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Kronprins Christian Land Orogeny Deformational Styles of the End Cretaceous Transpressional Mobile Belt in Eastern North Greenland

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THEME 6: Eurekan Tectonics in Canada, North Greenland, Spitsbergen; Fold Belts adjacent to Extensional Ocean Basins

Summary: In Kronprins Christian Land the end-Cretaceous Kronprins Christian Land Orogeny constitutes a fairly narrow, NW-SE oriented transpressional zone of deformation characterized by a high-intensity axis with diverging thrust displacement and a rapid, symmetric drop in deformational intensity and - probably - thermal alteration away from the axis. Strike-slip dominated deformation is centered along a system of prominent, reactivated along-axis faults, whereas compressional structural elements dominate in the areas between the main faults. The two axial tectono-stratigraphic terranes represent, respectively, the north and south verging flanks of a major flower structure. The Kilen Terrane exposes upper stockwerk level deformation characterized by oblique, *en échelon* domal folds with minor reverse faults and late, small-scale tear faults. The Ingeborg Terrane exposes deformation from a lower stockwerk level characterized by thrust fault ramp-and-flats, thrust fault folding, as well as by zones of chaotic cataclastic breccias. Vertical separation between the two levels is approximately 3 km; in spite of this, localized high-pressure zones in the lower level have reached greenschist facies metamorphic grades.

INTRODUCTION

In the complete absence of off-shore data the northeastern corner of Greenland provides all information presently available from the southwestern continental block in the transform system that displaced Spitsbergen dextrally more than 500 km to the southeast during the Cenozoic opening of the North Atlantic and Arctic Oceans. Most of this movement took place along the complex Spitsbergen Fracture Zone (SFZ; Fig. 1), with the Paleogene West Spitsbergen Orogeny as a prominent feature closely associated with the northeastern margin of the fracture zone. In contrast, in eastern North Greenland southwest of the SFZ, contractional deformation in the form of severe dextral wrenching took place not only some distance away from the SFZ, but also entirely prior to the spectacular transform displacement along this fracture zone. This wrenching event has been named the Kronprins Christian Land Orogeny (KCLO, PEDERSEN 1988), and it constitutes the only compressional element in the otherwise extensional regime of eastern North Greenland from the Carboniferous onwards.

The Wandel Sea Basin was designated to include the then little known Carboniferous to Paleogene post-orogenic cover succession superseding the Caledonian and Ellesmerian Orogenies in North Greenland (DAWES & SOPER 1973, Fig. 1). Knowledge of the Wandel Sea Basin was improved considerably through large-scale mapping in eastern North Greenland by the Geological Survey of Greenland in 1978 to 1980 (HÅKANSSON 1979, HÅKANSSON et al. 1981). In the wake of this campaign a number of models for the regional development emerged, including models pertaining to the Wandel Sea Basin (e.g. HÅKANSSON & PEDERSEN 1982, SOPER et al. 1982). In this process, the geology of Kronprins Christian Land was found to be of particular importance to the understanding of the regional Wandel Hav Strike-Slip Mobile Belt (WHSSMB) introduced by HÅKANSSON & PEDERSEN (1982) as the unifying frame for the structural and depositional development of the Wandel Sea Basin during the later part of the Mesozoic. Further understanding of the structures of the WHSSMB in Kronprins Christian Land was achieved during the Kilen 1985 and Ingeborg 1988 Expeditions (HÅKANSSON et al. 1989, 1993).

The conceptual understanding of the structural framework in the WHSSMB is rooted in the pioneering work on strike-slip fault systems by TCHALENKO (1970), HARDING (1973) and CROWELL (1974), and on *en échelon* folds in relation to wrench tectonics as reviewed by WILCOX et al. (1973). Inspiration to define a strike-slip orogeny cross cutting the northeasternmost corner of Greenland was gathered from LOWELL's (1972) work on the West Spitsbergen Orogeny and the definition of transpression by READING (1980) based on the initial use of the term by HARLAND (1971).

The aim of this paper is twofold. Partly we describe the geological features related to the end-Cretaceous transpressional orogeny in Kronprins Christian Land, and partly we present the sequential development of structural phases and their position in an upper and lower stockwerk within the orogeny.

TECTONIC SETTING

The Wandel Sea Basin comprises Carboniferous to Paleogene sediments deposited in a largely extensional, intracratonic setting closely related to deposition in Svalbard and the Sverdrup Basin (HÅKANSSON & STEMMERIK 1984). When tectonic activity related to the Caledonian and Ellesmerian Orogenies (HURST & MCKERROW 1981, PEDERSEN 1986) ceased, the subsequent geological development in North Greenland has been dominated by frequent episodes of extensional faulting

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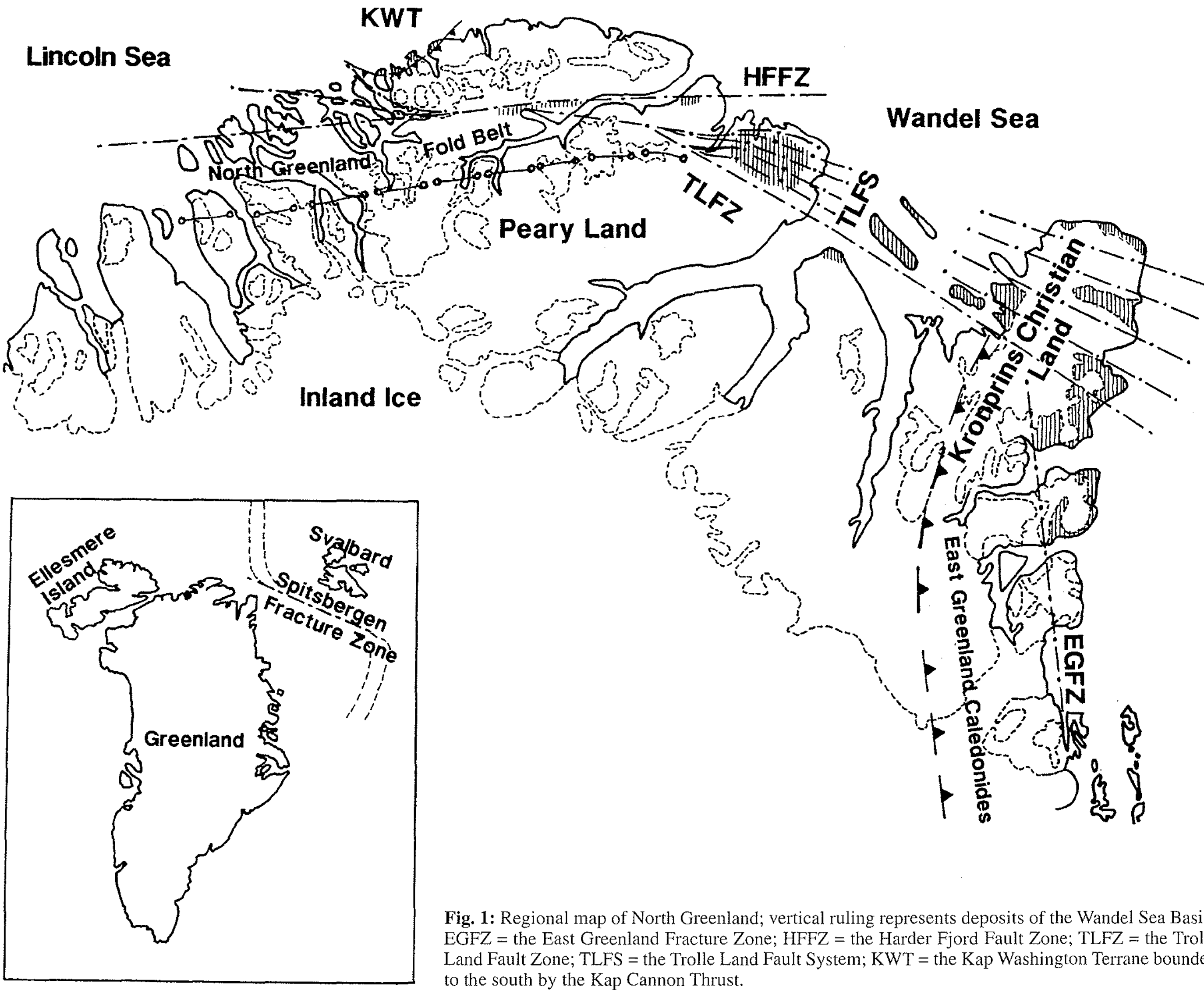

Fig. 1: Regional map of North Greenland; vertical ruling represents deposits of the Wandel Sea Basin; EGFZ = the East Greenland Fracture Zone; HFFZ = the Harder Fjord Fault Zone; TLFZ = the Trolle Land Fault Zone; TLFS = the Trolle Land Fault System; KWT = the Kap Washington Terrane bounded to the south by the Kap Cannon Thrust.

which by and large controlled deposition (HÅKANSSON & STEMMERIK 1989).

