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Higgins, A.K. &Frederiksen, K. (eds)

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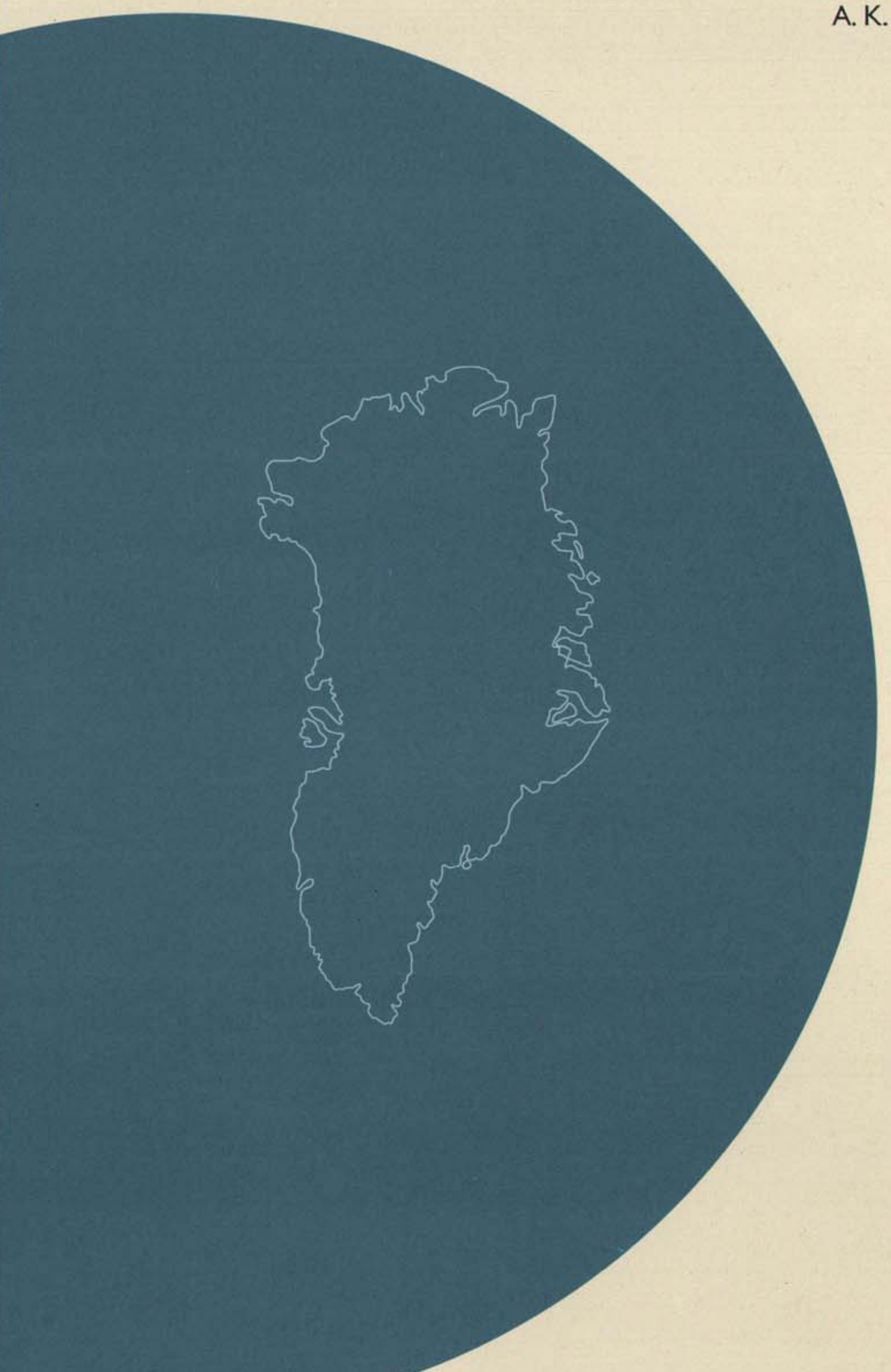

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

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Contents

Geological field work in the Kong Oscar Fjord region, East Greenland, 1997

Niels Henriksen

NH: *Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark*

The Geological Survey of Denmark and Greenland (Danmarks og Grønlands Geologiske Undersøgelse: GEUS) has undertaken a project for geological investigations in the southern part of North-East Greenland (72°–75°N); field work was initiated with a two-month field campaign in 1997 and will be completed by a second summer season in 1998.

A principal aim of the studies includes regional mapping leading to compilation of a 1:500 000 geological map sheet covering the area between Kong Oscar Fjord (72°N) and Grandjean Fjord (75°N). The work on this map sheet (sheet no. 11) represents a reinvestigation of areas intensively studied by geologists of Lauge Koch's geological expeditions to East Greenland (1926–58), the results of which were compiled by John Haller and published as a set of 1:250 000 map sheets covering the region 72°–76°N (Koch & Haller 1971). The new regional geological investigations, which aim at understanding the general geology of the region, range from studies of the geology of Precambrian basement complexes within the Caledonian fold belt to the post-Caledonian Mesozoic and Tertiary sediments and Tertiary volcanics. Attention will also be given to topics related to oil and mineral exploration. Field activities in 1997 included geophysical studies in cooperation with the Alfred Wegener Institute (AWI), Bremerhaven. Logistic support was also given to two groups of geologists from the University of Oslo with whom geological cooperation has been established.

The operation base in 1997 was at Mestersvig, where the Danish Polar Centre and the Sledge Patrol Sirius had organised base camp facilities and air traffic and security control. All internal Twin Otter flights and connections to Iceland during the season were arranged in cooperation with the Danish Polar Centre.

The geological work in 1997 included 10 two-man teams and three three-man teams, whose working commitments were: Caledonian and pre-Caledonian crystalline complexes between northernmost Nordvestfjord (72°N) and Andrée Land (74°N) – four teams; Caledonian and pre-Caledonian granites and migmatites – two teams; Upper Proterozoic carbonate sediments in the Caledonian fold belt – one team; Permian–Triassic sediments between Traill Ø and Wegener Halvø – two teams; Jurassic–Cretaceous sediments between Traill Ø and Hold with Hope (72°30′–74°N) – three teams. One team worked on mineral resource investigations in the Caledonian fold belt. A project in cooperation with AWI involved magnetic susceptibility investigations of rock units in the southern part of the crystalline complexes.

Funding from the Danish National Science Foundation (Statens Naturvidenskabelige Forskningsråd: SNF) supported the research in both the Caledonian fold belt and in the post-Caledonian sediments (Tupolar Project). Substantial support was also provided by

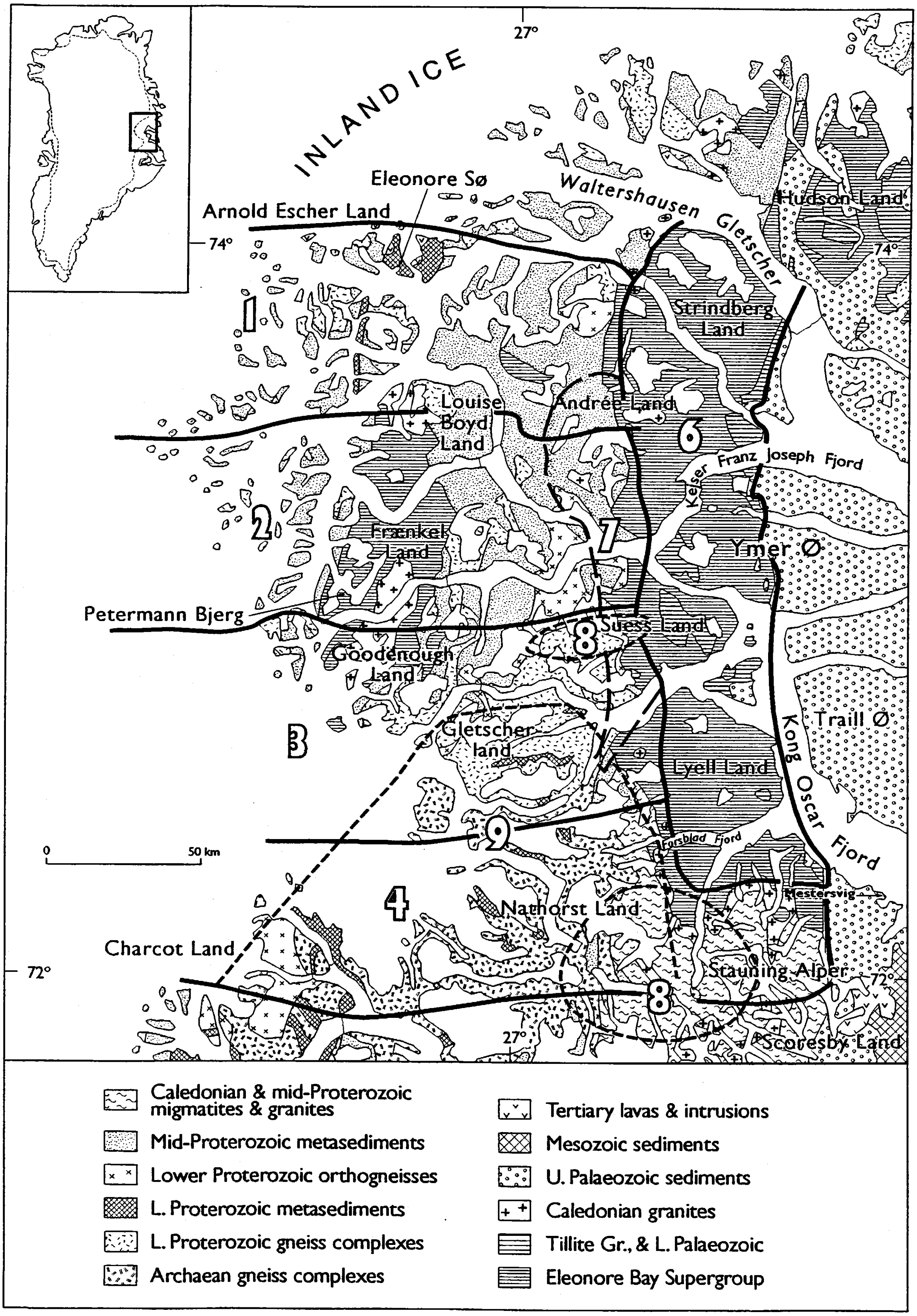

Figure 1. *Geological sketch map of the region 72°–74°N, and the areas of responsibility of the geological teams 1–4 and 6–9 (see opposite). Team 5 studied granitic rocks throughout the region.*

Carlsbergfondet for special metamorphic studies in the Caledonian fold belt. Significant external support was obtained through cooperation with invited guest scientists from institutions outside Denmark, whose participation in the field work was paid for by GEUS, whereas salaries and research facilities are covered by their home institutions.

1. Participants

This collection of articles summarises the provisional results of the 1997 field work as presented by the participating geoscientists immediately after the season. However, only the reports of activities by groups working in the Caledonian fold belt are included; the results of the work in the post-Caledonian sequences will be reported elsewhere. The general regional mapping responsibilities and special working subjects of the different teams are listed below. Working areas are indicated on Figure 1.

(1)	A. K. Higgins (GEUS) & A. G. Leslie (Belfast)	Caledonian geology of Andrée Land, Eleonore Sø and adjacent nunataks
(2)	J. C. Escher (GEUS) & K. A. Jones (Oxford)	Caledonian deformation in Frænkel Land and southern Louise Boyd Land
(3)	S. Elvevold (GEUS) & J. Gilotti (Albany,USA) (supported by the Carlsberg Foundation)	Metamorphic evolution of the Caledonian fold belt in Suess Land, Goodenough Land and Gletscherland
(4)	J. D. Friderichsen (GEUS) & K. Thrane (GEUS) (supported by SNF)	Caledonian crystalline complexes, incorporating pre-Caledonian basement and cover units, Nathorst Land
(5)	F. Kalsbeek (GEUS) & H. F. Jepsen (GEUS)	Granites in the Caledonian fold belt (72°–74°N)
(6)	K. S. Frederiksen (GEUS) & L. E. Craig (London) (Mainly financed by SNF)	Sedimentary studies of the carbonates in the Upper Proterozoic Andrée Land Group (72°–74°N)
(7)	H. Stendal (Copenhagen) & Maj B. Wendorff (Copenhagen)	Mineral resource investigations in the Caledonian crystalline complexes between Andrée Land and Lyell Land
(8)	G. R. Watt (Perth, Australia)	Partial melting studies in relation to migmatisation processes in the Caledonian fold belt of Frænkel Land, Nathorst Land and Scoresby Land
(9)	V. Schlindwein (Bremerhaven) (AWI-project fully integrated in GEUS activities).	Magnetic susceptibilities in Caledonian crystalline complexes of Gletscherland, Nathorst Land and Charcot Land

The activities in the post-Caledonian sediments (not reported here) included the work of the following teams, supported by GEUS, which was fully integrated in the expedition:

(a)	J. Therkelsen (GEUS) & H. Vosgerau (GEUS)	Mesozoic sediments Hold with Hope to Traill Ø
(b)	M. Larsen (GEUS), S. Olaussen (SAGA) & T. Nedkvitne (SAGA)	Mesozoic sediments Hold with Hope to Traill Ø

Activities financed by the Tupolar project (SNF-supported) included the following teams:

(c)	T. Preuss (GEUS), P. Alsen (GEUS) & Sarah Prosser (SAGA)	Permian to Cretaceous sediments, Traill Ø–Wegener Halvø
(d)	L. Seidler, M. Kreiner-Møller & M. Bjerager (all Copenhagen University)	Permian to Cretaceous sediments, Traill Ø–Wegener Halvø
(e)	L. Stemmerik (GEUS), S Piasecki (GEUS) & G. B. Larssen (SAGA)	Permian to Cretaceous sediments, Traill Ø–Wegener Halvø

The expedition was led by Niels Henriksen (GEUS).

