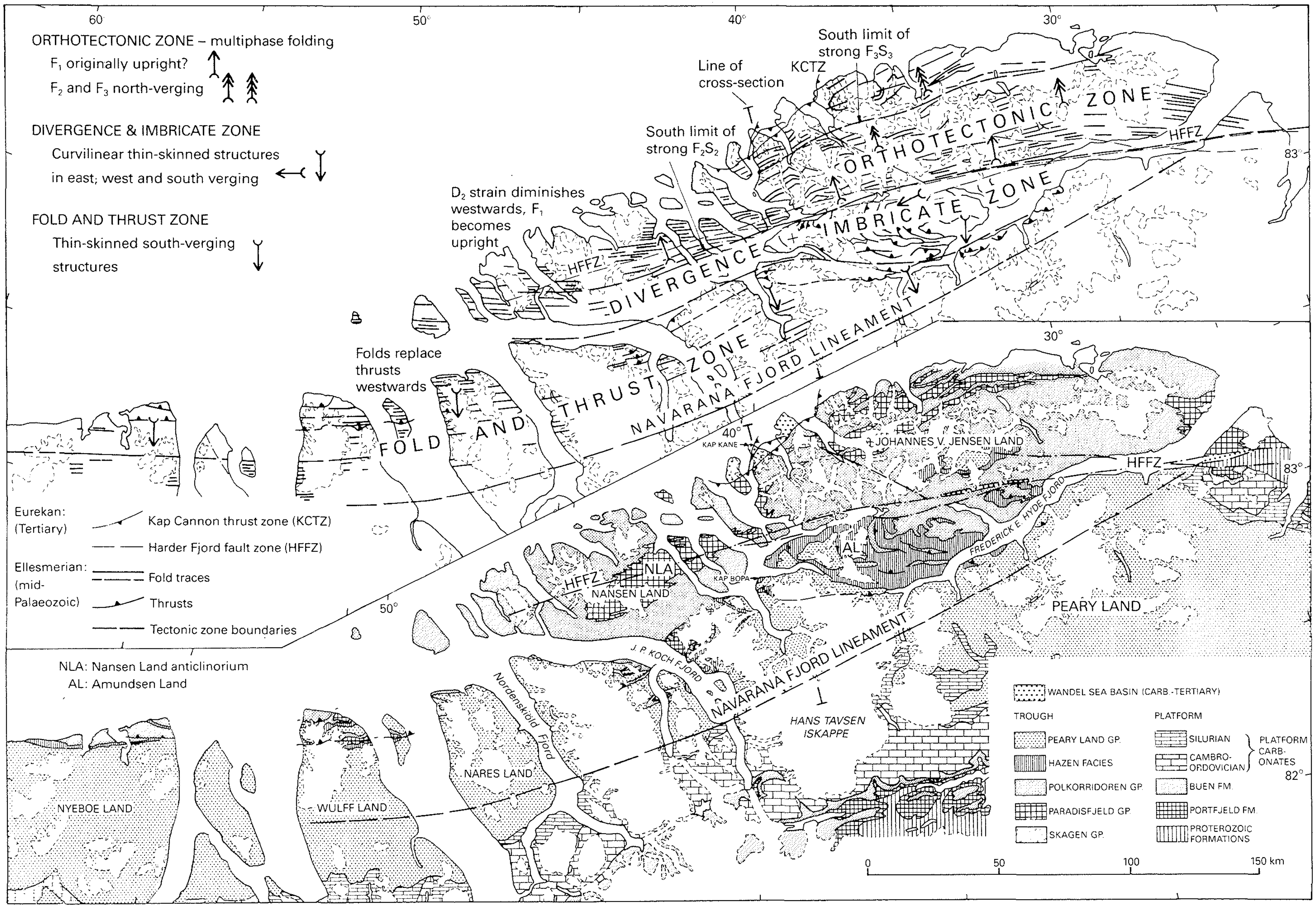


Fig. 5: Structural map (top) and stratigraphic map (bottom) of the North Greenland fold belt, after Soper & Higgins (1985, Fig. 2). Cross-section is shown in Figure 6. The "Hazen facies" of the legend (equivalent to the Hazen Formation of Ellesmere Island, Canada; Trettin et al. 1991) includes the Amundesen Land and Vølvedal Groups (trough) and the Kap Stanton Formation (starved platform margin and outer shelf deposits); see also Higgins et al. (1991a, b).