Multiple reactivation of individual faults was widespread in this development, particularly in the swarm of slightly diverging faults between the Trolle Land Fault Zone and the Harder Fjord Fault Zone - the Trolle Land Fault System (TLFS) - which, from an apex in eastern Peary Land, can be traced towards the southeast, at least to the broad shelf in the Greenland Sea east of Kronprins Christian Land (Fig. 1). As a result of the complex history only the younger pulses of deformation are regionally discernible. Three Mesozoic events are referred to the WHSSMB culminating in the transpressional KCLO, while the fourth, post-Paleocene episode represent onset of a new era of post-orogenic extension.

Mid-Jurassic continental transtensional tectonics is recorded in the Ingeborg Event (PEDERSEN 1988). This event probably marks the first major lithosphere thinning in the northernmost North Atlantic Region (ELDHOLM et al. 1987) and we therefore regard it as the earliest clearly discernible event in the WHSSMB. During further break-up of the continental crust in the region between Greenland and Norway a large transtensional event, the Kilen Event (PEDERSEN 1988), affected the Wandel Sea Basin in mid-Cretaceous time. We regard this tectonic event as the initial wrench faulting along the large-scale transform fault system that connected the North Atlantic and Arctic Oceans prior to actual ocean floor formation. End-Cretaceous, dextral transpression in the KCLO (HÅKANSSON 1988, PEDERSEN 1988) again reactivated this large-scale transform fault system, with severe compression along a narrow axis reaching greenschist facies metamorphism in local high-pressure zones. The WHSSMB constitutes a very central element in this oblique transform fault complex (HÅKANSSON & PEDERSEN 1982, in press). With its complex series of structural events preceding actual ocean formation in the North Atlantic - Eurasian Basin this mobile belt is therefore considered to be of considerable geotectonic importance in the Arctic region.

Northwest of the TLFS apex the NW-SE strike-slip displacements along the WHSSMB have conceivably been transmitted into bended wrench fault movements along the E-W trending Harder Fjord Fault Zone and via the Kap Washington Terrane into the Lincoln Sea (Fig. 1). However, the compressional features now preserved along most of this transmission zone show limited evidence of strike-slip movements (HÅKANSSON & PEDERSEN 1982, MANBY & LYBERIS pers. com. 1994). The WHSSMB most likely record the position of an early transform, intra-continental plate boundary, abandoned prior to the Paleogene onset of ocean floor formation (HÅKANSSON & PEDERSEN, in press).

The series of events conceived in this - and previous - papers constitute the minimal number of events and phases necessary to account for the structural data amassed over several years of fieldwork. The authors have little doubt that the actual history was even more complex, particularly if the entire length of the structural zone from Kronprins Christian Land to the Kap Washington Terrane is taken into account.

The WHSSMB *sensu strictu* is exposed in two main regions, eastern Peary Land and Kronprins Christian Land, separated by the Wandel Hav. Whereas exposures in Peary Land are extensive, the presence of the ice cap Flade Isblink constitutes a severe obstruction to observations in Kronprins Christian Land.

In eastern Peary Land the WHSSMB is characterized by rigid blocks separated by the repeatedly reactivated, near vertical series of faults of the TLFS (HÅKANSSON & PEDERSEN 1982, ZINCK-JØRGENSEN & HÅKANSSON unpublished data), radiating from an apex coinciding in one of the worlds largest exhalative sedimentary zinc-lead deposits (STIJL & MOSHER 1998). In this region the rigidity of the fault-blocks is retained in the KCLO, with fold- and trust-zones concentrated in the immediate vicinity of the fault zones. In Kronprins Christian Land, on the other hand, folding and thrusting is conspicuous everywhere, most likely reflecting the presence of substantial Upper

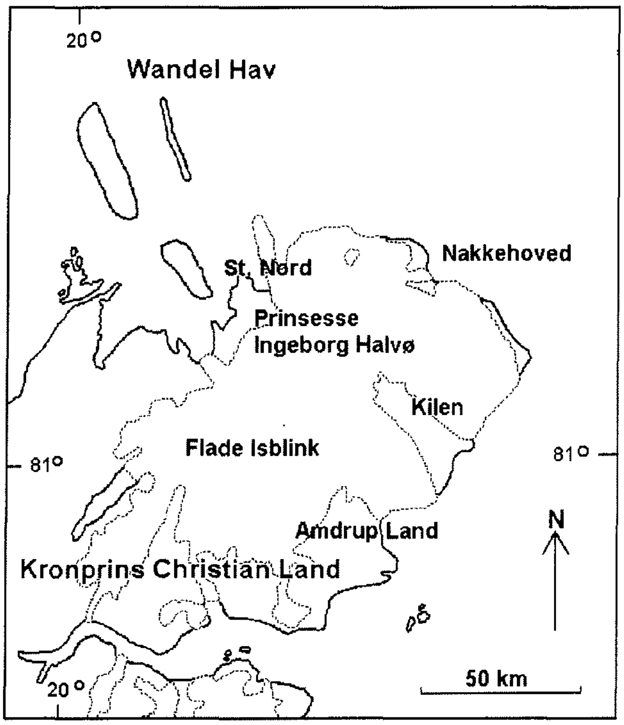

Fig. 2: Toponymic map of Kronprins Christian Land.

Paleozoic gypsiferous strata in this part of North Greenland only (HÅKANSSON et al. 1992).

This paper therefore focuses on the two fault bounded, tectono-stratigraphic terranes in Kronprins Christian Land (Figs. 2, 10), where the structural elements recognized in the development of the WHSSMB are particularly well discernible, in spite of the limited areal exposure. In the Kilen Terrane only the two youngest events are directly demonstrable, i.e. the mid Cretaceous transtensional Kilen Event, and the transpressional KCLO close to the Cretaceous/Tertiary boundary, whereas the preceding transtensional deformation - the Ingeborg Event - is detectable only indirectly, as the structural background for Late Jurassic basin formation. In the Ingeborg Terrane, occupying the northern half of Prinsesse Ingeborg Halvø, extensional faulting representing both the Ingeborg and the Kilen Events are discernible, and in this terrane structures originating from a relatively deep stockwerk level have been brought up into outcrop position due to pronounced inversion during the KCLO.

The transpressional KCLO is dated to be latest Cretaceous to earliest Tertiary in age (HÅKANSSON 1988), thus reflecting the main global Alpine contractional tectonics. In Kronprins Christian Land the youngest dated strata to be affected are Coniacian in age (BIRKELUND & HÅKANSSON 1983), while the Late Paleocene Thyra Ø Formation (BOYD et al., in press, LYCK & STEMMERIK 2000 show no sign of compression. The KCLO is therefore not directly related to neither of the two neighboring orogenies, the West Spitsbergen Orogeny in Svalbard and the Eurekan Orogeny in Ellesmere Island, which both experience their main contractional deformation in the Eocene.

When the main dextral displacement of the Spitsbergen (Eurasian) plate along the transform SFZ began in Eocene time (anomaly 24, MYHRE & ELDHOLM 1988, LEPVRIER 1992), deformation in the KCLO in the WHSSMB had long ceased. In eastern North Greenland tectonic activities were terminated by large-scale, extensional faulting developed in response to the stress relaxation along the Greenland continental margin subsequent to the transpressive passage of the Svalbard corner of the Eurasian continental plate. It should be noted, however, that the complete decoupling in time between the KCLO and the West Spitsbergen Orogeny does not in itself preclude the existence of Eocene transpressional deformation along the north-eastern margin of the North Greenland shelf - information from this off-shore part of the Greenland continental plate have yet to be procured.

THE KILEN TERRANE

The Kilen Terrane (Fig. 3) is composed almost entirely of Upper Mesozoic strata. The seaward part of Kilen is a flat abrasion platform, where a largely Lower Cretaceous succession (Gåseslette Group) comprising mudstones and sandstones is overlain by a thin, patchy cover of Pleistocene sediments. The inner part of Kilen consists of hills rising to just over 500 m outlining the shape of a series of prominent *en échelon* folds. The hills contain two major coarsening upward suites of silici-clastic sediments, an Upper Jurassic - Lower Cretaceous suite (Flade Isblink Group) predating the Gåseslette Group, as well as an Upper Cretaceous suite (Kilen Group) postdating it.