2. Logistic background

The GEUS expedition used Mestersvig (72°14'N; 23°55'W) as a base camp and centre for field operations the whole season. Mestersvig is a former airport which can be used for special purposes on request, and is manned by the military sledge patrol Sirius in combination during the summer with the Danish Polar Centre (DPC). Sirius and DPC had 5–6 persons stationed at Mestersvig during the field work, and among their other commitments supported the GEUS activities with radio surveillance of flight operations, Twin Otter transport, internal transport in connection with mobilisation and demobilisation and food and lodging of the GEUS group in transit or based at Mestersvig. GEUS maintained its own base radio station at Mestersvig for daily contact with all field teams and other groups and stations in the area.

The GEUS expedition numbered in all 38 persons, and was led by Niels Henriksen. The working group included 25 geologists and five student assistants, of whom 10 geologists participated for only half of the season.

On July 5th 1997, 24 participants and 7 tons of equipment and provisions left Copenhagen with a Hercules C-130 aircraft from the Danish Air Force (RDAF) bound for Mestersvig. Due to bad weather in the Mestersvig region the expedition spent five days at Keflavik in Iceland and did not arrive at Mestersvig until July 10th. At the end of the season the expedition with 28 passengers and 10 tons of equipment and rock samples returned from Mestersvig to Copenhagen with a RDAF C-130 on August 29th. Participants spending less than a full season in East Greenland travelled up or home via Iceland with chartered aircraft.

The expedition chartered two small helicopters from Greenlandair, Nuuk (Godthåb), one AS 350 Ecureuil and one MD 500 D, which were both operated out of Mestersvig. The Twin Otter support included two main tasks: (1) Supply of aircraft fuel from Constable Pynt airport (70°45'N) in the Scoresby Sund region to Mestersvig, and (2) establishment of depots of fuel and equipment in the field area in support of the helicopter operations. The Twin Otter transport was supplied by a combination of Greenlandair and Flugfélag Islands aircraft, via a charter agreement with the Danish Polar Centre, who arranged this work on behalf of the various expedition groups in the area.

In addition to the scientific participants mentioned above, the following expedition members took part in the work in a support capacity:

Ib K. Olsen	quartermaster	GEUS
Palle Bay	quartermaster	GEUS
Jakob Lautrup	photographer	GEUS
Göran Lindmark	pilot/mechanic	Greenlandair
Per-Henrik Westlund	pilot/mechanic	Greenlandair
Jan Refsgaard	pilot	Greenlandair

3. Visiting groups

In mid-August a Danish minister (Jytte Hilden) and a minister in Greenland (Marianne Jensen) visited Mestersvig together with their staff members, and were accompanied by the chairman of the GEUS board and the GEUS directors. This visiting group of 12 persons spent three to four days with the expedition, and as well as visiting four field parties were shown some of the main features of the regional geology.

On the Caledonian geology of Andrée Land, Eleonore Sø and adjacent nunataks (73°30′–74°N), East Greenland

A. G. Leslie & A. K. Higgins

Abstract: The region studied is dominated by metasedimentary rocks, variably intruded by granite sheets and veins, and shows a remarkable consistency of the deformation sequence from place to place; structures are therefore all interpreted as Caledonian in age. The dominant sense of displacement on all thrusts is westwards, and the 'detachment' at the base of the Eleonore Bay Supergroup which has been viewed by some workers as an extensional shear zone is, at least in northern Andrée Land, a broad top-to-the-north-west shear zone lacking true mylonites.

The Eleonore Sø complex of the nunatak region occurs within a major tectonic window through a thin-skinned thrust sheet. Details of its development indicate a rift setting for the Eleonore Sø volcano-sedimentary sequence, which is overlain unconformably by the 'Slottet Quartzite'. The latter contains *in situ* developments of classic Scolithus tubular trace fossils, indicating a latest Proterozoic–Cambrian age, and suggesting that the 'Slottet Quartzite' and correlatives elsewhere (e.g. the 'Zebra Series' of Dronning Louise Land) are the source of the abundant Scolithus-bearing quartzite erratics of the coastal region of East Greenland. In several places the 'Slottet Quartzite' is overlain by grey to orange weathering carbonates, which are probably Lower Palaeozoic in age and form the glide horizons for the major thrusts which outline the window.

A further smaller window in the Målebjerg area also preserves Scolithus-bearing quartzite overlain by grey carbonates, but in this area the Eleonore Sø complex is absent and the quartzite unconformable overlies basement gneisses..

New collections were made from the alkaline Tertiary basalts of the nunatak region, whose known extent was expanded to the western summits of J. L. Mowinckel Land. The lavas were erupted onto an irregular (*c.* 150 m relief) gently inclined peneplain surface, now at about 2000 m altitude. Three new Tertiary volcanic necks were recorded, one of which contained small hartzburgite nodules and fist-sized peridotite inclusions,both of which are assumed to be mantle-derived. Another of these necks contains metasedimentary xenoliths which may have been derived from a hidden foreland sequence at no great depth below the present exposure level. Hartzburgite nodules were also collected from a basalt outcrop which may be part of another volcanic neck or a remnant of a valley fill.

AGL: *Department of Geology, School of Geosciences, The Queen's University of Belfast, Belfast BT7 1NN, U.K.*
AKH: *Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark*

The segment of the East Greenland Caledonides between latitudes 73°30′N and 74°00′N, which was our study area during the 1997 regional mapping programme, is dominated by westwards transport on major Caledonian thrusts and shear zones, and exhibits four phases of essentially coaxial Caledonian folding. There is little evidence within this region to support the crustal scale extension invoked in some recent papers (e.g. Hartz & Andresen 1995) to explain major features of the East Greenland Caledonides.

The region of study includes the greater part of Andrée Land, the northern margin of Louise Boyd Land, J. L. Mowinckel Land, Arnold Escher Land (which includes Eleonore Sø), Hobbs Land and the nunatak region extending west to the limit of exposure (Fig. 1).

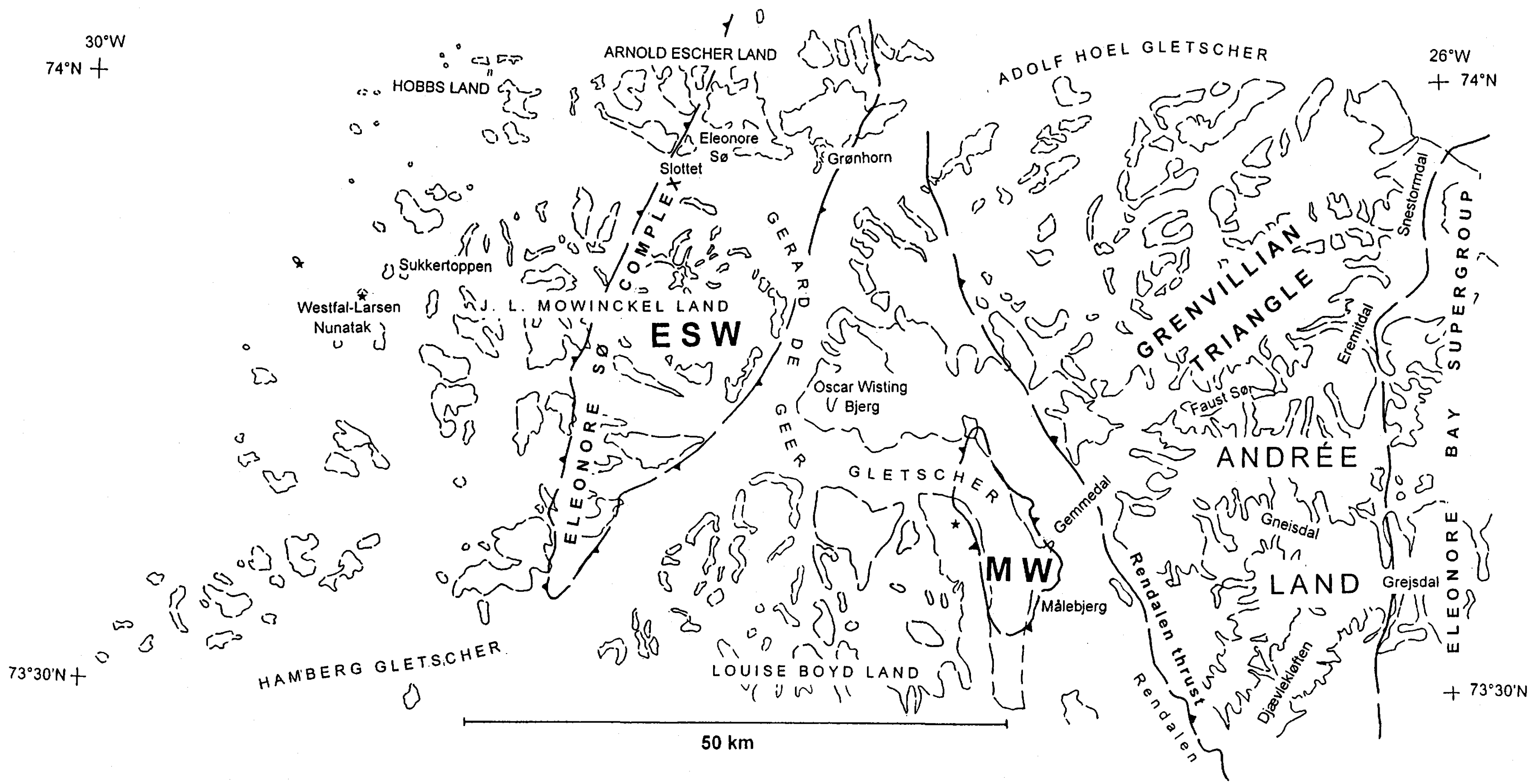

Figure 1. *The region of study, with place names mentioned in the text and the principal geological boundaries.* ESW: *Eleonore Sø window.* MW: *Målebjerg window. The locations of Tertiary volcanic necks are shown by stars.*

Geologically the region can be divided from east to west into: (1) the Eleonore Bay Supergroup which makes up the eastern part of Andrée Land (Fränkl 1953) and whose western contact against the sedimentary and igneous rocks of the so-called 'Grenvillian triangle' was the east limit of our study region; (2) the 'Grenvillian triangle', that part of Andrée Land between the Eleonore Bay Supergroup outcrops to the east and the 'Junctiondal fault' of Haller (1953) to the west (our Rendalen thrust), which is characterised by metasedimentary rocks (to some extent migmatitic) invaded by several generations of granitic sheets and bodies, some of which have yielded Grenville (*c.* 1000 Ma) Rb-Sr isotopic ages (Rex & Gledhill 1981); (3) widespread metasedimentary rocks (generally lacking granites), previously considered equivalents of the Eleonore Bay Supergroup (e.g. Haller 1956) or the supposedly older Krummedal supracrustal sequence (e.g. Higgins *et al.* 1981; Higgins 1988), and now thought likely to represent deposition in several Proterozoic sedimentary basins – they occur in west and north-west Andrée Land, western J. L. Mowinckel Land and the nunatak region farther west; (4) the sedimentary-volcanic complex of the Eleonore Sø region first described by Katz (1952a), which has been shown to be unconformably overlain by the Scolithus-bearing 'Slottet Quartzite' and possible Palaeozoic carbonates; (5) the Tertiary plateau basalts of Arnold Escher Land and Hobbs Land, notable for their isolation from other basalt areas and their alkaline mafic chemistry (Katz 1952a; Brooks *et al.* 1979).

Further provisional descriptions of all these topics are presented below. Note that there are very few areas of 'basement' gneisses in the area of study; the exceptions underlie the 'Slottet Quartzite' of the Målebjerg area, and include the granitoid rocks of uncertain age which make up part of eastern J. L. Mowinckel Land. Gabbroic rocks of unknown affinity occur in the westernmost nunataks north of Hamberg Gletcher and may represent part of the Caledonian foreland.

1. Structural chronology in the metasedimentary sequences

Metasedimentary rocks present in the region of study include: (1) siliciclastic rocks which pre-date the presumed 1000 Ma muscovite granites of the 'Grenvillian triangle', (2) the volcano-sedimentary rocks of the Eleonore Sø complex, (3) widespead psammitic, semipeltic and pelitic metasedimentary sequences (and minor carbonates) of presumed Proterozoic age which may or may not be correlatives of the Eleonore Bay Supergroup, and (4) possible Lower Palaeozoic rocks represented by the 'Slottet Quartzite' and overlying carbonates.

Four phases of deformation have been distinguished, of which the most important is the D_2 event responsible for the main regional schistosity which is recognised in all of the metasedimentary sequences regardless of age. Most dramatically perhaps, the S_2 cleavage can be traced without break across the unconformity at the base of the 'Slottet Quartzite'. All four phases are thus considered to be Caledonian in age. There is no indication on any older deformation events (e.g. Grenville) in the metasedimentary rocks of the region; low strain areas in the oldest sedimentary sequences preserve sedimentary structures (e.g. cross-bedding) and not older tectonic fabrics. By way of contrast, the few preserved segments of basement gneisses, although thoroughly retrogressed and overprinted by the D_2 event, do contain older fabrics and are immediately recognisable as 'basement rocks'.

D_1 – pure shear

D_1 is preserved as a bedding parallel schistosity for the most part, as slaty cleavage in semipelitic and pelitic rocks and as a spaced cleavage in psammites. Oblate strain ellipsoids are preserved in calc-silicate concretions and in grain shape fabrics. Many examples of F_1/F_2 interference have been seen as centimetre to metre scale folds in outcrop, but no large scale folds have been noted. Original orientation of F_1 fold axes is difficult to assess, but is thought to have been approximately N–S.