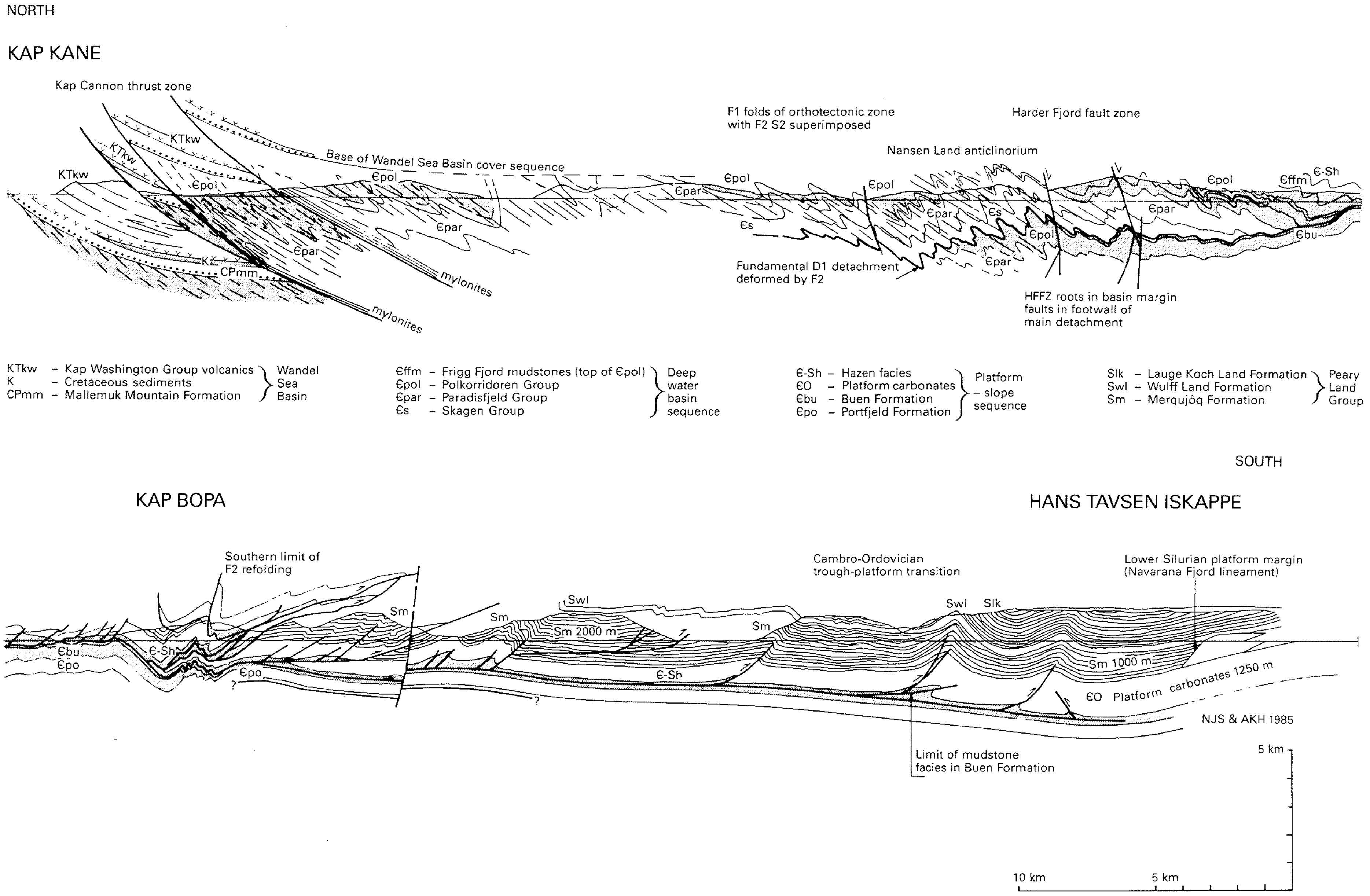


Fig. 6: North–south cross-section of the North Greenland fold belt, after SOPER & HIGGINS (1985, fig. 3). See Figure 5 for line of cross-section. For relationships between deep water and platform stratigraphy see HIGGINS et al. (1991a, b).

1990): a period of rapid fault-controlled extension in the early Cambrian, during which up to 4 km of turbidites were deposited; a long period dominated by thermal subsidence in which a "starved basin" sequence accumulated; and a second period of turbidite deposition in the Silurian when a cumulative thickness of some 5 km was laid down, eventually swamping the shelf. During the early Palaeozoic the trough expanded southwards in several stages by foundering of the platform margin along E–W trending lineaments which are presumed to have been fault controlled (Surlyk & Hurst 1983, 1984); the most important of these is the Navarana Fjord lineament or escarpment (Fig. 5) which formed the platform margin in early Silurian time.