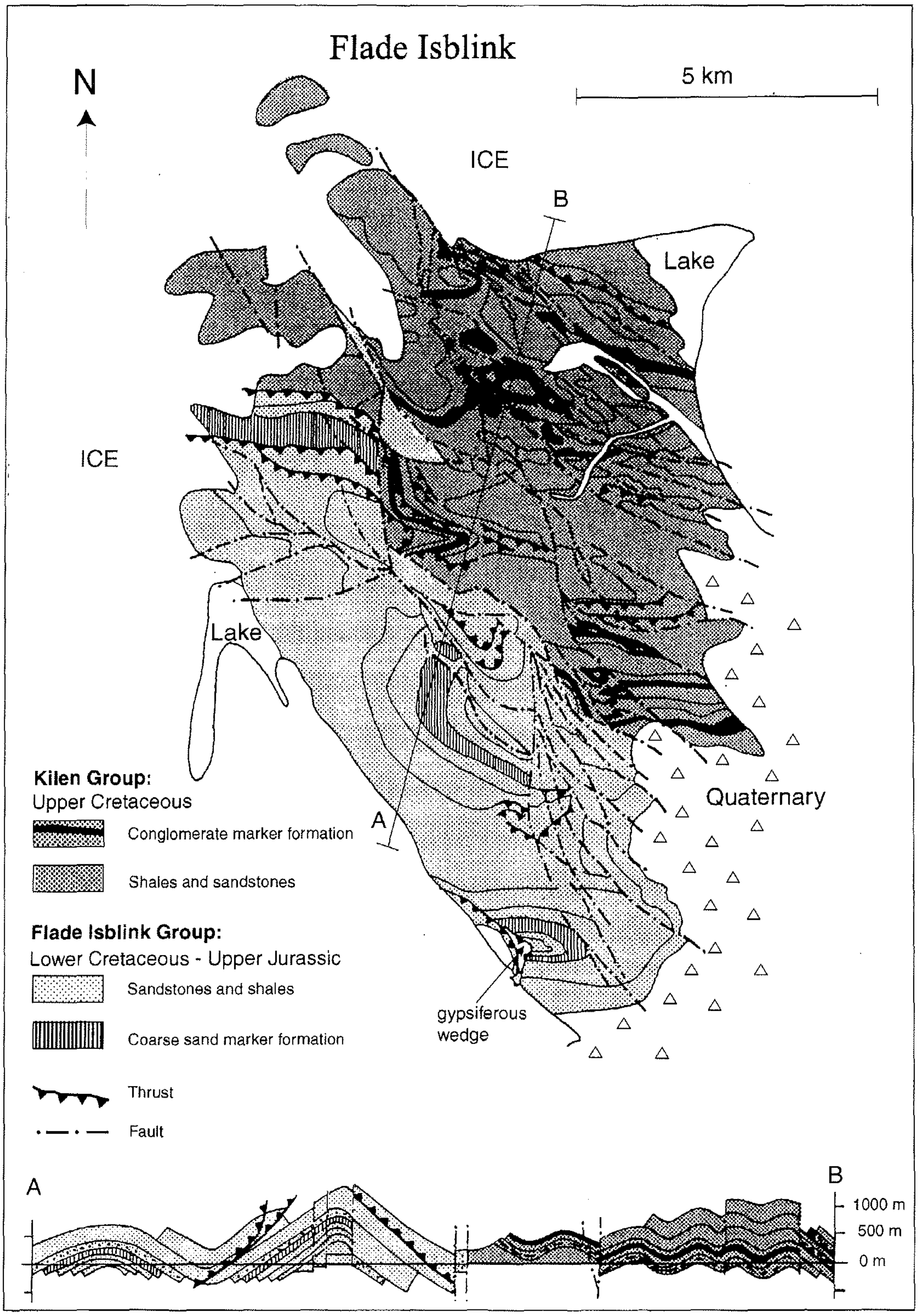

Fig. 3: Simplified geological map of the northern, mountainous part of the Kilen Terrane. Thin lines indicate formation boundaries; triangles signify glacial deposits.

A total of approximately 3500 m of Upper Jurassic to Upper Cretaceous sediments have been preserved in Kilen, and only to a limited degree are they related to contemporaneous sediments in other parts of North Greenland (HÅKANSSON et al. 1991, 1993). Both sets of circumstances most likely reflect the position in the center of the WHSSMB. The formal lithostratigraphy is in the process of being established elsewhere; hence this chapter merely summarizes the lithological and stratigraphic characteristics of the main units.

A highly conspicuous structural feature in the Kilen Terrane is that Lower and Upper Cretaceous strata have different deformation histories. While Lower Cretaceous sediments are deformed by both a single set of extensional faults and transpression, the Upper Cretaceous succession has been subject to transpression only. The extensional faults in Kilen are referred to the Kilen Event, whereas the compressional features are referred to the KCLO (HÅKANSSON et al. 1993). Transpression in the KCLO is thus also responsible for the tilting and reorientation of Kilen Event structures.

Late Jurassic - Early Cretaceous deposition

In the inner part of Kilen Upper Jurassic to Lower Cretaceous deposits constitutes a single, app. 900 m thick group, the Flade Isblink Group, named after the ice-cap surrounding Kilen (HÅKANSSON et al. 1994a and unpublished data). The group is subdivided into six formations.

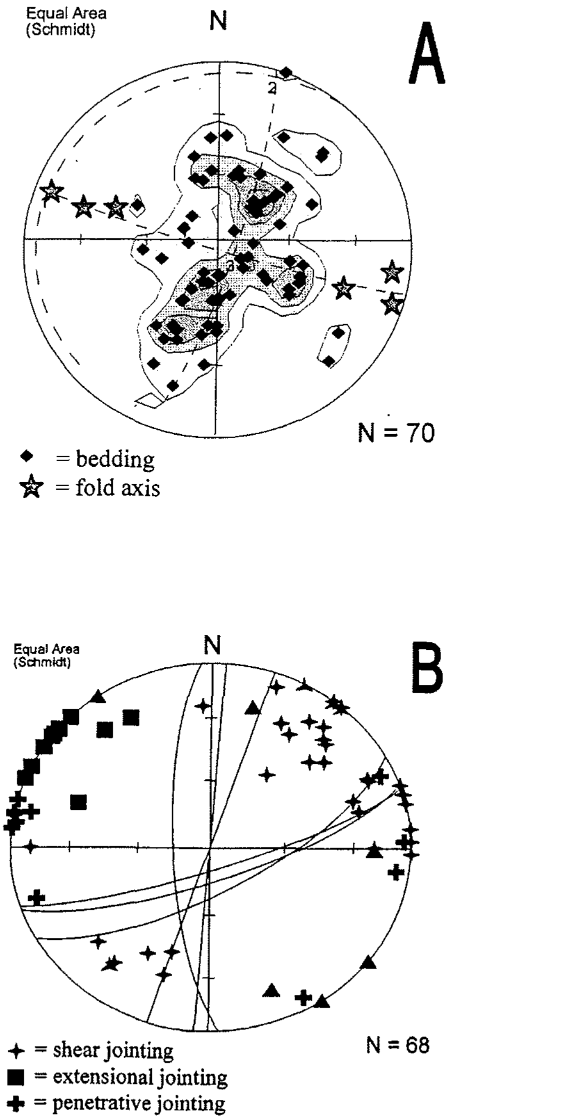

Fig. 4: Orientation of structures related to the Kronprins Christian Land Orogeny from the inner part of Kilen. A) Bedding and calculated fold axes. B) Joint measurements (triangles represent jointing of uncertain relation). Anastomosing shear joints, extensional joints, and penetrative joints are shown as normals to planes; selected sets of conjugate joints are shown as great circles. Shear joints and extensional joints are dynamically related by a right angle; penetrative joints are late transpressional shear joints superimposing all other features. The strike of the shear joints thus rotates from NW-SE to nearly N-S during transpression. The direction of compression is NNE-SSW, corresponding to the main stress direction indicated by the conjugate joints.

Sandy and silty shales capped by a prominent, coarse-grained sand unit forming a conspicuous marker bed (Fig. 3) dominate the lithology in the lower part. The remaining part of the group constitutes a single major coarsening upward sequence. The geological age of the deposits extends from Kimmeridgian to Valanginian (BIRKELUND & HÅKANSSON 1983) and, possibly, somewhat younger Early Cretaceous ages. Similar lithologies, mostly of Aptian and Albian age, also characterize the Gåseslette Group on the outer plains in Kilen.

Late Cretaceous deposition

The Upper Cretaceous Kilen Group attains a thickness of app. 1500 m (HÅKANSSON et al. 1994a and unpubl. data). The dominant lithology is black, silty to sandy shale with an increasing proportion of sand towards the top. The known age range from Middle Turonian to Early Coniacian, with the oldest and youngest formations in the group still undated. Nine formations are distinguished, with a siderite cemented, conglomeratic formation as the most prominent marker horizon (Fig. 3).

Late Cretaceous sedimentation is dominated by a number of coarsening upward sequences which, in general, become more and more coarse-grained towards the top of the succession. In successive pulses of basin rejuvenation deposition of black, silty mudstone follows rapid deepening, and within each sequence the gradual increase in sand accumulation is associated with a gradual shallowing. Frequently, the background mud deposition was interrupted by incoming conglomerate units containing redeposited phosphoritic and quartzite pebbles. The geotectonic frame envisaged for the depositional evolution in the Late Cretaceous of Kilen is a pull-apart basin in an outer shelf environment (HÅKANSSON et al. 1993), where the first (Middle Turonian) black mudstone sequence corresponds to the initial depression, formed in the early phases of pull-apart basin formation. The isolated conglomerate beds represent sudden sediment influx supposedly related to earthquake activity and escarpment exposure along the strike-slip faults at the basin margins, while the repeated occurrence of mudstone units could be related to stepwise elongation and widening of the basin. Towards the top of the succession shallow marine conditions prevail as transtensional forces faded.