D_2 – simple shear

D_2 probably represents the progressive development and amplification of pure shear flexural D_1 folds. The F_2 shear folds have a predominant easterly vergence across the entire area, from the basal part of the Eleonore Bay Supergroup outcrop in the east to the westernmost nunataks. Strongly non-coaxial simple shear with a top-to-the-west or north-west sense of shear is pervasive, always overthrust. A penetrative axial planar cleavage is always seen. The long limbs of the east-verging folds are always highly attentuated, and as exemplified in the Målebjerg and Eleonore Sø cross-sections (see also below, and Figs 2 & 3), are shear zones with overturned stratigraphy. Abundant criteria for the sense of shear are preserved on these limbs, most often as quartz or dolomite sigma-style augen in the metasediments. In some of the metasedimentary sequences abundant granite has been generated, effectively straddling the D_2 event so that granite veins are always foliated to a greater or lesser extent, and may be tightly (even isoclinally) folded, or simply sheared or boudinaged in the S_2 fabric.

An intense stretching lineation is generally developed on S_2 on the attenuated fold limbs, usually quartz rodding (L_R) or a muscovite/quartz mineral lineation. The orientation of L_R is approximately constant across the area plunging at *c.* 20–30° to 120°N ± 10°, except where rotated on later folds. F_2 fold axes are often co-parallel with this rodding lineation on the attenuated limbs and are most probably sheath-like in form.

The short limbs of the regionally east-verging F_2 folds are always relatively low strain, frequently preserving west-verging tight to isoclinal folds and generally lacking strong shear indicators and strong development of L_R. This is best seen in pelitic rocks where quartz sweats have no strong preferred shape despite general orientation on S_2. F_2 fold axes are generally N–S to NW–SE trending, usually making a high angle with the stretching lineation.

The D_2 deformation is responsible for the west-directed thrust stacking in this part of the fold belt. The contact zone at the base of the Eleonore Bay Supergroup, and the thrusts recognised at Målebjerg and in the Eleonore Sø region, are relatively discrete zones of D_2 strain intensification (see also below).

Peak metamorphic assemblages appear to have developed synchronously with D_2, as well as the *in situ* melting of semipelitic lithologies in some areas to produce granite. The fact that both the 'Slottet Quartzite' (?basal Cambrian) and the overlying (?Palaeozoic) limestone carry this D_2 fabric make this a strictly Caledonian deformation. D_1 and D_2 can be viewed as continuous Caledonian deformation which produced a stack of westerly transported nappes.

D_3 – crenulation folds

D_3 is strongly developed throughout the region as mm to cm scale angular crenulations in outcrop, and also as larger dm to even km scale structures in valley walls and cliffs. F_3 folds generally lack significant development of axial plane crenulation cleavage. Axial planes generally dip gently westwards, fold axes are sub-horizontal and N–S trending. Vergence is apparently towards the east in the western part of the area. Preliminary interpretation suggests the box-fold like structures developed in the lower levels of the Eleonore Bay Supergroup in eastern Andrée Land may belong to this generation.

D_4 – open flexures

D_4 is characterised by broad open, upright, N–S trending flexures which produce local culminations and depressions in the regional structure. These are in part responsible for revealing the lower nappes in the Eleonore Sø and Målebjerg areas. D_4 is probably represented by the major N–S trending folds developed in the Eleonore Bay Supergroup outcrop in the fjord region and in the Petermann Bjerg area (e.g. Fränkl 1953; Wenk & Haller 1953; Bengaard & Larsen 1992).

D_4 and D_3 combine to produce anomalous orientations for the regional S_2 (typically dipping at 20–30° to the east or east-south-east). D_3 produces sub-vertical to steeply west-dipping panels, and D_4 broad zones of moderate west or south-west dips. Care is required in the intepretation of D_2 shear indicators in these zones, especially where S–C fabrics are developed.

2. Eleonore Bay Supergroup basal contact

In eastern Andrée Land the western boundary of the Eleonore Bay Supergroup is everywhere against the rocks of the 'Grenvillian triangle' (Fig. 1). This contact has been variously interpreted, as a transitional contact with metamorphosed Eleonore Bay Supergroup rocks of the central metamorphic complex (e.g. Haller 1971), as a décollement (Higgins *et al.* 1981), and as the Caledonian sole thrust in the extensional scenario of Hartz & Andresen (1995). The contact was examined in continuous exposures beside Nunatakgletscher, in a gully section in central Snestormdal, and a stream section in Eremitdal. The contact is clearly identifiable; Eleonore Bay Supergroup sediments above the contact are invaded by scattered Caledonian granite sheets, while below the contact foliated augen granites and metasediments dominate, with occasional amphibolitic rocks and concordant and cross-cutting granite veins.

The basal part of the Eleonore Bay Supergroup comprises a several hundred metres thick sequence of sandstones in beds up to one metre thick interbedded with thin shale layers, overlain by a further thick sequence of semipelites with thinner sandstone units. The lower sandstones are locally deformed by decametre scale folds, and sedimentary structures such as cross-bedding and ripple marks are well preserved. The higher semipelitic sequence preserves evidence for at least three of the Caledonian deformation phases. An early bedding parallel fabric is crenulated by strong simple shear, with the attenuated fold limbs rotated to the north-west. A strong rodding (quartz) or mineral (muscovite/quartz) lineation is always present and consistently oriented towards 125°N ± 10°, plunging at *c.* 20°. Quartz veins are boudinaged, and asymmetric augen preserve evidence for top-to-the-north-west shear on L_R. Granite sheets become abundant towards the base of the Eleonore Bay Group and are locally also boudinaged or podiform, preserving top-to-the-north-west shear. The main schistosity is crenulated on subhorizontal axial planes.

Contact with the older (?Grenvillian) sequence is marked beside Nunatakgletscher by a muscovite-rich schist unit, and in Snestormdal by a quartz and quartz-muscovite schist. Below this horizon are found semipelitic and psammitic rocks, and rusty weathering kyanite-bearing pelites. Schistose rocks from above and below the contact seem almost identical, with abundant muscovite and common euhedral garnet; muscovite in rocks below the contact may be slightly coarser grained and biotite possibly more abundant than in rocks above the contact. The older sequence is notable for an almost complete absence of sedimentary structures other than bedding, and the presence of garnet amphibolites or hornblende-biotite schists broadly concordant with S_0. Granites are abundant, most commonly as broadly concordant foliated sheets or veins boudinaged and podiform in S_2; these are medium to coarse-grained, even textured rocks. Coarser pegmatitic veins are often sharply cross-cutting but still may be folded and crudely foliated in F_2.

There is ubiquitous evidence of top-to-the-north-west shear in this older sequence, with boudins and asymmetric augen at all scales from single crystals to pods 50–100 m in length. Vein quartz, psammitic units and amphibolite bodies (as well as occasional calc-silicates) are similarly deformed. The shear fabric deforms a bedding parallel schistosity and is crenulated on gently west-dipping axial planes.

The shear fabric is pervasive almost everywhere. However, in a few areas of low strain isolated examples of west-verging isoclinal folds occur corresponding to the short limbs of the attenuated folds carrying the S_2 fabric. Relict cross-bedding is preserved in the hinge areas of such folds.

Augen granite sheets many tens or hundreds of metres thick carry the same shear fabric with top-to-the-north-west sense of shear. Amphibolites occur as sheath-like disrupted bodies within the augen granites. Even textured granite and pegmatite veins cross-cut the augen granites, but share the same shear fabric.

There is no sign of a major structural break or discontinuity at the base of the Eleonore Bay Supergroup in eastern Andrée Land – no true mylonite is present at or near the boundary. The older (meta)sedimentary sequence appears to have been invaded by muscovite granites (which in some cases have yielded Grenvillian *c.* 1000 Ma ages: Rex & Gledhill 1981) and then by mafic intrusions prior to deposition of the Eleonore Bay Group. There is (Caledonian) structural and metamorphic continuity across the present boundary, which may thus represent an original basal Eleonore Bay Supergroup unconformity transposed and inverted by top-to-the-north-west shear during the Caledonian orogeny.

In Andrée Land there are almost no indications of the 'crustal scale extension' invoked by Hartz & Andresen (1995); two minor examples of brittle/ductile extension were noted in Snestormdal cross-cutting the top to north-west shear fabric with a total displacement of 4 m down to the east.

3. Grenvillian triangle of Andrée Land

The 'Grenvillian triangle' is an informal field term for the area of rocks west of and structurally underlying the Eleonore Bay Supergroup in Andrée Land. The 'Grenvillian triangle' is bounded to the west by the NW–SE trending 'Junctiondal fault' of Haller (1953) (our Rendalen thrust) which separates the metasediments and granites of the 'triangle' from granite-free metasediments to the west in Rendalen and Målebjerg. The 'Grenvillian' part of the name, as noted above, derives from Rb-Sr isotopic dating on two foliated muscovite granite bodies, one in Eremitdal and the other in western Gneisdal (Rex & Gledhill 1981). More recently a *c.* 1000 Ma SHRIMP age has been obtained from a granite body north of latitude 74°N (Jepsen & Kalsbeek 1998), in a region that can be viewed as the northern extension of the 'Grenvillian triangle'.

The eastern boundary of the 'triangle' is the broad zone of high D_2 strain described above, which is some 2 to 3 km thick and overlaps the base of the Eleonore Bay Supergroup. The junction is sharp but with no angular discordance; no unconformable relationships are preserved, but may have been obscured by deformation and western inversion of the basin, nor is there any sign of a 'basal' facies of the Eleonore Bay Supergroup with the possible exception of a relative increase in abundance of calc-silicates. The shear zone has a consistent top-to-the-north-west sense of shear (*c.* 310°). The south-western boundary of the triangle, Haller's 'Junctiondal fault', is also a top-to-the-west or north-west shear zone (*c.* 290°), termed in the field the Rendalen thrust, which varies in character from a several tens of metres thick zone of tectonised schist to a sharply defined (*c.* 10 m) zone of cataclastic mylonite. This north-east dipping junction is characterised in the field by the sharp contrast between rocks with abundant granite veins and sheets above and metasediments lacking granites below; there is also a sharp discordance between the foliation in the rocks above and the shear/thrust plane, whereas the latter is co-planar with the schistosity in the rocks below.

The metasediments of the 'Grenvillian triangle' comprise dominantly psammites and semipelites; aluminous pelites are rare as occasional brown weathering units containing kyanite. Garnet, muscovite and biotite are common. Muscovitic pelites are often interlayered with micaceous psammites and occasional quartzites, with no thick sections of a single lithology. Calc-silicates are sporadically developed. In general the strong Caledonian deformation has removed evidence of sedimentary way-up, and trough cross-bedding has only been observed occasionally in relatively low strain areas on the short limbs of east-verging F_2 folds.

Granites are abundant in the 'triangle'. Porphyritic biotite augen granites appear as thick sheets or pod-like bodies broadly concordant with the regional 'banding', with sheeted or interfingering contacts. Some relict of contact metamorphism may be preserved, but these rocks and the granite bodies carry the pervasive D_2 Caledonian fabric. Sheared feldspar megacrysts in the granites often preserve good evidence for top-to-the-west or north-west sense of shear.

Pre-, syn- and late tectonic even-textured muscovite granites occur as sheets and pods at all scales from a few centimetres or less to thick sheets up to hundreds of metres thick. All carry the D_2 fabric and many examples of top-to-the-west or north-west shear are provided where the fabric wraps asymmetric (sigma-style) pods of granite. Muscovite granite bodies have yielded the two *c.* 1000 Ma isotopic ages reported by Rex & Gledhill (1981). However, most of the sheets seem to have been generated more or less synchronously with the Caledonian D_2 deformation – a number of sheets can be traced around D_2 folds, while others are simply podded in the shear fabric. They have presumably been generated by *in situ* melting of semipelitic units in the metasedimentary sequence as strain progresses in D_2.

A phase of later pegmatite veins is grossly discordant with respect to the metasediments and earlier granite sheets, but is also deformed in D_2 and carries a weakly defined S_2 fabric. This is notably well seen in Djævlekløften where the earlier sheets are often isoclinally folded. Sheets of both muscovite granite and pegmatite cross-cut the augen granite, and the S_2 fabric cuts across all contacts without interuption.

Amphibolites are uncommon, but always strongly deformed; they carry the S_2 fabric and are frequently boudinaged providing good criteria for top-to-the-north-west shear. Hornblende-biotite and garnet-hornblende types also occur, and are highly schistose on high strain F_2 fold limbs. The amphibolites cut augen granites, and are veined by syn-D_2 Caledonian granites. The most abundant amphibolites are almost certainly pre-tectonic and are broadly concordant with the regional fabric. A later phase of discordant amphibolite dykes and sheets, conspicuous in upper Gemmedal, was preferentially intruded along the axial planes of major F_2 folds, but as it carries the S_2 fabric is thus early to syn-D_2.

The 'Grenvillian triangle' is dominated by folds of D_2 and D_3 age. F_2 folds are tight to isoclinal and fold a bedding-parallel S_1 fabric. F_2 fold axes are often co-linear with the stretching lineation suggesting sheath-like forms. A pervasive axial planar S_2 fabric is developed throughout the area in all lithologies. Occasional small scale examples of D_1-D_2 interference are seen, but the over-riding impression is one of structural simplicity since the granite sheets are broadly S_2 and exploit and enhance S_2 giving a planar aspect to most outcrops in cliff sections. However, close inspection always reveals S_1 as well as S_2 fabrics.

The regional east to south-east dip is interruped by F_3 angular crenulations, generally lacking an axial planar fabric. Large scale interference of D_2 and D_3 is seen particularly around Faust Sø. Most examples of F_3 crenulations verge east or south-east on gentle west to north-west dipping axial planes. The latest phase of major structures (F_4) produced major upright open folds, giving north-west or west dipping sheet dips locally.