A southern thin-skinned fold and thrust zone coincides with a region which was transitional between the platform and the trough for much of the Cambrian (Fig. 5). Folds verge southwards, and thrusts dip at gentle to moderate inclinations northwards and have a southwards sense of displacement. Major fold traces and linear steep belts trend parallel to the slightly curved Navarana Fjord escarpment and exhibit the same arcuate trends between E–W and ENE–WSW. Clearly the early Silurian facies boundary represented by the Navarana Fjord escarpment constrained the pattern of deformation which developed in the trough sediments as they were compressed against the platform margin.

The divergence and imbricate zone (Fig. 5) corresponds with a tract across which the vergence of folds changes from south to north. It also coincides with a profound change in the stratigraphic level of rocks exposed at the present surface; to the north in the orthotectonic zone on the site of the former deep-water trough Lower Cambrian rocks are exposed, while to the south Silurian rocks are exposed except where older rocks are brought to the surface in anticlinal fold cores and thrust sheets. The divergence zone widens eastwards, where it is characterised by imbricate thrusts with curvilinear traces which verge to the west and south (Håkanson & Pedersen 1982, Pedersen 1986). Soper & Higgins (1985) viewed the imbricate thrusts as an integral part of the Ellesmerian North Greenland fold belt, and attributed their arcuate trends to bending of south-verging thrusts as they impinged obliquely against the buried Navara Fjord escarpment; alternative interpretations of this curvilinear imbricate thrust zone are given by Surlyk & Hurst (1984) and Pedersen (1986). In the extreme east the divergence and imbricate zone appears to be truncated by the Harder Fjord fault zone (Fig. 5).

The northernmost orthotectonic zone developed on the site of the deep water trough of the Franklinian Basin, with its thick fill of Lower Cambrian calcareous and siliciclastic turbidites. In the eastern part of this zone structures are all broadly E–W trending, again essentially parallel to the Navarana Fjord escarpment, except in the extreme east where the Harder Fjord fault zone (HFFZ, Fig. 5) truncates the southern two zones; the structures are referable to three, coaxial tectonic episodes (Soper & Higgins 1985, 1987). F1 folds are dominant in the south where they are upright. To the north F2 folds become superimposed on F1 and are consistently overturned northwards. Near the north coast of Greenland F1 and F2 are isoclinal, third folds appear superimposed on the S2 schistosity and the metamorphic grade rises to low amphibolite facies. In the western part of the orthotectonic zone D1 has produced spectacular trains of F1 folds, upright or slightly northwards verging; D2 strain is weak and decreases westwards (Friderichsen & Bengaard 1985).

A cross-section through the North Greenland fold belt (Fig. 6) illustrates the relationships between the three tectonic zones. Note that in the northernmost part of this cross-section the situation is complicated by superimposed Eurekan (Paleogene) deformation with north-directed displacements on the south-dipping thrusts of the Kap Cannon thrust zone.

In North Greenland crystalline basement rocks are exposed only locally in the southern foreland at the margin of the Inland Ice. Evidence that the Franklinian Basin developed above continental crust is seen in the occurrence of crystalline xenoliths in end-Cretaceous to Paleogene dykes and volcanic plugs related to the Eurekan orogeny. Interpretative cross-sections of the southern margin of the North Greenland fold belt (Soper & Higgins 1990) demonstrate that some of the extensional faults which governed sedimentation in the Franklinian Basin were reactivated as thrusts during the Ellesmerian orogeny (Fig. 7); displacements on these reactivated structures was modest, of the order of a few kilometres, and directed southwards, but was insufficient to bring basement lithologies to present exposure levels on Ellesmerian thrusts.

INTERSECTION OF THE ELLESMERIAN AND CALEDONIAN FOLD BELTS

The assumed intersection of the North Greenland (Ellesmerian) fold belt and the East Greenland Caledonides is obscured beneath post-Ellesmerian sedimentary successions offshore eastern North Greenland. These Carboniferous to Paleogene successions are known as the Wandel Sea Basin (e.g. Stemmerik & Håkanson 1991, Håkansson et al. 1991, Håkansson & Stemmerik 1984, 1989), and onshore are seen to be disturbed by Eurekan (Paleogene) deformation related to the Wandel Hav strike slip mobile belt (Håkansson & Pedersen 1982), one of the major fracture zones in North Greenland associated with the opening of the North Atlantic Ocean. There is little evidence onshore to indicate the nature of the intersection of the two fold belts, although there is a marked change in strike of the marginal thrust systems of the extreme northernmost section of the East Greenland Caledonides in northern Kronprins Christian Land. There the regional N–S trending strikes swing to NNE–SSW and to almost NE–SW trends where last seen, as the fold belt plunges beneath the later Wandel Sea Basin sediments (Fig. 3). The hidden continuation may even continue this swing such that the Caledonian orogenic trends become sub-parallel to the later Ellesmerian trends of the North Greenland fold belt.