The Kronprins Christian Land Orogeny in the Kilen Terrane

Three structural phases related to the KCLO have been distinguished in the Kilen: Anastomosing shear jointing, *en échelon* dome folds, and strike-slip faulting.

Phase 1. In all rock units in Kilen anastomosing jointing is developed, varying in intensity relative to their position close to the straight fault fracture zones or the splay zones. The geometry of the anastomosing joints and conjugate joint sets vary depending on the lithology. The most obvious correlation recognized is the spacing between joints and the thickness of beds. The jointing is generally perpendicular to bedding and strikes SE-NW to ESE-WNW (Fig. 4). An associated system of extensional planar joints is cross cutting the shear joints perpendicularly and thin veins of calcite and quartz are

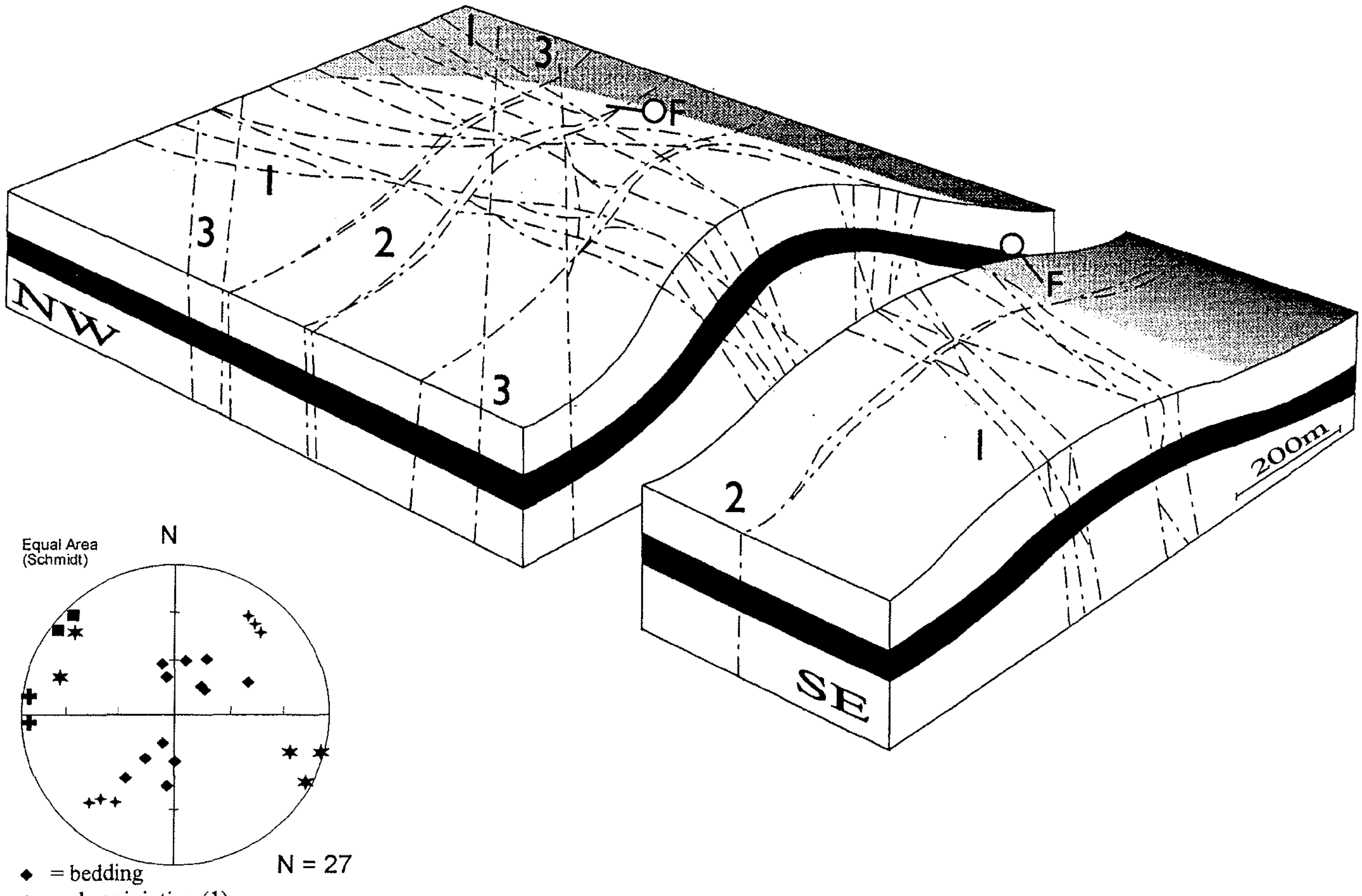

Fig 5: The suite of structural elements related to the Kronprins Christian Land Orogeny in a single *en échelon* dome fold from the inner part of Kilen. The stereographic projection displays the main orientation of structures, while the block diagram illustrates their spatial relations. Note that shear joints are early features with consequent tilt due to the dip of bedding on fold limbs.

commonly formed (Figs. 4, 5). The anastomosing joint systems are tilted by the dome folding and are therefore regarded as the earliest phase in the transpressional deformation.

Phase 2. The Kilen Terrane is totally dominated by *en échelon* dome folds, both in the hills and on the coastal plain. The size of the dome folds tends to be larger in the lower stratigraphical levels, but in general the elongated domes have dimension of 0.5 km x 2 km with a fold amplitude of about 100 m. The maximum plunge of the fold axes in the anticlinal domes is ca. 10-25° with plunges directed towards west and east from a flat axis culmination. Along the non-faulted limbs of the domes bedding is tilted up to about 45° (Fig. 5). In cross-section the *en échelon* folds form upright anticlines with vertical axial planes (Fig. 3). In the later part of domal folding thrust faults are developed in the synclinal areas, and consequently thrust faults strike mainly E-W, parallel to the axes of the *en échelon* folds. The geometry of the thrust faults is characteristic of strike-slip thrusting, i.e. steepening downwards and flattening towards the frontal part of the thrust sheet, with tectonic transport towards the north.

Phase 3. The third type of strike-slip deformation is tear faulting, where major faults segmented the area into rhomb-shaped fault blocks (Fig. 3). The displacement along the leading faults is in the order of one kilometer. Minor dextral off-set of the domes within each fault block is in the order of 25-100 m, while a second order of sinistral faulting is abundant with an off-set of about 5 m. Two distinct macroscopic fault patterns have been recognized in the inner part of Kilen. One is a parallel alignment of rhomb-shaped blocks dominating in the northeastern margin of the hilly area, while a southerly fanning splay zone in the transition area to the plain constitute another (Fig. 3). Straight planar penetrative joints are associated with the tear faulting (Figs. 4, 5).

It thus appears that the three types of transpressional deformation distinguished in the Kilen Terrane constitute a progressive deformational series comprising the following phases (Fig. 6): 1) Anastomosing shear jointing with associated extensional planar joints; 2) *En échelon* domal folding and minor thrusting; 3) Strike-slip faulting with associated penetrative, planar jointing.

Finally it should be noted that a few thrust slivers of Upper Carboniferous gypsum and limestone appears along the (inferred) southwestern boundary fault of Kilen. This coincides well with the overall fault framework, as this fault is regarded to be the boundary fault between the Kilen Terrane and the Ingeborg Terrane (Fig. 10). The gypsum is poly-deformed with fold patterns mirroring the KCLO thrust fault folding superimposing the extensional detachment structures and/or earlier strike-slip shear fold structures (HÅKANSSON et al. 1993).

THE INGEBORG TERRANE

The Ingeborg Terrane (Fig. 7) constitutes the northern half of Prinsesse Ingeborg Halvø, and it thus contains the spot in North Greenland visited by most geologists - the Station Nord airstrip. However, very modest topography, limited exposure and prolonged snow cover combine to make the Ingeborg Terrane one of North Greenland's least appealing sites for geological fieldwork.

The Ingeborg Terrane exposes mainly Upper Paleozoic shales and limestones with a comparatively low stockwerk style of deformation which, along its southern margin, is faulted against undeformed, slightly tilted fluvial and limnic strata of the Late Paleocene Thyra Ø Formation in the southern part of Prinsesse Ingeborg Halvø. Among the most characteristic features of the KCLO in the Ingeborg Terrane are thrust fault ramp-and-flats and thrust fault folding. In more intensely deformed structural settings greenschist metamorphic grades are reached.