There is no evidence of any significant tectonic or metamorphic history pre-dating the early granites. The *c.* 1000 Ma granites may therefore date a period of pre-Eleonore Bay Supergroup extension or rifting, not accompanied by orogenic deformation. All deformation is therefore taken to be Caledonian, with peak metamorphic assemblages (kyanite grade) developed synchronously with D_2. The rocks of the 'Grenvillian triangle' lack evidence for any significant late-Caledonian extension.

4. Målebjerg rift shoulder unconformity

The spectacular exposures of quartzites and marbles, together with varieties of mica schist, found on the cliffs at Målebjerg and in Gemmedal and adjacent valleys (Fig. 2) are central to the understanding of the structural development of this part of the Caledonian fold belt. Haller (1953) assigned the sequence to his 'Marble Series' and 'Maalebjerg Series', which he initially correlated with the Lower Eleonore Bay Group (promoted by Sønderholm & Tirsgaard 1993 to a Supergroup). He later (Haller 1971) placed the sequence in the lowest part of the group, the 'Basal Series', and it is clear that he suspected the presence of underlying gneissic basement (Haller 1971, p. 86). Haller (1971, p. 87) also noted the similarity between the 'Slottet Quartzite' of the Eleonore Sø region and the lower quartzite unit in the Målebjerg sequence. The presence of an unconformity below the quartzite unit was first demonstrated by Tage Thyrsted (in Higgins *et al.* 1981). Our new observations and are summarised in the simplified map and cross-section (Fig. 2).

The gneisses below the unconformity, exposed along the east side of Gerard de Geer Gletscher, are often strongly sheared and typically thoroughly retrogressed, so that even where gneissic banding survives the micaceous component of the rock largely comprises chlorite and white mica.

A sequence of up to 200 m of white, often cross-bedded quartzites rests unconformably on the gneisses. Pebble conglomerates or gritty quartzite are found at the base of the quartzite, and on the north side of the lake in Gemmedal a spectacular boulder conglomerate (?tillite), with boulders up to 60 cm in size in a grey-green tremolitic matrix, marks the base below clean washed quartzites. The upper half of the quartzite unit comprises rusty, planar bedded quartzite and quartz schist in which variably sheared examples of Scolithus are preserved. The quartzite is overlain by a blue-grey 'flinty' limestone. The sequence of Scolithus-bearing quartzite overlain by limestone is strikingly similar to that in the Eleonore Sø region (see below), where the Scolithus-bearing 'Slottet Quartzite' is also overlain by limestones. Both sequences are taken to represent an Upper Proterozoic–Lower Palaeozoic transition. At Målebjerg and Gemmedal the sequence traces out a major antiform/synform D_2 fold pair.

D_2 Caledonian structures dominate the distribution of lithologies in the region, and as always F_2 folds with overturned limbs sheared to the west or north-west are the most important element. Locally F_2 axial planes (and S_2) have been steepened by asymmetrical F_3 crenulation folds with gentle west-dipping axial planes. The repetition of the lithologies on the west side of Gerard de Geer Gletscher is, as clearly illustrated by Haller (1953, fig 49, plate 3), due to a broad open N–S trending anticlinal structure (F_4 in our chronology). Large scale complex interference results from the F_2 and F_3 coaxial folding; F_1 fold closures folded by F_2 have also been recorded.

The top of the grey (?Palaeozoic) limestone (above the quartzite unit) is coincident with an isoclinal F_2 syncline, which brings platy mylonitic quartzite with an intense down-dip rodding over the much less deformed sequence on the lower limb. On the upper limb of

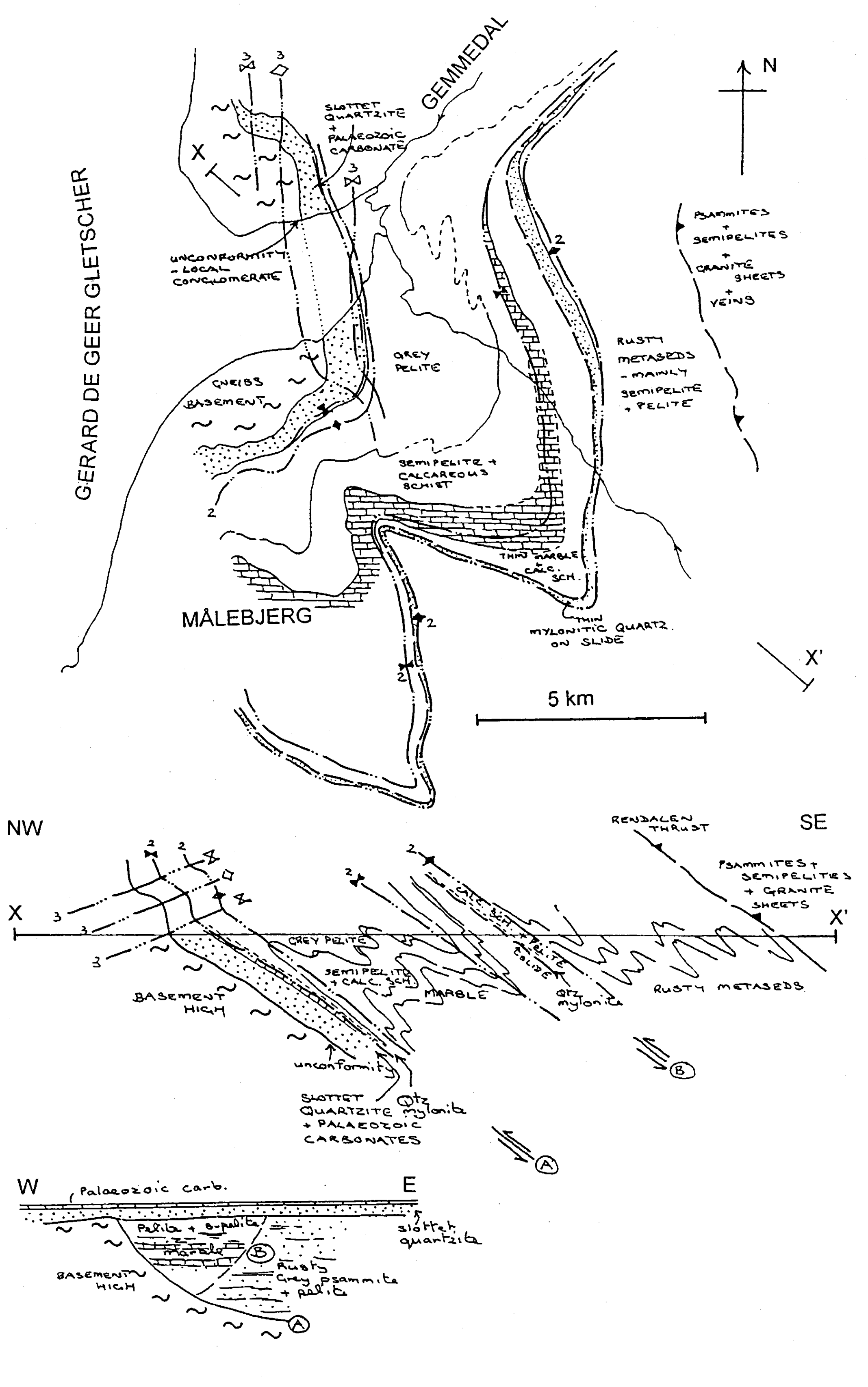

Figure 2. *Simplified geological map and cross-section of the Målebjerg area. The bottom sketch shows the east-facing half-graben model of development.*

this syncline the quartz mylonite passes structurally upwards into grey chlorite to biotite grade pelites and semipelites with an intense shear fabric (top to 310°) demonstrated by ubiquitous quartz augen. These pelites become much less deformed on the upper limb of the higher F_2 anticline, and then reappear in the core of the next higher syncline wrapped by calcareous schists and calc-silicate schists with conspicuous buff to cream or orange marble bands.

The Caledonian deformation appears to be inverting a Late Proterozoic rift sequence of pelites and carbonates, itself overlain by quartzite, westwards over the original rift shoulder; the rift shoulder unconformity is preserved in this instance at the base of the sequence of Scolithus-bearing quartzites at Målebjerg. The model envisages an eastward-facing fault system opening into a half-graben structure. Comparisons can be drawn with the half-graben model developed in Kronprins Christian Land in eastern North Greenland (Higgins & Soper 1994, 1995) for the Late Proterozoic 'Rivieradal Sandstones', which have similarly been thrust westwards over the rift shoulder of their depositional basin.

The structural pattern is repeated to the east in a higher syncline/anticline fold pair, again marked by the presence of a thin band of highly sheared to mylonitic quartzite on the high strain overturned limb. Structurally higher a different sedimentary succession is introduced on the uppermost right-way-up limb, a sequence of rusty weathering pelites and semipelites and grey arkosic psammites which can be traced southwards along Rendalen, and which is interpreted as a thrust sequence of older sediments from the rift basin transported up and over the younger carbonates and pelites.

Still farther east, the Rendalen thrust, in effect another strongly attenuated D_2 fold pair, transports still older(?) psammitic and pelitic metasediments with their associated 1000 Ma granites (the 'Grenvillian triangle') westwards across the entire section

5. Eleonore Sø volcanic-sedimentary rift sequence

The volcano-sedimentary complex of the Eleonore Sø region was first described by Katz (1952a), who proposed a correlation with the upper part of the Eleonore Bay Supergroup and Tillite Group. Haller (1956) initially followed this interpretation, and proposed that the sequence occupied a late Caledonian graben structure. Subsequently the sequence was assigned to the 'Basal Series' of the Eleonore Bay Supergroup (Haller 1971), following the suggestion of Wenk (1961), and Haller speculated that the complex might occur in a window through a Caledonian thrust and represent part of the overridden Caledonian foreland. The extension of the outcrops of the Eleonore Sø complex southwards through J. L. Mowinckel Land to the north side of Hamberg Gletscher, depicted on the maps in Haller (1956) and the subsequent 1:250 000 printed map sheets (Koch & Haller 1971), were based on inspection of photographs and observations from the air, and proved to be essentially correct. A prospecting party from Nordisk Mineselskab A/S and a geological party comprising G. C. Bond and P. A. Nickesen are known to have visited the Eleonore Sø region in respectively 1975 and 1984, but there appear to be no published reports of their work.

Our observations (Fig. 3) show the sedimentary successions of the Eleonore Sø region to outcrop beneath a broad arched roof thrust transporting granite-veined and sheeted metasediments to the north-west (*c.* 310°). The broad arch is probably in part an open F_4

fold, perhaps with elements of F_3 assymetric folding, but these fold phases are superimposed on a D_2 antiformal stack developed in the Eleonore Sø sequence and 'Slotted Quartzite', where the attenuated, overturned F_2 fold limbs accomodate the westward stacking. Extensive mylonitic developments are associated with both the east-dipping and west-dipping elements of the roof thrust.

The Eleonore Sø volcano-sedimentary sequence is best seen in the east dipping, essentially right-way-up short limb panels of the F_2 folds. The oldest parts of the sequence comprise dark grey, compact arkosic psammites and semipelites. Brown calcareous concretions occur as oblate spheroids flattened in S_1. A thin 10–15 m red-green slaty semipelite to pelite horizon overlies the psammites, and is in turn overlain by a possibly several thousand metre thick carbonate sequence. The presence of stromatolites at several levels in the carbonates would be compatible with a Late Proterozoic age (as deduced by Katz 1952a), in which case a comparison might be made with Late Proterozoic developments in Kronprins Christian Land, eastern North Greenland. ('Rivieradal Sandstone'-Campanuladal Formation-Kap Bernhard and Fyns Sø Formations; Sønderholm & Jepsen 1991). However, stromatolites are also common in earlier Proterozoic carbonate sediments.

Evidence of tectonic instability in the sedimentary environment is evident at several levels in the carbonate sequence, most spectacularly in the form of syn-sedimentary olistostromes in the northern part of the Eleonore Sø area. Here individual blocks of limestone several tens of metres across and intact slabs of banded carbonates several hundred metres in extent are enclosed in a carbonate matrix. Similar but less spectacular carbonate breccias occur at several levels. One example of an apparent karstic surface was also recorded. The well preserved stromatolites at several levels suggest the carbonates were essentially shallow water accumulations.

The carbonates are succeeded by quartzose psammites and black shales, suggesting inundation of the foundering shelf by siliclastic detritus. This interval is apparently unconformably overlain by mafic volcanics, which are best seen in succession along the axial trace of the D_2 syncline (A–A' on Fig. 3) . Elsewhere the base of the volcanics is always highly attenuated in overturned F_2 fold limbs and the passage upwards from the sediments is obscured; on the east side of Eleonore Sø the western margin of the volcanics cuts across several members of the carbonate succession from south-east to north-west along the highly attenuated west-facing F_2 anticline/syncline fold pair that constitutes the boundary (B–B' on Fig. 3).

Pillow lavas are abundant throughout the volcanic sequence, and a rift setting is strongly suggested when the F_2 structure is unfolded and the relationships with the unconformably overlying 'Slottet Quartzite' are considered. This model is reinforced by the presence (along boundary C–C') of intensely sheared, but laminated, siliceous rocks which may constitute a sheared fault breccia. The limestones west of this contact contain a series of lenticular zones of iron-rich mineralisation and breccia perhaps indicative of hot-spring activity which could be linked with the putative fault zone.