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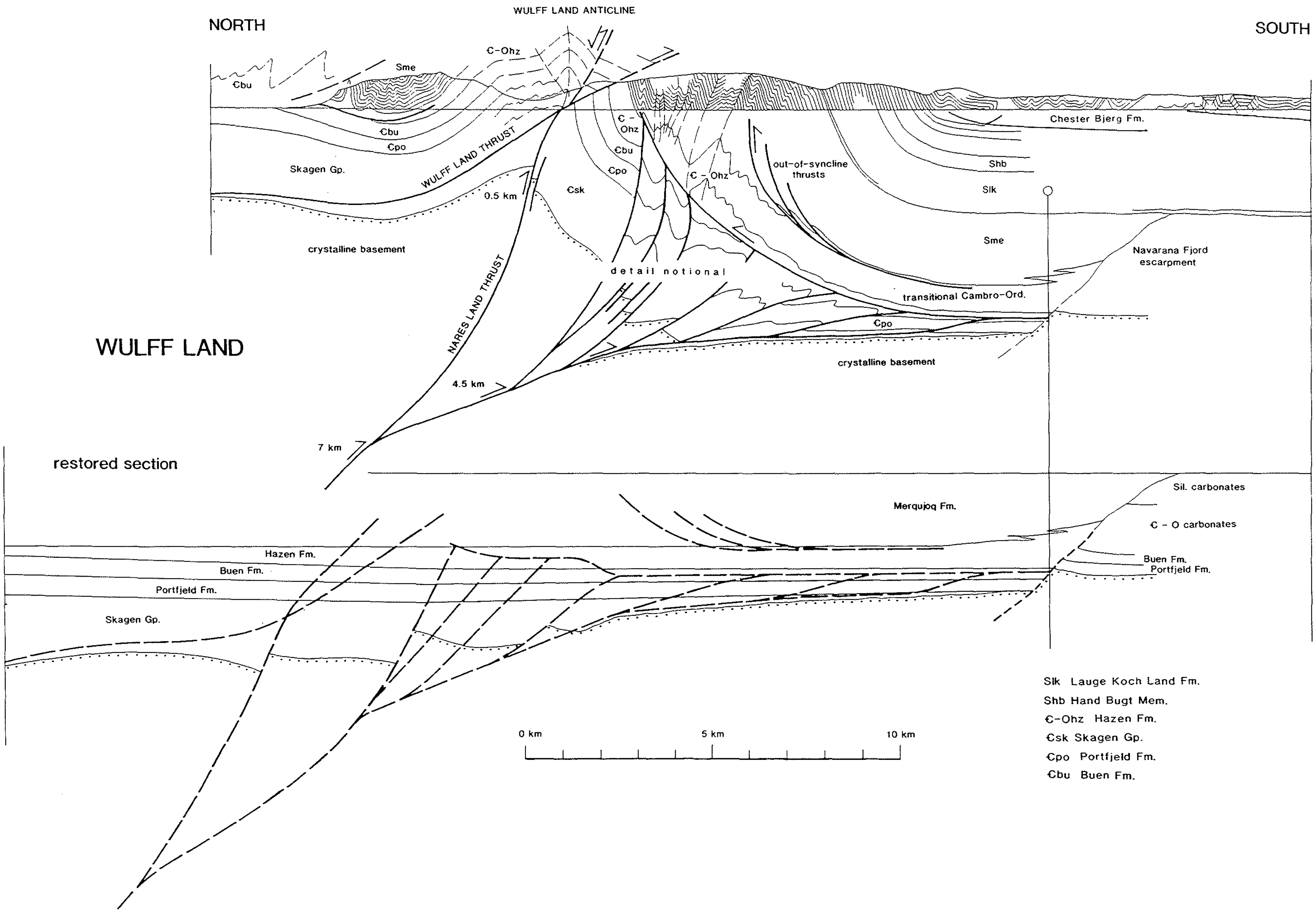

Fig. 7: Interpretative deep section through the marginal fold and thrust zone of the North Greenland fold belt in Wulff Land, with restored section below. Illustrates reactivation of extensional faults during sedimentation as thrusts during Ellesmerian compression. After SOPER & HIGGINS (1990, Fig. 7). The 'crystalline basement' underlying the basin may include Proterozoic rift-related sediments.

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