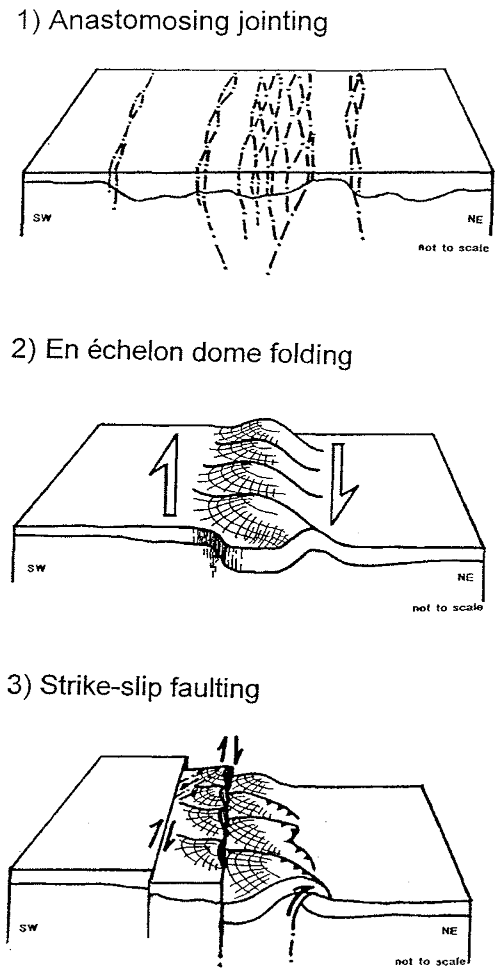

Fig. 6: Sequential series of block diagrams illustrating the progressive development of wrench fault structures in the upper stockwerk levels of the Kronprins Christian Land Orogeny. 1) Penetrative, anastomosing jointing with a main trend striking NW-SE. 2) *En échelon* dome folding is the main phase of transpression in the strike-slip orogeny. 3) The terranes were separated in rhomb-shaped strike-slip fault-bounded segments, and compressional thrust faulting with development of ramp and flats created duplexes.

One of the complexities in the structural geology of Prinsesse Ingeborg Halvø is the presence of two crosscutting sets of extensional faults, with ankerite bearing veins and slaty cleavage characterizing the older set. The older, more prominent fault structures are referred to the Ingeborg Event (HÅKANSSON et al. 1989) which, in the Ingeborg Terrane, comprises NE-SW to N-S oriented normal extensional faults with vertical displacement of about 1 km. These structures are superimposed by extensional normal faulting referred to the Kilen Event (HÅKANSSON et al. 1989). The recognition of two separate extensional phases is emphasized by structural relationships in the Kilen Terrane (see above), where structures related to the Ingeborg Event are absent (HÅKANSSON et al. 1993). However, the separation of the two sets of normal fault structures is commonly difficult due to the fact that they are both overprinted by the KCLO. Consequently all originally horizontal structural features are tilted, whereas primary vertical and steeply dipping structures are inclined.

The formal lithostratigraphy of the Upper Paleozoic strata on Prinsesse Ingeborg Halvø will be treated elsewhere; hence this chapter merely summarizes the lithological and stratigraphic characteristics of the main units.

Late Paleozoic deposition

The oldest Upper Paleozoic suite of sediments comprises limestones, gypsum, coal and shales of Carboniferous age. These sediments or metasediments occur only in highly deformed complexes connected to the imbricate thrusting and strike-slip brecciation. The rocks are correlated to the marine Kap Jungersen and the non-marine Sortebakker Formations south of Prinsesse Ingeborg Halvø (HÅKANSSON et al. 1981, STEMMERIK & HÅKANSSON 1989), in part based on biostratigraphic data (NILSSON et al. 1991).

Higher in the succession more than 300 m of platform carbonates, partly sparitized and dolomitized, may be related to the Lower Permian Kim Fjelde Formation found both north and south of the Ingeborg Terrane (HÅKANSSON et al. 1989). However, the very early Sakmarian or Asselian age found for these carbonates (NILSSON et al. 1991, RASMUSSEN & HÅKANSSON 1996) pre-dates the Kim Fjelde limestones in the rest of North Greenland (HÅKANSSON & STEMMERIK 1995, STEMMERIK et al. 1996). The platform carbonates crop out mainly in the southeastern part of the terrane, and in exposures they always appear brecciated, jointed or deformed by faults related to more than one of the events affecting the terrane.

The remaining part of the succession is composed of mid- to Upper Permian sediments, by and large restricted in distribution to the Ingeborg Terrane, where they constitute two distinct shallowing upward sequences capped by prominent bryozoan limestones. In total the Permian sediments in the Ingeborg Terrane approaches 2 km in thickness, which is close to twice the thickness reached anywhere else in North Greenland (HÅKANSSON et al. 1989).

Finally a very restricted occurrence of Proterozoic metasediments has been identified close to the (inferred) fault zone

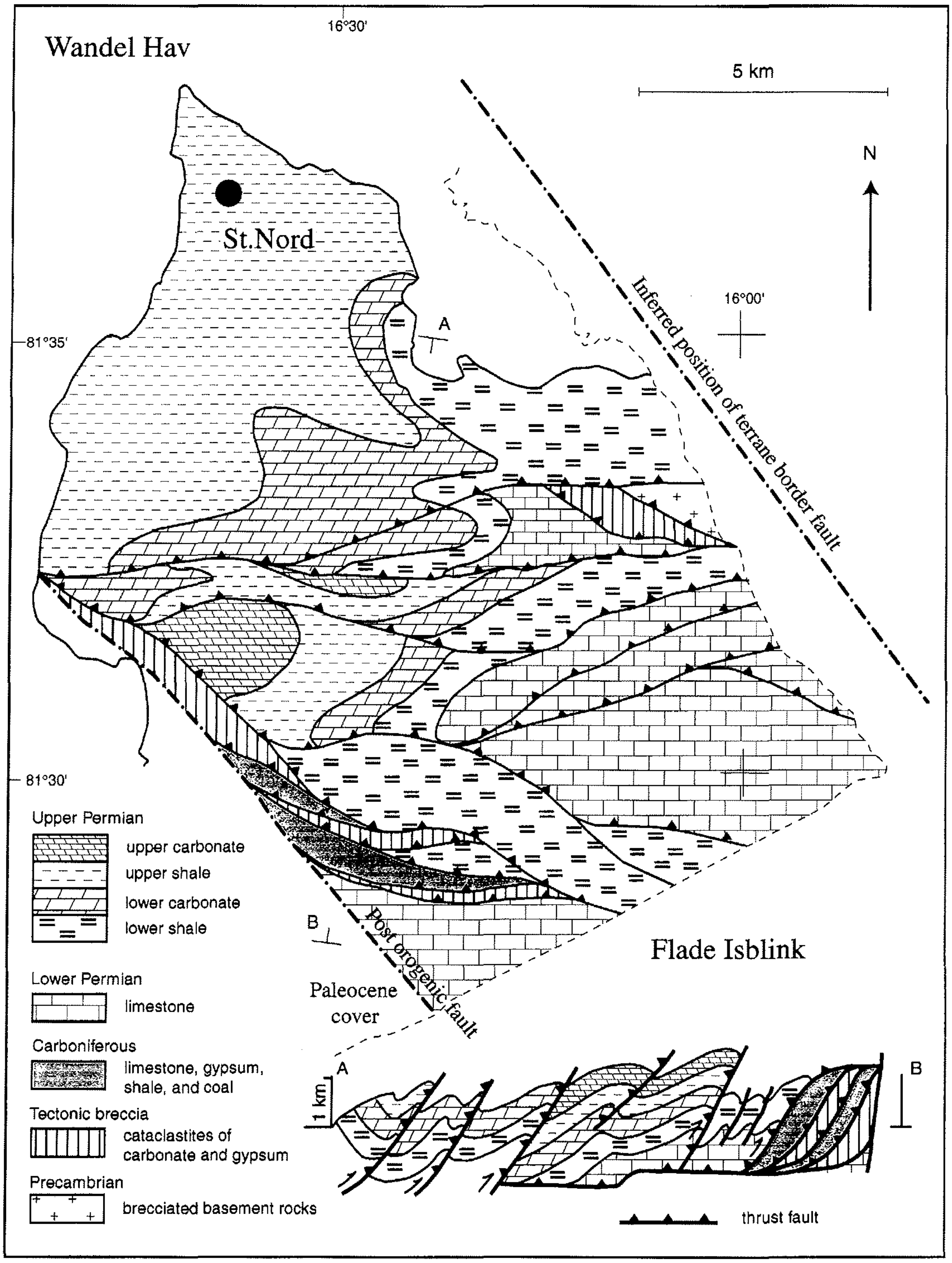

Fig. 7: Simplified geological map of the Ingeborg Terrane (the northern part of Prinsesse Ingeborg Halvø).

bordering the Ingeborg Terrane to the northeast.