The post-rift 'Slottet Quartzite' rests unconformably on each member of the Eleonore Sø rift sequence, notably with angular unconformity on the older sandstones and carbonates (see also below). A schematic restoration of the scenario is given in the cross-section (Fig. 3), where major syn-rift faults (1, 2, 3) are interpreted as the locus of high D_2 strain as the basin inverts (thrusts 1, 2, 3), while the higher nappe translates westwards above. It is

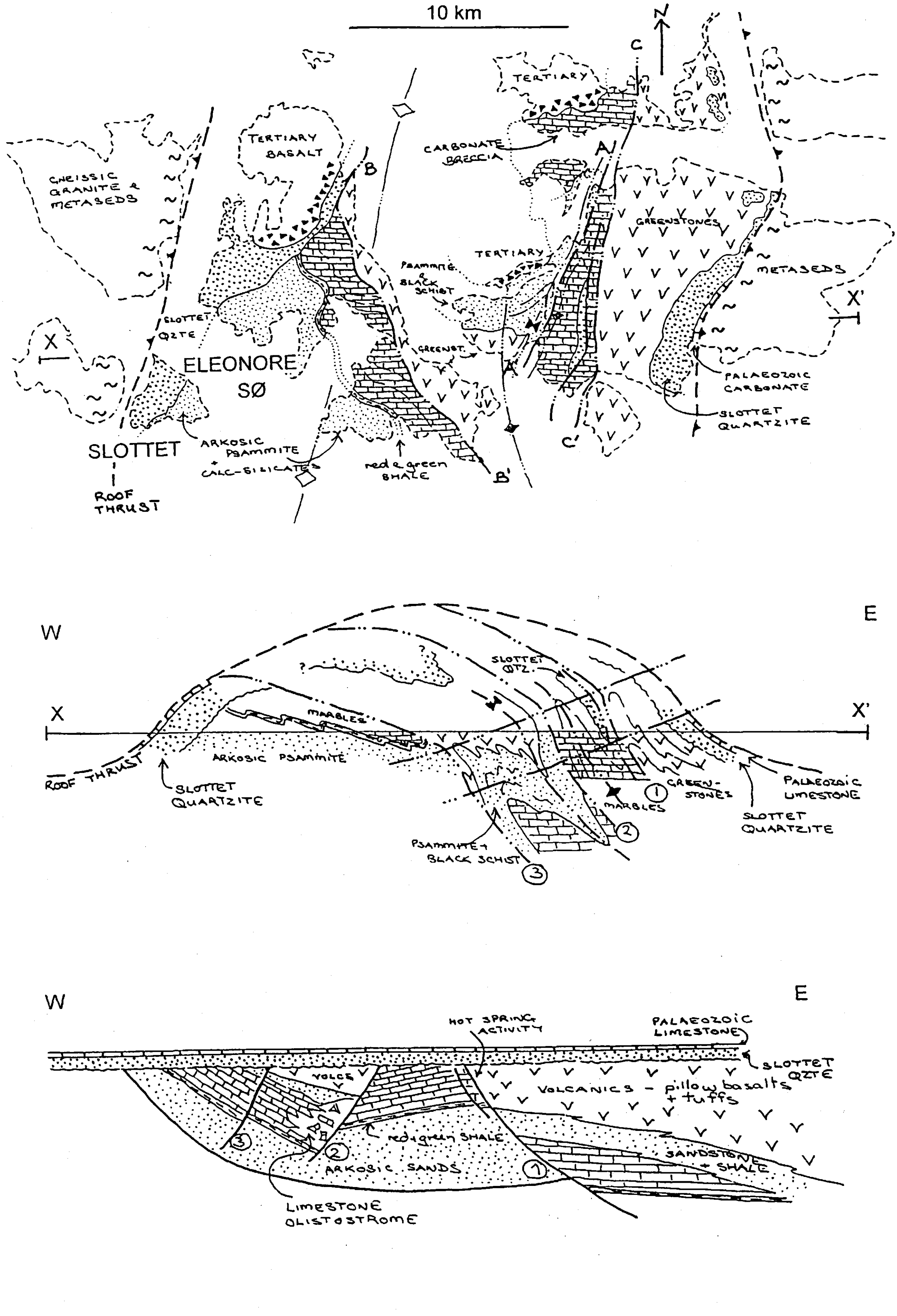

Figure 3. *Geological sketch map and cross-section of the Eleonore Sø area, together with an interpretation of the unstable rift setting.*

clear that the ?Palaeozoic carbonates above the 'Slottet Quartzite' form important glide surfaces in this construction, and again similarities can be drawn with the Målebjerg section, as well as other areas in the East Greenland Caledonides where Palaeozoic carbonates make up the glide surfaces for major nappe sheets (e.g. Kronprins Christian Land: Rasmussen & Smith 1995; ?Palaeozoic carbonates of the 'Zebra Series' in Dronning Louise Land: Strachan *et al.* 1994; mylonitic 'Cambrian-Ordovician' marbles in the Gåseland window of the Scoresby Sund region, which overlie tillites correlated with the Eocambrian Tillite Group: Phillips *et al.* 1973, Moncrieff 1989). A basement rift shoulder was not observed in the Eleonore Sø region, but may be present below and west of present exposure.

The basement to the Eleonore Sø complex may be represented by the gneissic and granitic rocks of eastern J. L. Mowinckel Land, which in this case would occupy the central core of the window; the window would then be an oval region up to 17 km across and at least 60 km from north to south (Fig. 1).

Since all rock units beneath the roof thrust in the Eleonore Sø area are affected by the full sequence of Caledonian deformation, the area does not constitute a true 'foreland window', but is a window exposing a lower Caledonian thrust sheet or parautochthonous foreland.

6. 'Slottet Quartzite' unconformity

The unconformity at the base of the 'Slottet Quartzite' has been studied at three main locations in the Eleonore Sø region, and can be deduced at a number of others with varying degrees of certainty. The 'Slottet Quartzite' rests with marked angular unconformity on all members of the Eleonore Sø sequence. The unconformity is folded, and the main Caledonian D_2 fabric cross-cuts the depositional surface without break. Both Katz (1952a) and Haller (1956, 1971) interpreted the contact as a thrust plane, and correlated the quartzite with units of the Lower Eleonore Bay Supergroup.

At Slottet the quartzite rests on the lowermost sandstone and shale member of the Eleonore Sø sequence. The surface is sharp, irregular in detail but planar in aspect, and is marked by a thin layer (10–20 cm) of basal conglomerate overlain by a metre or so of gritty quartzite. The S_2 cleavage cuts straight across the unconformity, and the quartzite is deformed into upright decametre scale flexural folds.

On a cliff north of Grønhorn the quartzite rests on intensely (S_2) cleaved metavolcanic rocks. Bedding in the quartzite and layering in the metabasalts are approximately parallel. The unconformity here is marked by a 10 cm layer of heavy mineral 'dark sand'; several similar heavy mineral layers occur within the first 10 m or so of the quartzite sequence. The basal layers of the quartzite sequence are commonly gritty or pebbly.

About 10 km to the north of the last locality, the quartzite again rests unconformably on the metavolcanics, but here with a spectacular metre thick basal conglomerate with a heavy mineral sand matrix.

The 'Slottet Quartzite' is a very pure and conspicuously white quartzite, and comprises 20–40 cm thick beds of quartz arenite frequently with well developed trough cross-bedding. A yellowish or rusty weathering colour is sometimes developed. The uppermost part of the sequence contains abundant Scolithus tubes; these were observed *in situ* at several localities, and are common in erratic blocks throughout the Eleonore Sø area. Most tubes are 3–5 mm in diameter, with occasional larger examples, and up to 80 cm in length. The pitted nature produced by the tubes on bedding plane surfaces was frequently observed. Occasional examples were noted to be sheared in S_2. It is curious that neither Katz nor Haller connected the 'Slottet Quartzite' with the widespread erratic occurrence of Scolithus boulders in East Greenland, although Haller (1971, fig. 48) drew attention to possible source areas. It is now clear that outcrops of the 'Slottet Quartzite' and its correlatives (e.g. Kap Holbæk Formation in eastern North Greenland: Sønderholm & Jepsen 1991, Clemmensen & Jepsen 1992; 'Zebra Series' in Dronning Louise Land: Strachan *et al.* 1994), in western areas of the Caledonian fold belt or on the foreland farther west beneath the Inland Ice, are the ultimate source of the widespread erratic Scolithus-bearing quartzite boulders in the present coastal region of East Greenland.

Pale blue-grey and yellow-orange weathering limestones occur in structural continuity above the easternmost outcrops of the 'Slottet Quartzite' in the Eleonore Sø area. Similar limestones were observed on the north side of Hamberg Gletscher in stratigraphical contact with the top of the 'Slottet Quartzite'. It is likely that the limestones are Lower Palaeozoic, although no macrofossils were observed. Wegmann (1935, p. 14) reported limestone erratics containing poorly preserved gastropods on Cecilia Nunatak (72°30′N; ?Ordovician, Haller 1971, p. 131), and limestone erratics from the same locality have yielded Middle Ordovician conodonts (J. S. Peel in Higgins *et al.* 1981). Haller (1956, 1971) remarking on the presence of these limestone erratics considered a derivation from the Caledonian foreland beneath the Inland Ice likely.

7. Tertiary basalts

Alkaline mafic lavas were discovered in the nunatak region of Hobbs Land and Eleonore Sø by Katz (1952a) in the course of an extended sledge journey. They unconformably overlie the rocks of the Caledonian fold belt and a Tertiary age was presumed. Haller (1956) extended their known area of distribution on the basis of aerial observations and aerial photography, and incorporated this data in the 1:250 000 geological map of East Greenland (Koch & Haller 1971). Additional observations and new collections were made in 1975 and 1976 by J. D. Friderichsen, A. K. Higgins and A. Steenfelt, and formed the basis for the detailed petrographical and geochemical studies of Brooks *et al.* (1979), which also confirmed the Tertiary age of this basalt province.

The known outcrops of the basalts were further extended in 1997, when basaltic lavas were found capping the summits of central J. L. Mowinckel Land immediately south of the hitherto known outcrops. Outcrops were conspicuous for their dark colour and often spectacular columnar jointing. The lavas were evidently erupted onto a slightly tilted peneplained surface, now at about 2000 m altitude. However, observations in the field indicated several examples of former valleys in this peneplain infilled by lava flows (Fig. 4). Photogrammetric studies confirm these observations, and suggest the peneplain was irregular with a preserved relief of up to 150 m. The preserved thickness of the lavas exceeds 75 m at a few localities. Photogrammetric studies also support the presence of basic dykes (first reported by Katz 1952a) in a few localities, although these were not examined in the field.

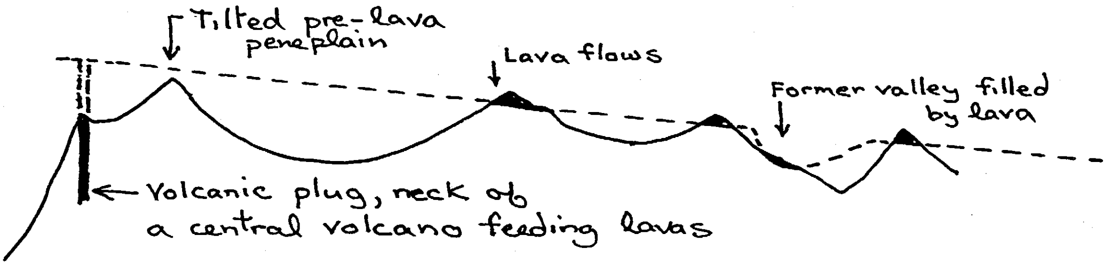

Figure 4. *Sketch showing modes of preservation of the Tertiary volcanic rocks in the nunatak region.*

Several new examples of Tertiary volcanic necks or plugs were discovered and sampled (for location see Fig. 1), and new collections made from a neck on Strindberg Land previously reported by Katz (1952b, fig. 4). One of the westernmost nunataks visited, 10 km west of Sukkertoppen and about 20 km west of the nearest lava outcrop, was cut by a 50–100 m wide neck. The lavas were columnar jointed, and noted for the presence of small harzburgite nodules as well as numerous fist-sized peridotite nodules, presumed to be mantle-derived. A second new volcanic neck cutting the northern part of Westfal-Larsen Nunatak contained abundant angular metasedimentary fragments; the latter do not match the adjacent country rocks, and may derive from a ?foreland sedimentary sequence at no great depth. A third new volcanic neck close to a high summit in eastern Louise Boyd Land, and the southernmost known example from this province (73°39'N), had previously been mapped as an amphibolite (Koch & Haller 1971). Small harzburgite nodules were also collected from a basalt outcrop 20 km north of Louise Boyd Land; it is uncertain at present whether this outcrop is a volcanic neck or a remnant of a valley fill.

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Caledonian thrusting and extension in Frænkel Land, East Greenland (73°–73°30′N): preliminary results

J. C. Escher & K. A. Jones

JCE: *Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark*
KAJ: *Oxford Brookes University, Gipsy Lane Campus, Headington, Oxford OX3 0BP, U.K.*

The region of study between 73° and 73°30′N (Fig. 1) forms part of the N–S trending Caledonides of East Greenland. Some of the earliest studies were undertaken by geologists associated with J. M. Wordie's climbing expeditions of 1926 and 1929 (Wordie 1930; Wordie & Whittard 1930), and by N. E. Odell during a voyage with Louise A. Boyd's arctic expedition of 1933 (Odell 1939, 1944). More comprehensive regional studies were undertaken during Lauge Koch's geological expeditions (e.g. Huber 1950, Wenk & Haller 1953, Haller 1953, 1955). Reconnaissance studies in more recent times were made by parties from the Geological Survey of Greenland (e.g. Higgins *et al.* 1981). The present studies form part of the 1997–1998 regional mapping programme of the Geological Survey of Denmark and Greenland (see Henriksen 1998). Mention may also be made of ongoing local studies by a University of Oslo group and associates (see e.g. Andresen *et al.* in press; Hartz & Andresen 1995)

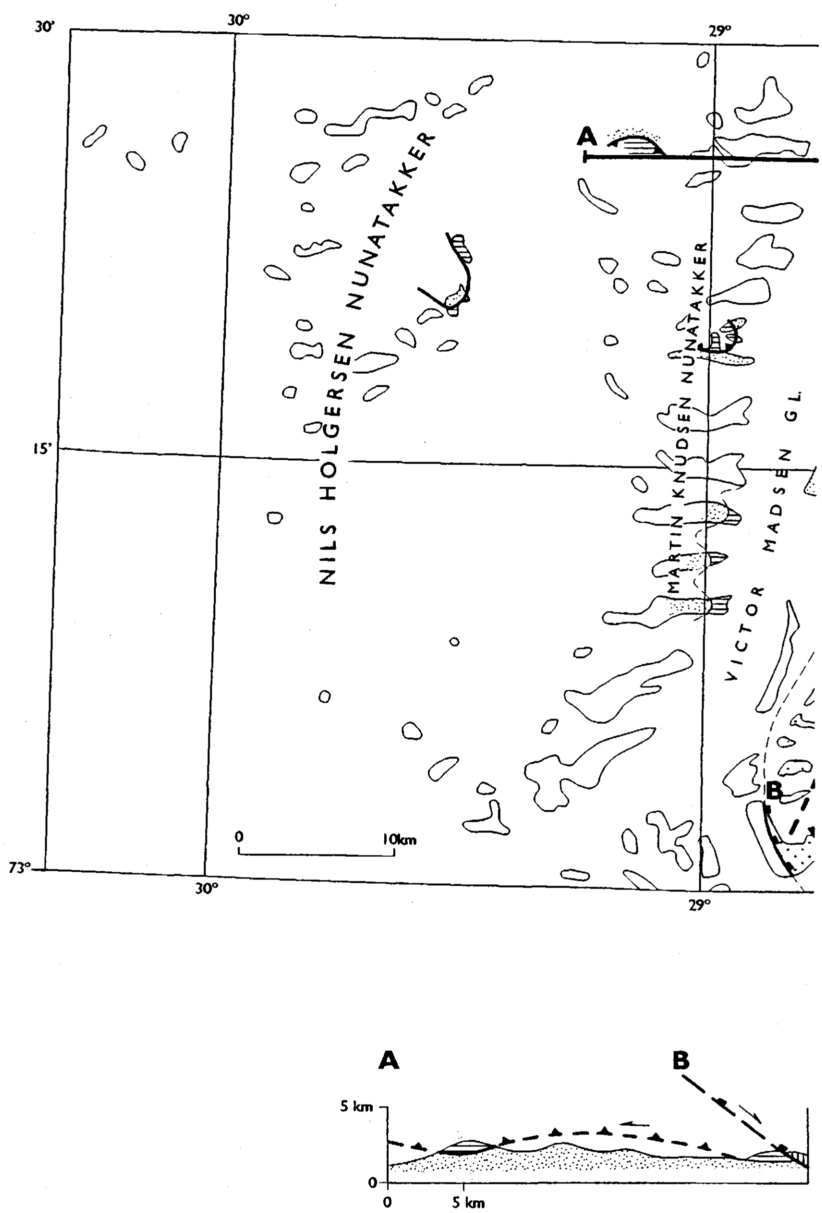
Our observations in 1997 were made from eight field camps, mainly in Knækdalen in western Frænkel Land, and in the E–W trending valley of southern Louise Boyd Land, for convenience informally named by us as "Jættedalen" after nearby Jættegletscher; one camp was erected in southern Rendalen and one at the mouth of Kjerulf Fjord.

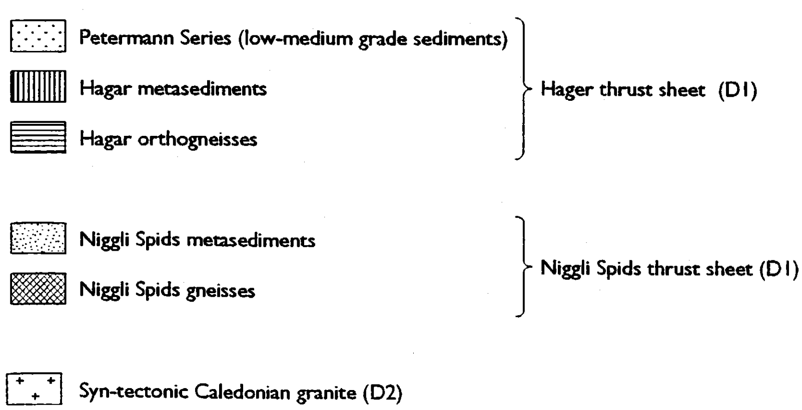
The region of study can be interpreted in terms of a relatively simple 'layered cake' structure comprising two superimposed thrust sheets (see tectonostratigraphy section below), which also preserve evidence of extensional collapse during later Caledonian deformation. A map of the region and a cross-section are presented in Figure 1.

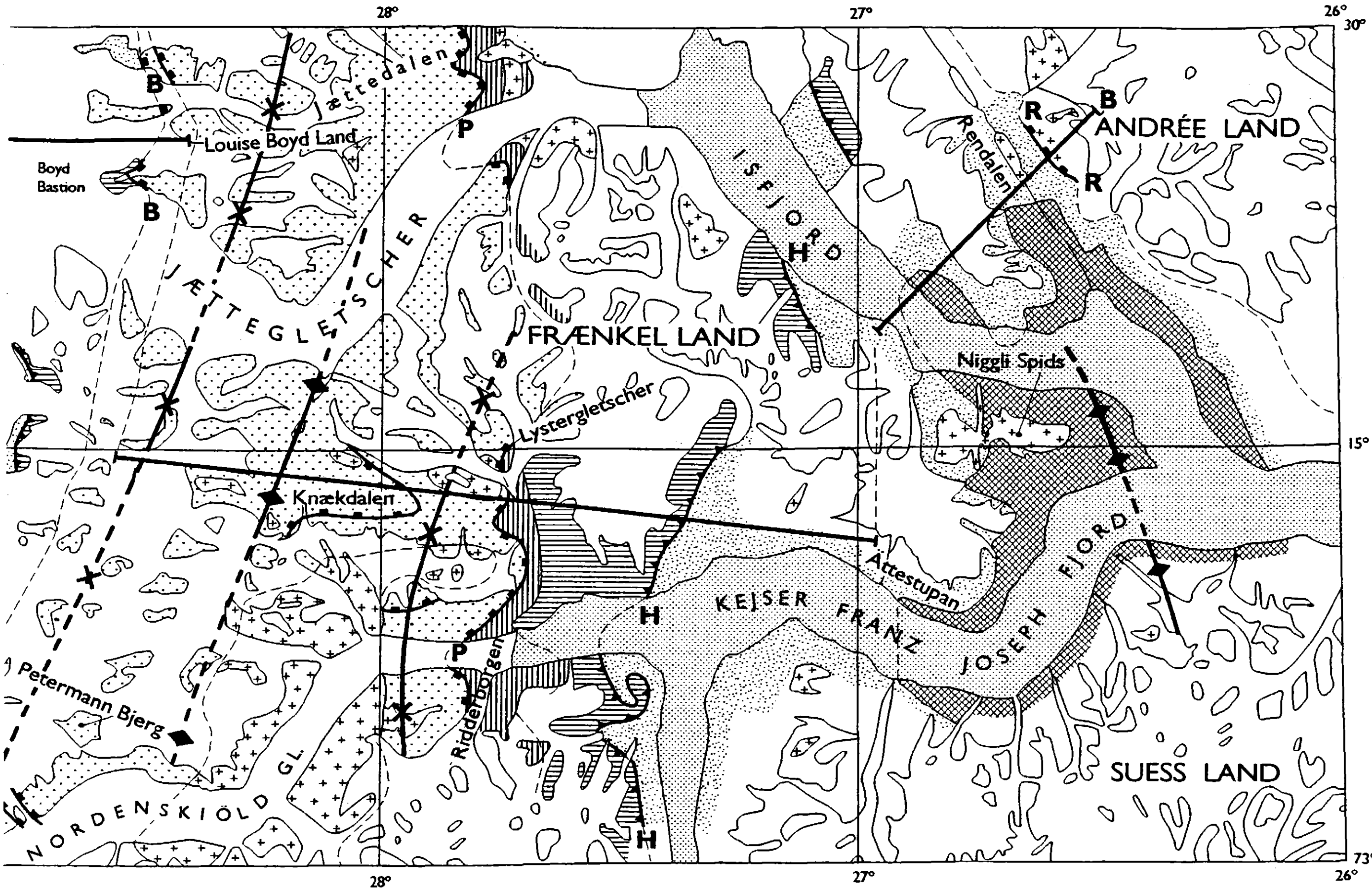
The Caledonian deformation has been divided into four successive events (see also Caledonian deformation section below). These may be summarised as:

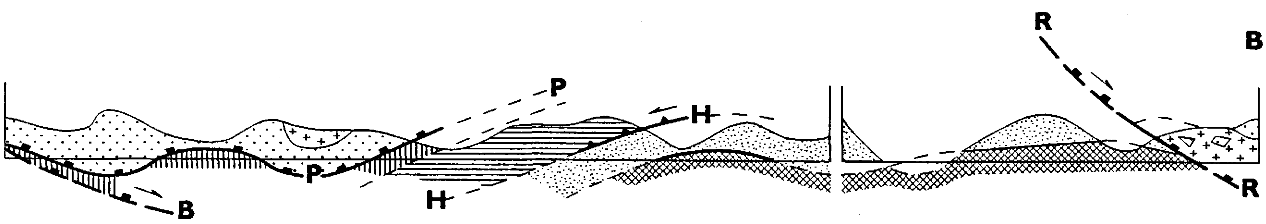
- **D1.** Orogen-normal (E–W) crustal shortening during crustal subduction of Laurentia below Baltica. Westwards-directed thrusting and formation of a thrust-wedge.
- **D2.** Transpression of the thrust-wedge with ductile orogen-parallel (NNW–SSE) extension. Formation of NNW–SSE trending lineations and tight to isoclinal folds.
- **D3.** Continued, but weaker orogen-normal crustal shortening with the formation of large-scale, upright, open-style, N–S trending folds.
- **D4.** Orogen-normal extension (E–W) during re-opening of Iapetus. Formation of a few, major, brittle, normal listric faults with down-to-the-east displacement.

Figure 1. *Preliminary geological map of the region and E–W cross-section. Modified after Haller (1955) and Koch & Haller (1971).*









H Hagar thrust (D1)

P Petermann detachment (D2)

unnamed detachments (D2)

major open-style folds (D3)

B Boyd Bastion fault (D4)

R Rendalen fault (D4)

1. Tectonostratigraphy

Two major thrust units are distinguished, the lower Niggli Spids thrust sheet, and the upper Hagar thrust sheet (Fig. 2); they are separated by the Hagar thrust.

Niggli Spids thrust sheet (NSTS)

The Niggli Spids thrust sheet (NSTS) has been named after Niggli Spids in eastern Frænkel Land. The NSTS consists of two different rock sequences: a thick sequence of augen orthogneisses, called the Niggli Spids gneisses, which are unconformable overlain by a sequence of metasediments, called the Niggli Spids metasediments. The NSTS is bounded by the Niggli Spids thrust below and the Hagar thrust above (Fig. 2).

Niggli Spids thrust (NST)

The Niggli Spids gneisses are structurally the lowest rock unit occurring in Frænkel Land. However, further to the south along the north side of Kempe Fjord, a boundary has been mapped by John Haller (Haller 1955; Koch & Haller 1971) between a unit of unnamed metasediments (below) and Niggli Spids gneisses (above), suggesting the existence of a tectonic unconformity between these two rock units which we provisionally name the Niggli Spids thrust (NST). During the1998 field work it is planned to visit this possible key locality.

Niggli Spids gneisses

As mentioned above, the Niggli Spids gneisses are structurally the lowermost rock unit in Frænkel Land. They have granitic to granodioritic compositions and show a well developed feldspar megacryst texture. They contain locally xenoliths of foliated amphibolite. Both gneiss and amphibolite are cross-cut by a well developed, net-vein system of granites and pegmatites which, as far as we were able to observe, do not occur in the unconformably overlying Niggli Spids metasediments.

Samples of the cross-cutting veins have been collected for zircon age dating.

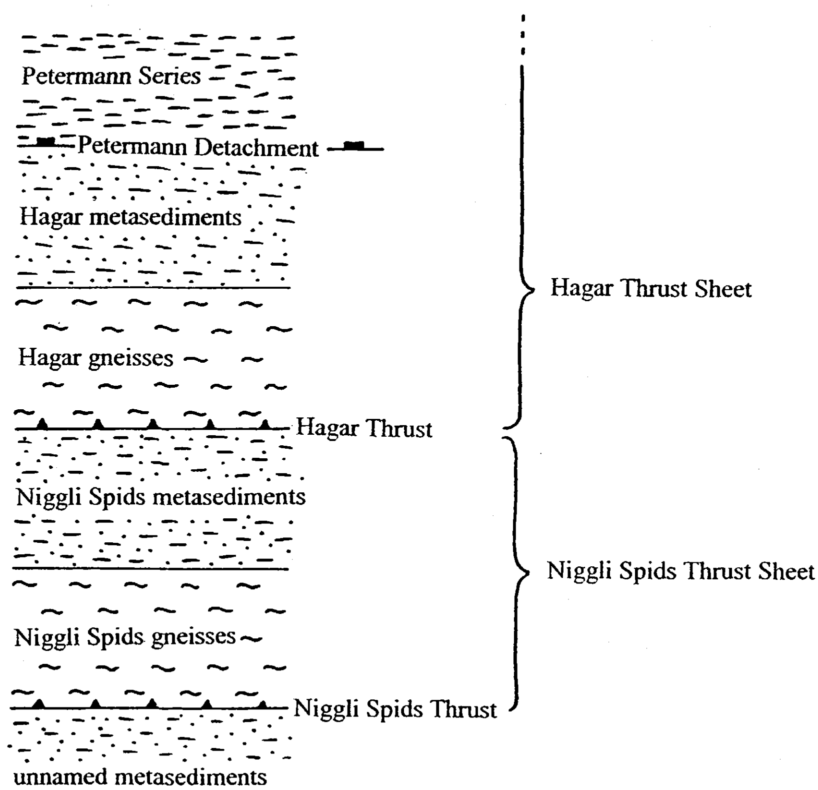
Niggli Spids metasediments

The Niggli Spids metasediments unconformably overlie the Niggli Spids gneisses. A lower and an upper sequence have been distinguished:

(a) Lower sequence

In the areas of Ättestupan and Rendalen a thick composite layer of metasediments and (?)metavolcanic rocks occur on top of Niggli Spids gneisses. Individual layers vary from a few metres up to 100 m in thickness and consist of: (I) strongly deformed marbles, (II) 'pale weathering' quartzites, (III) calcareous and pelitic metasediments with garnet, staurolite and kyanite, and (IV) a thick unit of pale grey epidote-chlorite-actinolite-biotite schist. The schists (IV) contain numerous thin amphibolite/biotite streaks and pods, and are thought to be of volcanic origin.