The Kronprins Christian Land Orogeny in the Ingeborg Terrane

In Prinsesse Ingeborg Halvø the KCLO is dominated by thrust faulting and thrust fault folding (incl. both thrust fault propagation folding and ramp fault bend folding) with hanging wall anticlines and footwall synclines, and fault bend folds dominated by ramp-and-flat geometries (compare cross-sections in Figs. 3 and 7). Large-scale, symmetric folds comparable in style to the *en échelon* dome folds of Kilen are restricted to the northern part. A number of areas may be discerned, each with a characteristic structural signature.

Central thrust fault complex

A series of app. E-W trending thrust faults are crossing the central part of the Ingeborg Terrane, connecting the NW-SE oriented boundary faults delimiting the terrane (Fig. 7). The thrust faults are in general characterized by ramp and flat structures, which are responsible for a general dip of 45°

towards the north (Fig. 8 : A), indicating a thrust displacement towards the south. The northernmost thrust sheet has been found to contain a more than 150 m thick succession of Upper Permian shales interbedded with thin sandy turbidites, but the thickness of the thrust sheets varies considerably. Within the central thrust fault complex the shaly units are thrust-faulted towards extensive occurrences of Lower Permian platform carbonates in the southern part of the belt, where only a limited number of imbricates and duplexes are discernible due to fairly monotonous lithologies and the high degree of fracturing.

Conodont color alteration index values (CAI 6) from these carbonates indicate a post-depositional temperature regime between 360 and 550° C (RASMUSSEN & HÅKANSSON 1996).

Breccia zones.

In the western part of the Ingeborg Terrane the thrust sheets appear to be bended into a drag along the southwestern boundary fault (Fig. 8 : B) from an initial orientation more or less E-W. These features are markedly deformed by mega-scale

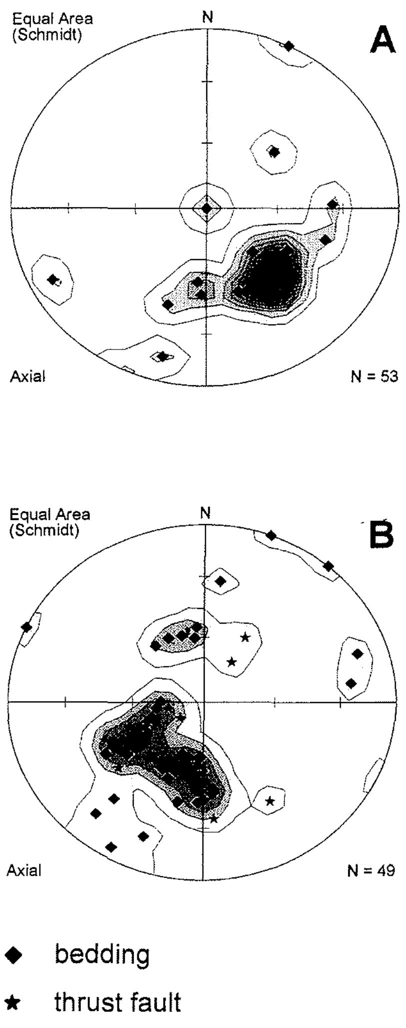

Fig. 8: Structural elements in the Ingeborg Terrane. A) Orientation of bedding from the central thrust fault complex. B) Orientation of bedding and thrust faults from the western part of the Ingeborg Terrane rotated through dextral drag (thrust faults indicated with stars).

dextral drag along the NW-SE striking strike-slip fault zone as indicated by the densely packed imbricates including complex breccias. These extremely deformed thrust fault complexes are here referred to as apex zones (Fig. 9).

In the apex zones along the strike-slip fault the main lithologies involved are carbonates and gypsum derived from the Upper Carboniferous Foldedal Formation as well as silty shales and coal referable to the Lower Carboniferous Sortebakker Formation (cf. Håkansson et al. 1981). Widespread green-gray chloritic slates also occurring in the apex zones have no stratigraphic signature preserved; however, gypsiferous mélanges of these slates and quartzite may represent tectonic inclusions of completely altered Proterozoic basement rocks (compare detached basement below). The green-gray slates are poly-deformed through intensive brecciation and cataclastic shearing; they commonly contain notable amounts of hematite. Along some of the thrust faults the catablastic shear alteration of the rocks created green, glass-clear, lineated aggregates. The intense brecciation resulted in impure carbonate mixtures that altered into skarn-type metamorphic rocks; the occurrence of neomorphic tremolite in these rocks is considered indicative for greenschist facies metamorphism in the apex zones.

A comparable breccia zone is situated in the eastern part of the Ingeborg Terrane, terminated by thrust faults both to the north and the south (Fig. 7). In the southern part of this segment carbonate breccias dominate. Due to a local content of chertified fusulinid foraminifera and fenestrate bryozoans these rocks are correlated to the Asselian-Sakmarian carbonate platform referred to the Kim Fjelde Formation. Three types of cataclastic alteration of greenschist grades affected these limestones: 1) Irregular breccias with cataclasts in a clayey or earthy matrix. 2) Light carbonate catablastite where carbonate recrystallization has cemented the cataclastic limestone. 3) Banded dolomitic hornfels. In the northern part of the transplaced breccia segment the rocks consist of light gray dolomitic carbonates including large cataclastic blocks and mélanges of gypsum; in places the mélanges are bound by fault zones with sulfide mineralisations. Neomorphic chlorite in the bryozoan bearing rocks indicates greenschist facies metamorphic grades.

The main trend of this segment of the breccia zone is NNW-SSE, but a complex variety of structural elements cross cut each other in nearly all directions. Since the breccia zone is cut off by thrust faults in both ends, it should most likely be regarded as a displaced, deep seated segment of one of the main transpressional fault zones bordering the Ingeborg Terrane. The structurally simplest model, where the breccia zone is derived from the inferred terrane border fault northeast of the Ingeborg Terrane in the KCLO, implies that the associated Proterozoic basement rocks (see below) are derived from the part of Kronprins Christian Land northeast of the Kilen-Ingeborg border-fault, from where we have no other indications of such rocks. Alternative models deriving the detached basement from the more likely source area in the southwestern part of Kronprins Christian Land will require repetitive displacement in at least two of the WHSSMB events. The disjunct breccia segment thus illuminates the complexity of structures in the superimposed series of deformational events in this strike-slip mobile belt.

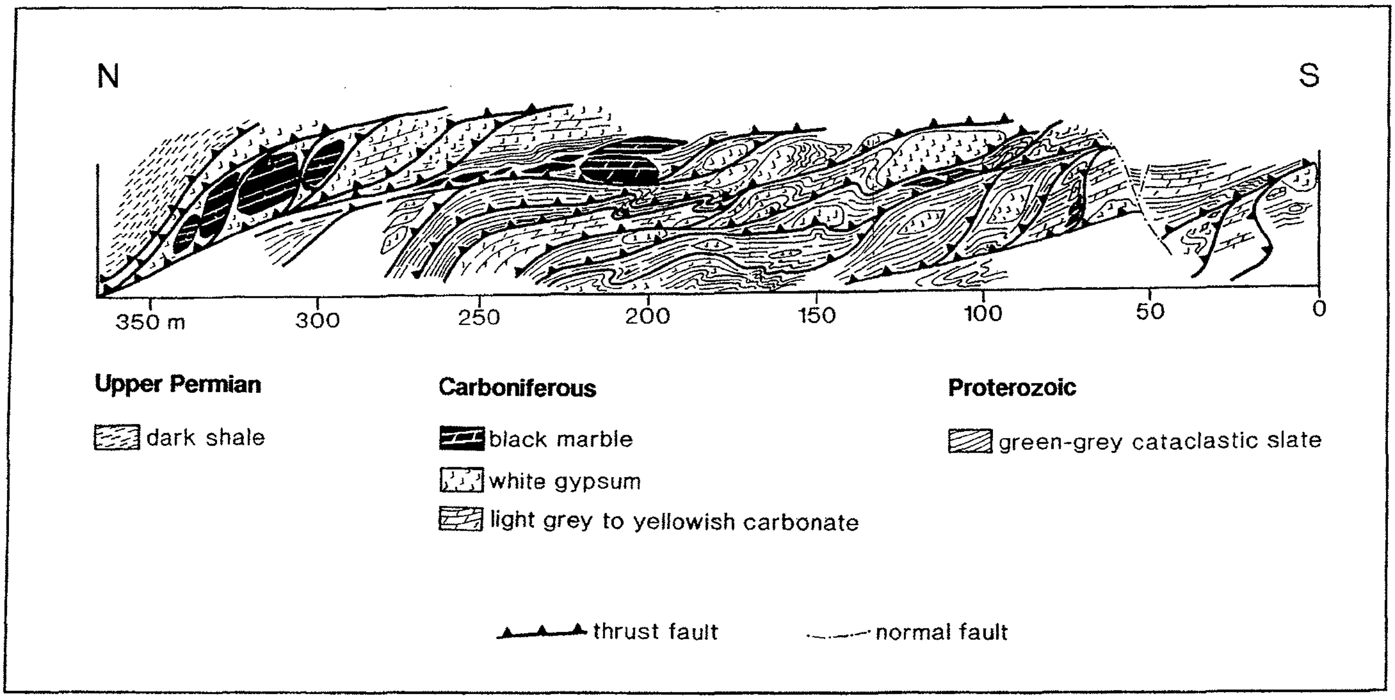

Fig. 9: Cross-section in a thrust fault apex zone of the transpressional thrust faulting along the southwestern boundary fault of the Ingeborg Terrane. Note the mélanges of gypsum in the intensively brecciated limestones and dolomites. Vertical and horizontal scales equal.