Figure 2. *Tectonic and lithostratigraphic divisions in the Frænkel Land region.*



(b) Upper sequence
A thick, monotonous sequence of brown weathering rocks, consisting of interbedded pelitic and psammitic layers, makes up the remainder of the Niggli Spids metasediments. The sequence includes a few, up to 60 m thick, quartzite units.

Hagar thrust sheet (HTS)

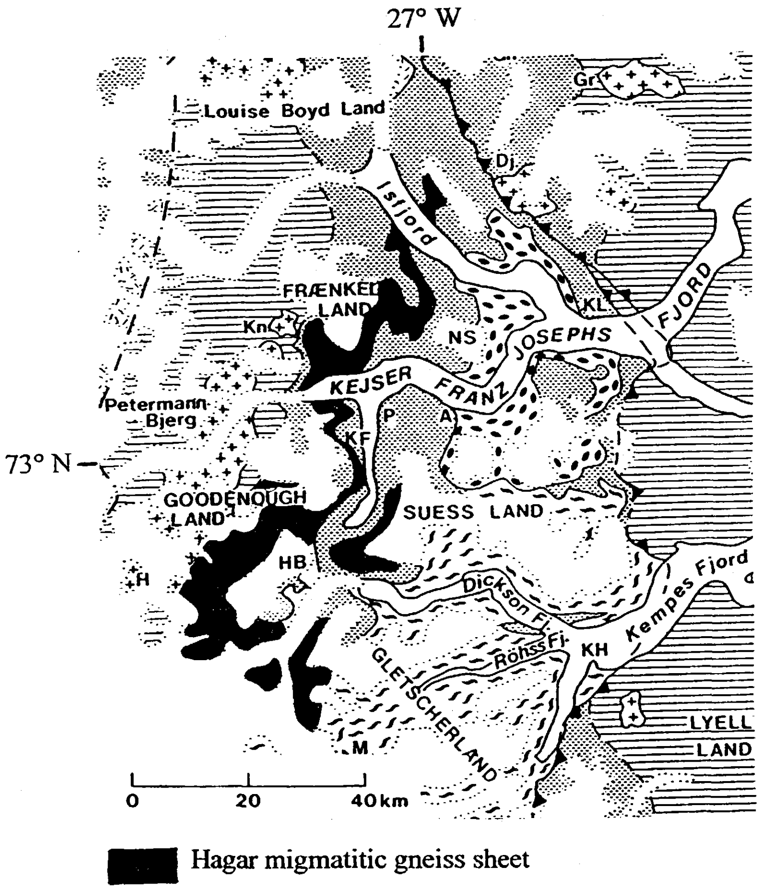
The Hagar thrust sheet (HTS) has been named after the 'Hagar sheet of migmatitic gneisses' of Wenk & Haller (1953), which they considered as representing a nappe-like structure of migmatites. Our field observations indicate, however, that during orogen-normal crustal shortening (D1), the HTS was displaced over the NSTS along the Hagar thrust. The HTS consists of :

(a) a lower sequence of migmatitic orthogneisses, called the Hagar gneisses;

(b) a middle sequence of metasediments, called the Hagar metasediments, and;

(c) an upper sequence of medium to low-grade metasediments, called the Petermann Series by Wordie (1930; the Petermann Bjerg Group of Sønderholm & Tirsgaard 1993). Note that we use 'Petermann Series' in this report in preference to the new formal stratigraphy, for reasons stated below. We also use the subdivisions of the Petermann Series in the abbreviated forms employed by Wenk & Haller (1953), although these are also confusingly called 'Series'.

Figure 3. *Distribution of the migmatitic orthogneisses of the Hagar sheet, modified after Haller (1971) and Higgins et al. (1981).*



Hagar thrust (HT)

Our Hagar thrust (HT) is indicated on Haller's maps as a boundary between gneisses and metasediments. The 1997 field observations indicates that it forms a tectonic unconformity with up to 50 m thick mylonites between Niggli Spids metasediments (below) and migmatitic Hagar gneisses (above). The HT has been traced from Kjerulf Fjord in the south to the Lacroix Bjerge in the north. Detailed observations of the HT were limited to the west side of Kjerulf Fjord and the north side of the inner part of Kejser Franz Joseph Fjord. Further studies are planned for 1998.

Hagar gneisses

The Hagar gneisses are identical with Wenk & Haller's 'Hagar migmatitic gneiss sheet', which they were able to follow over a distance of more than 100 km as a more or less continuous, NNW–SSE trending unit (Fig. 3).

The Hagar gneisses are granitic to granodioritic in composition. Where the rock is less deformed, a feldspar megacryst texture has been preserved. The Hagar gneisses look similar to the Niggli Spids gneisses. Generally, the rock has been strongly deformed giving rise to grey migmatitic gneisses with or without hornblende. These are cross-cut by granodioritic to dioritic gneisses and again by pink weathering granitic and gabbroic sheets.

A Rb-Sr whole rock isochron (Rex & Gledhill 1981) obtained from a pink weathering Hagar granitic gneiss (collected *c.* 5 km east of Knækdalen) yielded a Rb-Sr isochron age of 1950 ± 40 Ma, indicating an Early Proterozoic age of origin.

Hagar metasediments

The Hagar gneisses are unconformably overlain by a thick sequence of migmatitic pelitic metasediments with psammitic and quartzitic components. Pelitic beds contain garnet ± kyanite. The Hagar metasediments are similar in appearance to the upper sequence of the Niggli Spids metasediments.

Petermann detachment (PD)

The Petermann detachment is a collective name for several associated, low angle, ductile, extensional detachments which have top-to-the-NNW slip direction. The PD was formed during D2 and occurs along the base of the Petermann Series and above a foot-wall of higher grade metapelitic rocks (Hagar metasediments). Although the PD is an important tectonic feature, other similar detachment zones have also been observed in the region; only a few are indicated on our preliminary map (Fig. 1). Detailed observations of the PD were limited to the following four localities:

(a) Knækdalen river gorge

Here the PD forms a 2–5 m thick dirty-yellow weathering zone of mylonitic metapelite and quartzite. It is located above migmatitic metapelites (Hagar metasediments) and below quartzites of the Mystery Series (a unit within the Petermann Series) which contain well preserved cross-bedding.

(b) Nordenskiöld Gletscher, north side

The tectono-stratigraphic setting here is identical to that of the Knækdalen river gorge locality.

(c) Lystergletscher (c. 5 km north of Knækdalen)

Here the PD has climbed to higher stratigraphic levels juxtaposing the Layered Series (a unit within the Petermann Series of our usage) against migmatitic metapelites (Hagar metasediments);

(d) Jættedalen, eastern part of the valley

The PD here cuts at a low angle the inverted limb of a major, west-verging, recumbent antiform formed during D2 (Fig. 4). The detachment places quartzites of the Mystery Series and medium-grade metapelites of the Phyllite Series (both units within the Petermann Series of our usage) against a footwall of higher grade migmatitic metapelites (Hagar metasediments) containing garnet and kyanite.

Petermann Series

In their first detailed description of the Petermann Series, Wenk & Haller (1953) subdivided the succession using natural lithological boundaries, each with a characteristic weathering colour and lithological composition. In their description of the lithostratigraphic framework of the Eleonore Bay Group, which they raised to Supergroup status, Sønderholm & Tirsgaard (1993) redefined the Petermann Series as the Petermann Bjerg Group, and assigned uninformative numbers (Formations PB1–PB6) to the subdivisions of Wenk & Haller

(1953). Their redefinition was not based on new work in the Petermann Bjerg region. However, we have found the descriptive names given by Wenk & Haller so obviously useful that we have retained the abbreviated versions of their division names in this report. Thus, from lowest to highest stratigraphic levels, six different series have been identified: these are the Mystery Series, Phyllite Series, Layered Series, Shoulder Series, Summit Series and Synclinal Series; for detailed lithostratigraphic descriptions, see Wenk & Haller (1953).

In central and western Frænkel Land and in southern Louise Boyd Land, the Petermann Series forms a thick succession of metasediments occurring above higher grade migmatitic metapelites (Hagar metasediments). As mentioned above, the PD forms a tectonic unconformity between the two sequences. The western boundary of the Petermann Series is formed by the Boyd Bastion fault (see below).

The Petermann Series comprises low to medium-grade rocks in which the metamorphic grade rapidly increases downwards perpendicular to the foliation. This condensing of the isograds appears to be the result of extensional deformation (flattening) during D2 (see also below in metamorphism section).

The Petermann Series was correlated by Wenk & Haller (1953) with the lower part of the Eleonore Bay Supergroup in Andrée Land. Comparison of our 1997 observations of the Eleonore Bay Supergroup in central Andrée Land and the Petermann Series in Knækdalen and Jættedalen, support the correctness of this correlation. In our view there is little basis for the statement by Sønderholm & Tirsgaard (1993, p. 19) that "lithological patterns found east and west of the central metamorphic complex are *not directly comparable* and the precise correlation of units is still uncertain" (our italics).

Detailed mapping of the Petermann Series in Knækdalen, along Nordenskiöld Gletscher and in southern Louise Boyd Land, has shown that the map of Koch & Haller (1971) needs revision in these areas.

Basic dykes

Deformed basic dykes (mainly amphibolites) occur in all the different rock units of the region, and can therefore not be used as a reliable time marker. However, depending on the relative age of the host unit, the number of dykes occurring varies. Remnants of strongly deformed basic dykes are common in the Niggli Spids and Hagar gneisses; they are less common in the Niggli Spids and Hagar metasediments, and only very few have been observed in the Petermann Series.

2. Pre-Caledonian primary structures and deformation

Lithological variations within the gneisses and metasediments, and sedimentary structures (mainly cross-bedding, ripple marks and mud-cracks within the Petermann Series) are considered to be pre-Caledonian in age.

Evidence for pre-Caledonian deformation is observed in the Niggli Spids gneisses. As described earlier, these foliated augen gneisses are cross-cut by a well developed net-vein system which, as far as we were able to observe, does not occur in the overlying unconformably Niggli Spids metasediments. It is therefore assumed that the gneissification, migmatisation and foliation of the Niggli Spids gneisses was developed prior to the deposition of the Niggli Spids metasediments.

3. Caledonian deformation

Folding and shearing of rocks, including that of syntectonic Caledonian granitoid rocks (Rex & Gledhill 1981), indicates that the whole region was deformed during the Caledonian orogeny. Based on a number of critical field observations and related field relationships four different deformation events of Caledonian age are recognised (see below).

Critical field observations and relationships

The critical observations on which our distinction of four deformation events are based include the following:

1. Mapping of the region revealed the existence of the Hagar thrust and of the Hagar thrust sheet. The inferred existence of the Niggli Spids thrust and the Niggli Spids thrust sheet are based in part on information from Haller's maps (Haller 1953, 1955; Koch & Haller 1971).
2. E–W (orogen-normal) trending lineations predominate on the three most western nunataks of the region. These nunataks were briefly visited during helicopter-reconnaissance.
3. Everywhere else in the region, N to NW-trending (orogen-parallel) stretching/mineral lineations predominate; NNW-trending directions are most common with plunges of 0°–20°. Wenk & Haller (1953, Plate 1), Haller (1953, Table III) and Higgins *et al.* (1981, Fig. 25) also recorded this persistent NNW-trending direction in Frænkel Land. Well exposed, N to NW-trending, generally west-verging, tight to isoclinal folds occur along both sides of Nordenskiöld Gletscher and at Ridderborgen. In central "Jættedalen" (Louise Boyd Land) the occurrence of a spectacular, large-scale, west verging, recumbent anticline with quartzites (Mystery Series) in the fold core, indicates intense folding during Caledonian deformation (Fig. 4).
4. Rocks from Frænkel Land and southern Louise Boyd Land show good evidence of ductile, foliation-parallel extension, with top-to-the-NNW sense of shearing. This is based on many recordings of top-to-the-NNW shear-sense indicators. The main types are small and medium-scale S-C fabrics, asymmetric feldspar porphyroblasts with tails, pulled apart quartzite layers or bedding-parallel pegmatites forming asymmetric boudins, and a few, ductile, large-scale, low-angle, normal detachments with top-to-the-NNW displacement (e.g. the Petermann detachment).
5. In the lower part of Knækdalen, gneisses with extensional shear fabrics have been folded by tight to isoclinal NNW-trending folds. This relationship indicates that at least some of the extensional deformation occurred before the folding.
6. The reversed limb of the west-verging, recumbent anticline in "Jættedalen" (3. above) has been neatly cut off at a low angle by the Petermann detachment (Fig. 4). This rela-

tionship indicates that at least some of the folding took place before formation of this extensional detachment.