Detached basement

Associated with the eastern breccia zone a single outcrop area exhibits high-grade altered cataclastic basement rocks (Fig. 7). Two types of rocks occur: A felsic light rock with cherty and brittle habitues, and a dark green basic cataclastic rock also dense and brittle in character. Microscopical examination of these cataclastic mylonites shows that they contain cataclastic grains of plagioclase and mikrocline in a catablastic matrix of chlorite and epidote. The chlorite and epidote forms an S-1 fabric which is cut by a penetrative S-2 fabric of a micro-grained to tachytic cleavage.

Subsequent to field work in the Caledonian deformed Proterozoic rocks in the southern part of Kronprins Christian Land (Pedersen et al. 1995) the cataclastic basement rocks are now interpreted as cataclastically deformed, partly mylonitized, rocks of the Proterozoic Independence Fjord Sandstones and Midsømmersø Dolerites (cf. Collinsson 1980, Kalsbeek & Jepsen 1983). In this reinterpretation the S-1 fabric is related to possible detachment zones in the Ingeborg Event or, alternatively, to the shear zones of the Caledonian thrusting, whereas the S-2 fabric represents the inversion tectonics of the KCLO.

Fold dominated area

The northern part of the Ingeborg Terrane is dominated by folded Upper Permian sediments (Fig. 7). The folds are upright with axes plunging 20-25° towards either WNW or ESE. These rather steeply plunging fold axes are clearly compatible with the style of domal folding characterizing the KCLO in the Kilen Terrane.

The most pronounced fold feature is emphasized by the hill Knuth Fjeld east of Station Nord, which constitutes the northeastern limb of a large syncline outlined by a prominent, partly silicified bryozoan limestone unit. In the remaining part of this area Upper Permian strata crop out locally, with structural dips mainly in the order of 30-40°.

Post orogenic extensional faulting

The NW-SE striking boundary fault zone in the central part of Prinsesse Ingeborg Halvø is regarded to be one of the most prominent strike-slip faults exposed in the WHSSMB in Kronprins Christian Land. However, subsequent to the KCLO inversion also the final, extensional deformation affecting Kronprins Christian Land reactivated this fault zone. This deformation resulted in large-scale, rigid block faulting so that the southern block in Prinsesse Ingeborg Halvø containing the post orogenic Paleocene cover (the Thyra Ø Formation) is down-faulted relative to the uplifted Ingeborg Terrane to the NE (Figs. 7, 10).

SMALLER TERRANES

A number of additional, fault bound terranes in Kronprins Christian Land were also involved in the contractional regime of the end-Cretaceous KCLO (Fig. 10).

Along the north coast of Kronprins Christian Land the Nakkehoved Terrane(s) exposes a very monotonous succession of Upper Cretaceous fine-grained sandstones, which bear no resemblance to Upper Cretaceous strata in the Kilen Terrane, nor to any other strata in North Greenland (Birkelund &

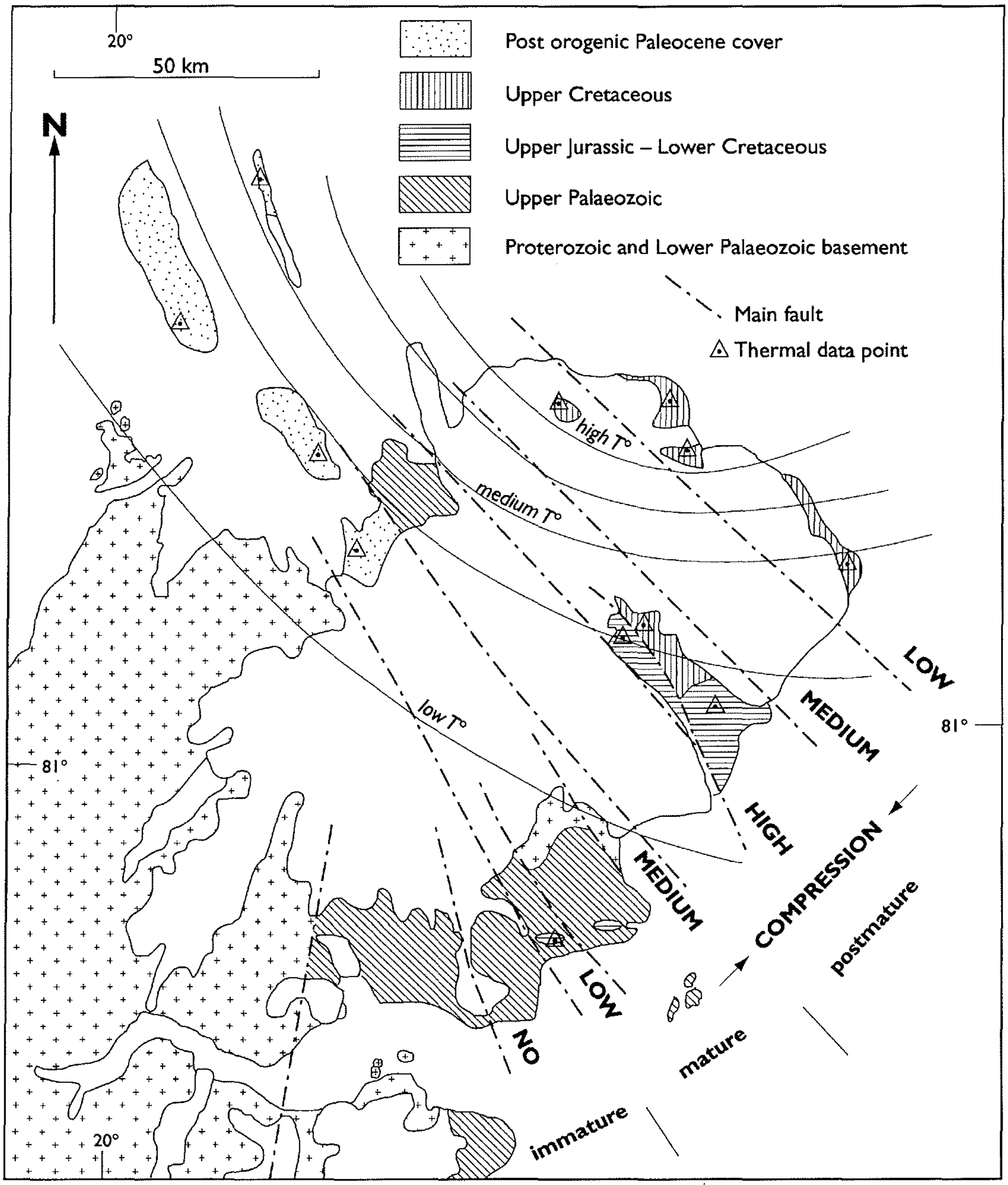

Fig. 10: Geological map of Kronprins Christian Land. The main geology of the Kronprins Christian Land Orogeny is outlined with special reference to fault zones, intensity of deformation, and thermal maturity. The superimposed post-orogenic thermal event is outlined by iso-temperature contours (thin lines). Iso-temperature data points (including Upper Jurassic to Paleogene strata only) are indicated; most represent averages of several samples investigated for vitrinite reflectance (range: Rm 0.36 to Rmax 9.9) and palynomorph color-index (range: TAI 1 to >5). (Thermal data from HÅKANSSON et al. 1994b and STEMMERIK et al. 2000)

HÅKANSSON 1983). In spite of limited areal exposure it is evident, that the Nakkehoved Formation is only mildly deformed into broad, open folds with flank dips rarely exceeding 10° (HÅKANSSON et al. 1981).

South of the Ingeborg and Kilen Terranes a number of fault-bound terranes in the northern part of Amdrup Land, northeast of the Trolle Land Fault Zone (TLFZ), have similarly been subjected to contractional deformation in the KCLO (STEMMERIK et al. 2000). Here a thin Upper Jurassic succession conformably overlying Upper Paleozoic strata is folded into gentle, *en échelon* domal folds with amplitudes increasing from approximately 100 to almost 300 m from SW to NE, whereas, southwest of the TLFZ, contractional deformation is absent (STEMMERIK et al. 2000).

DISCUSSION AND CONCLUSION

The structural complexity in a terrane affected by one or two events of strong extensional deformation and subsequently overprinted by a compressional, partly strike-slip dominated deformation may be disturbingly high. However, careful structural analysis has revealed that repetitive episodes of large-scale extensional basin subsidence followed by prominent tectonic inversion affected both the Ingeborg and Kilen Terranes. The main extensional faults delimiting the terranes of Kronprins Christian Land may be regarded as members of the Late Paleozoic TLFS reactivated repeatedly up through the Mesozoic. In the early part of the Mesozoic they were most likely transected down section into a number of detachment zones coinciding with the gypsum and carbonates of the Kap

Jungersen Formation. However, when they were reactivated in the extensional events of the WHSSMB in the later part of the Mesozoic some of the faults transected deeper involving also the Proterozoic basement. When these deeper faults were reactivated during the transpressional KCLO, parts of the previously deformed detachment zones were thrust faulted up under the inversion tectonics. This structural interplay created a number of tectonic breccias in the zones of maximum movement. Probably the cataclastic breccias were trapped in crushing polygons that acted as hinge zones for the renewed tectonic activities.

The southwestern border fault of the Ingeborg Terrane is the best-exposed main fault zone in Kronprins Christian Land; it therefore provides an illustration of the complexity of the TLFS in this region. From our investigations it follows that this particular fault zone experienced 1) severe strike-slip brecciation in the Ingeborg Event, with associated subsidence in the order of 1 km; 2) renewed brecciation and - possibly - dextral segmentation in the Kilen event; 3) inversion in the order of 3 km associated with mega-scale dextral drag in the Kronprins Christian Land Orogeny.

Most of Kronprins Christian Land was affected by transpressive deformation during the latest Cretaceous - early Paleocene KCLO with the Kilen and Ingeborg Terranes displaying the most pervasive inversion tectonics. The deformation is expressed through a combination of structural features related to particular stockwerk levels. *En échelon* dome folds with opposite plunging fold axis, and penetrative anastomosing shear jointing are dominant in upper stockwerk levels; whereas thrust folding, apex zones with compressed thrust fault imbricates along the main dextral strike-slip faults, as well as chaotic cataclastic breccias are restricted to lower levels. However, all stockwerk levels exposed are characterized largely by brittle deformation.

The main difference between the KCLO structures in the two terranes most severely affected thus relates to the fact that different stratigraphical and structural levels are exposed at the surface. With some probability vertical separation between these levels is in the order of 3 km, corresponding roughly to the difference in their stratigraphic level. While the upper, Late Cretaceous level exposed in the Kilen Terrane displays structures comparable to those created by the classic clay plate models (cf. Tchalenko 1970, Harding 1973), the lower, Late Permian level of the Ingeborg Terrane has been subjected to considerably stronger deformation regimes. However, the 3-km vertical separation is not sufficient to account for the green-schist metamorphic facies registered in several regions within the Ingeborg Terrane. More likely this metamorphic grade is developed within localized high-pressure zones as indicated by the recognition of fossiliferous, Permian limestone through a gradient from seemingly unaffected to pervasively cloritized. The possibility that some of the green-schist facies rocks may have an even deeper origin cannot be ruled out entirely.

Kronprins Christian Land Orogeny symmetry

The variation in stockwerk levels between the Kilen and Ingeborg Terranes along the NW-SE structural grain of the KCLO constitutes a conspicuous element of this orogeny in its type area. However, this differentiation is accompanied by an even more important structural symmetry across the axis defined by the high intensity deformation in these terranes (Figs. 10, 11). Thus, it must be considered highly significant that thrust transport is consistently away from the axis in the two terranes, consistent with an overall dextral sense in the strike-slip regime of the KCLO. And, considering the difference in stockwerk level exposed, the two terranes may well represent mirror images in a major flower structure. Furthermore, the high intensity deformation in the Kilen and Ingeborg Terranes is rapidly replaced by weak deformation in neighboring terranes both towards the northeast, in the Nakkehoved Terrane(s), and towards the southwest in the Amdrup Land terranes. In Amdrup Land a complete transition into totally

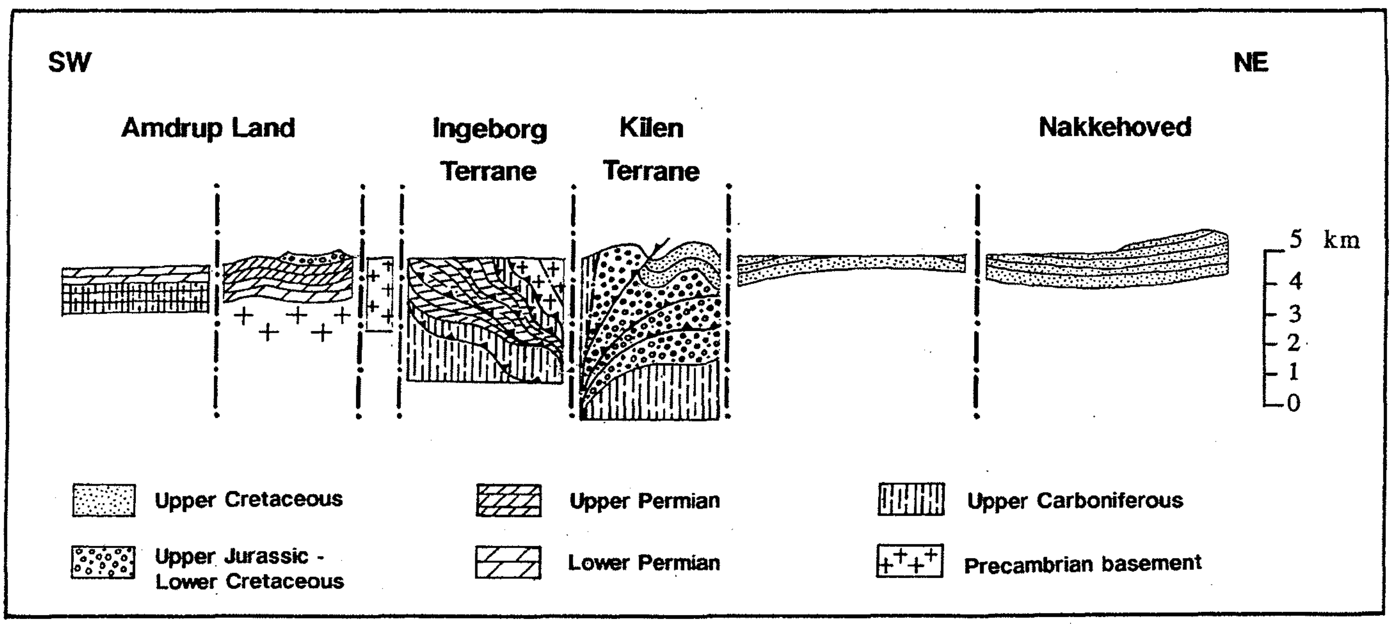

Fig. 11: NE-SW cross-section through Kronprins Christian Land. Note opposing polarity in thrust vergens in the Kilen and Ingeborg Terranes.

undeformed strata southwest of the TLFZ has been demonstrated (STEMMERIK et al. 2000), whereas the presence of undeformed strata northeast of the Nakkehoved Terrane(s) must remain speculative. Nevertheless, it is quite evident that the Kronprins Christian Land Orogeny in its type area is quite narrow, with pronounced structural symmetry around the NW-SE axis defined by the Kilen and Ingeborg Terranes, and with deformation intensity tapering out rapidly away from this axis in both directions (Figs. 10, 11).

Across the Amdrup Land terranes thermal maturity levels also raise in intensity towards the KCLO axis (Fig. 10, STEMMERIK et al. 2000). However, the gradual nature of this raise is based on the Late Paleozoic part of the succession, whereas the very limited data available for Mesozoic strata in these terranes may indicate a more abrupt shift in thermal maturity levels (STEMMERIK et al. 2000). In the northern part of Kronprins Christian Land a pronounced, yet highly localized post-Paleocene thermal event (HÅKANSSON & PEDERSEN 1982, HÅKANSSON et al. 1994b and unpublished data) have completely obliterated most previous thermal signatures (Fig. 10), including those related to the KCLO. As evident from the iso-temperature contours (Fig. 10), a comparable decrease away from the orogenic axis towards the northeast is therefore no longer to be detected.

The pronounced structural symmetry of the KCLO in its nominal area may therefore well have been accompanied by an equally pronounced symmetry in thermal maturity. Even though half the thermal signal is considered lost, this strike-slip orogeny nevertheless stands out as markedly symmetric and very narrow, with a high intensity deformation along-axis core of less than 30 km width associated with prominent strike-slip fault zones.

It is noteworthy, that the high intensity core is located within the Greenland continental block, well away from the present day plate margin between Greenland and Svalbard. The regional extension of the KCLO is at least 400 km along strike, and if compressional features along the HFFZ and in the Kap Washington Terrane are included, the length will be in excess of 750 km. In a separate paper (HÅKANSSON & PEDERSEN, in press) we explore the notion that the narrow, high intensity core of the KCLO in Kronprins Christian Land may in fact represent a segment of the (Late) Mesozoic intra-continental plate boundary separating Laurentia and Eurasia.

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