7. The study of metamorphic assemblages in the Petermann Series, and sequences below, shows evidence for condensing of metamorphic isograds. These isograds have been mapped as sub-parallel to the Petermann detachment, indicating pure shear deformation during NNW extension (see later in metamorphism section).
8. A series of major, late Caledonian, large-amplitude, upright, open folds with orogen-parallel (NNE–SSW) axes, fold earlier Caledonian textures and structures (Fig. 1). A steep axial plane parallel crenulation cleavage is associated with the folding.
9. A few major, NNE–SSW trending, E-dipping, brittle, normal listric faults represent the latest phase of Caledonian deformation. As far as we could see, these faults do not show any trace of later deformation. The Boyd Bastion fault and the Rendalen fault are the dominant examples in the region.

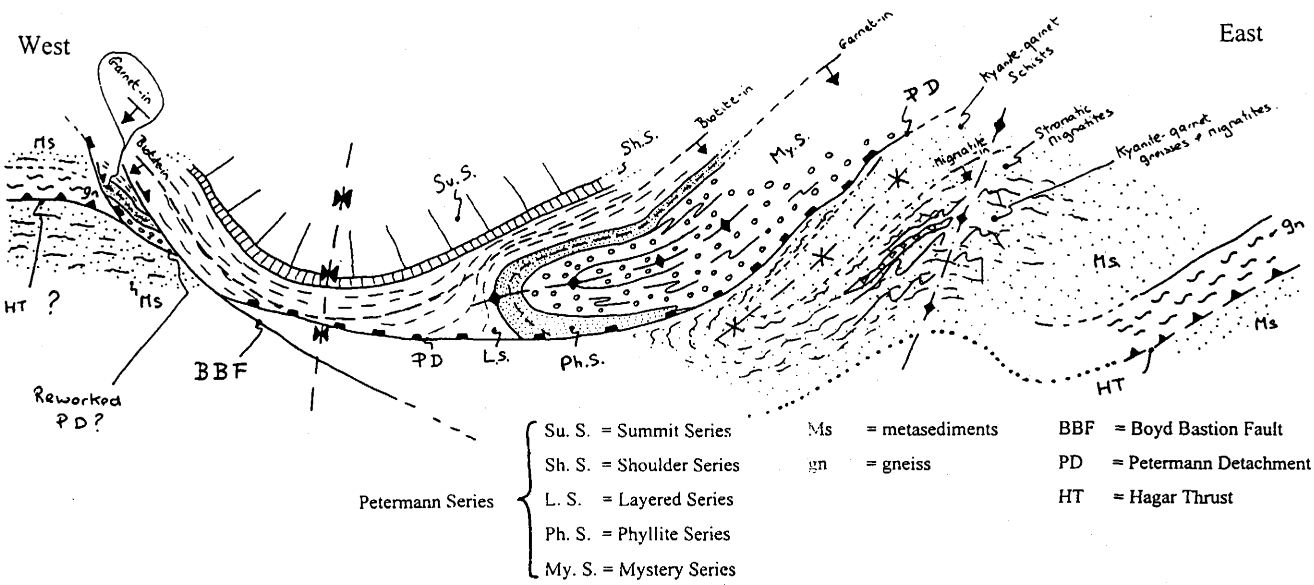


Figure 4. *Schematic cross-section along "Jættedalen", southern Louise Boyd Land.*

Boyd Bastion fault (BBF)

Although the Boyd Bastion fault is clearly indicated on the map of Wenk & Haller these authors state that "Major faults are entirely absent in the region explored" (Wenk & Haller 1953, p. 15); this remark seems to be mainly an attack on observations by Odell (1939). The regional importance of the BBF was apparently first appreciated by Larsen & Bengaard (1991), where as the 'Nunatak fault zone' it plays a role in their Caledonian extensional collapse scenario.

Mapping in the western part of Louise Boyd Land has identified two parallel fault splays situated close to each other. The BBF, which is the most westerly splay, is dominant. It places low and medium-grade metasediments of the Petermann Series (hangingwall) against migmatitic orthogneisses and migmatitic metasediments (both within the footwall) of the nunatak region (Fig. 1). There is thus a marked contrast in metamorphic grade across the fault zone. Further to the south, at the western end of Nordenskiöld Gletscher, at least three splays (also very close to each other) of the same fault system have been observed. At Boyd Bastion, which we regard as the type locality of the fault and therefore the new suggested name of 'Boyd Bastion fault', the dislocation dips at 26° to the east and has an associated, up to 80 m wide, brittle zone of coarse-grained cataclastic breccias and dark grey ultra-mylonites. Numerous kinematic shear sense indicators, including fibrous slickensides, within the shear zone, clearly indicate easterly down-throw of the hanging wall.

Rendalen fault (RF)

Our Rendalen fault (RF), which follows the north-east side of Rendalen in Andrée Land for at least 30 km, was probably observed for the first time at Junctiondal by Parkinson & Whittard (1931). In Haller's (1953) description of Andrée Land it is referred to as the 'Junctiondal fault'. The regional implications of this fault as an extensional structure were recognised for the first time by Larsen & Bengaard (1991), in which it forms the northern part of their 'fjord zone fault'. A slightly different interpretation of this structure was given by Hartz & Andresen (1995), which in Andresen *et al.* (in press) is designated the 'Fjord Region Detachment'. The latter follows much the same line as the 'fjord zone fault' of Larsen & Bengaard (1991) northwards as far as Junctiondal, but then diverts eastwards to follow the base of the Eleonore Bay Supergroup. To the south in Suess Land and Lyell Land Elvevold & Gilotti (1998), who use the term 'fjord region detachment' for the structure, describe it as an east-dipping normal fault dropping low-grade Eleonore Bay Supergroup sediments down against high grade gneisses of the basement complex. This description is in line with our observations in Rendalen. Leslie & Higgins (1998) use 'Rendalen thrust' for the same feature in Andrée Land as our Rendalen fault.

The Rendalen fault (RF) is well exposed as a prominent feature along the north-eastern side of Rendalen, and extends southwards to Junctiondal. Junctiondal was not visited by us during the 1997 field season, but it is planned to do so in 1998. At the south-east end of Rendalen, the Rendalen fault places low-grade sediments of the Eleonore Bay Supergroup and Caledonian granites (both in the hangingwall) against migmatitic orthogneisses and migmatitic metasediments (in the footwall). The RF has been studied in detail in one of the gullies along the eastern side of southern Rendalen. The detachment dips at *c.* 30° to the ENE. Well developed E–W trending stretching lineations, S-C fabrics and asymmetric feldspar augen with tails of crushed feldspar trailing into the mylonitic foliation, clearly indicate easterly down-throw of the hanging wall. Cataclastic breccias of various types and dark grey mylonites occur within a *c.* 50 m wide fault zone.

Deformation events

In broad terms, the East Greenland Caledonides as interpreted on the basis of our observations in Frænkel Land show striking similarities with the Alps, the Himalayas, and other orogenic belts. Based on the critical field observations and relationships (noted above) and on recent published ideas regarding the development of major orogenic belts, we distinguish the following four major deformation events (from oldest to youngest):

- **D1**. The earliest event starts with intense orogen-normal crustal shortening during subduction of Laurentia below Baltica, leading to formation of thrust sheets and nappes. Evidence for D1 is based on the recognition of the Hagar thrust and the Hagar thrust sheet, and the inferred existence of the Niggli Spids thrust and the Niggli Spids thrust sheet (critical observation 1, above). Other evidence from nearby regions supporting major thrusting includes: (1) the Charcot Land tectonic window where Vendian tillites occur immediately below a thrust, which can be structurally linked with the *c.* 70 km long Charcot Land nappe (Friderichsen & Thrane 1998); and (2) the major thrust above a window of low-grade Eleonore Sø volcanic-sedimentary sequences overlain by Scolithus-bearing quartzites, with in the hanging wall higher grade migmatitic metasediments (Leslie & Higgins 1998). The E–W trending lineations of the three most western nunataks (observation 2, above) are attributed to D1. The almost complete absence of E–W lineations in the rest of the study region are thought to be a consequence of strong overprinting by N to NNW-trending lineations during D2.
- **D2.** At the beginning of the D2 event the subduction which began during D1 apparently became blocked somewhere down in the upper mantle. Compression continued however, and orogen-normal subduction was replaced by orogen-parallel ductile transpression (extension). Ductile extension is recorded with orogen-parallel, top-to-the-NNW movements (3, 4 above), followed by formation of NNW-trending lineations, folds and low-angle detachments with top-to-the-north sense of movement (3, 4, 5, 6 above); Thinning of the crust (pure shear) led to condensing of metamorphic isograds (7, above), and introduction of large, syn-tectonic granitoids (see below in Caledonian magmatism section). At the end of D2 the orogen-parallel transpression/extension came to an end. [A sample for zircon age dating was collected from one of the Martin Knudsen Nunatakker. It was taken from a foliated, *c.* 100 m long, 1–4 m thick, zig-zag-shaped (due to D2 flattening) granite vein which cross-cuts a D1 thrust separating metasediments (bottom) from migmatitic gneisses. It is hoped to constrain the timing of thrusting and set an age for the flattening.]
- **D3.** Orogen-normal compression is still active but less aggressive. Due to isostatic adjustment, nappes and thrust sheets have now arrived near surface level. A series of large-scale, NNE–SSW trending, upright, open-style folds with axial plane parallel cleavage were developed (8, above). At the end of D3, the orogen-normal compression comes to a definitive stop.
- **D4.** During this last stage of Caledonian deformation, the Caledonides were subjected to orogen-normal crustal extension during which Iapetus re-opened. A few, major, brittle, normal faults are recorded with down-to-the-east displacement of the hangingwall (9, above). No evidence was observed of E–W ductile crustal thinning (extension) in the study region. The Boyd Bastion fault and the Rendalen fault (described above) are the two most prominent dislocations formed during D4 (Fig. 1).

4. Caledonian metamorphism

Two phases of Caledonian metamorphism have been recorded:

(a) Kyanite-grade metamorphism and migmatisation.
Kyanite-grade migmatites and gneisses have been observed in many localities in the footwall rocks of the Petermann detachment; similar grade rocks also occur in several places in the nunatak region. These medium to high pressure assemblages have been attributed to D1 metamorphism (crustal thickening).

(b) Low to medium-grade metamorphism with garnet, biotite and chlorite.
The Petermann Series in the hangingwall of the Petermann detachment is characterised by low to medium-grade metamorphic assemblages. Detailed mapping in Knækdalen and "Jættedalen" indicates that the metamorphic grade increases rapidly downwards through the Series, and that the chlorite, biotite and garnet isograds are developed more or less parallel to the Petermann detachment. The presence of these low to medium-pressure assemblages and the condensing of the metamorphic isograds are attributed to crustal thinning during D2 extension. High-grade, D1 kyanite-bearing assemblages, have progressively been overprinted by lower, garnet-grade assemblages during D2.

5. Caledonian magmatism

Only limited field work has been carried out on the granitoid intrusions of the region. Where studied, they show felsic two-mica mineralogy, indicating an S-type origin. Nearly all occurrences are thought to have been emplaced during D2 as the result of partial melting of metasediments (see also Jepsen & Kalsbeek 1998). The rocks are generally weakly foliated. The largest pluton of the region occurs at Nordenskiöld Gletscher, and thick K-feldspar augen granite sheets are found at the eastern end of "Jættedalen". Granitoid veins also occur along axial plane parallel fractures of D2 folds; examples have been observed along Nordenskiöld Gletscher. D3 syntectonic granitoid veins also occur along axial plane parallel fractures of D3 folds.

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Metamorphic and structural studies in the Caledonian fold belt of East Greenland (72°30′–73°N)

Synnøve Elvevold & Jane A. Gilotti

SE: *Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark*
JAG: *Geological Survey, New York State Museum, The State Education Department, Albany, NY 12230, USA*

The main aims of our 1997 field work in the East Greenland Caledonides were: (1) to map the area dominated by gneiss complexes and their overlying cover between 72°30′–73°N; (2) collect structural data; and (3) collect samples for detailed analysis of the metamorphic evolution of the study area. This report summarizes the first year of an anticipated two year field project, and forms part of the 1997–1998 regional mapping programme by the Geological Survey of Denmark and Greenland (GEUS) which centres on the production of a 1:500 000 map sheet of the region 72°–75°N.

The investigated area (Fig. 1) is part of the Caledonian orogen in East Greenland. The exposed geology reflects a composite of events which include crustal formation and deformation in the Precambrian, followed by crustal thickening and orogenic collapse of a Caledonian mountain belt. Some of the earliest work in the region was carried out by C. E. Wegmann (1935). The first detailed geological mapping was by John Haller (1955), and formed the basis for the printed coloured map sheets at 1:250 000 by Koch & Haller (1971); our study area is represented in remarkable detail on the Kong Oscar Fjord (72 Ö 1–2) and Nathorst Land (72 Ö 3) sheets. Higgins *et al.* (1981) contributed additional structural observations and detailed mapping. The geology of the study area can be divided into two major units (Henriksen 1985): (1) a medium- to high-grade gneiss complex of Archean to Middle Proterozoic age, which is overlain by (2) a moderately to non-metamorphosed, Late Proterozoic to Ordovician sedimentary sequence. The two units are in fault contact.

Our mapping was carried out at a scale of 1:100 000 on a new, but incomplete, topographic base. The study area includes parts of Lyell Land, Gletscherland, Suess Land, Goodenough Land, and a western nunatak region. Access is severely limited by steep fjord walls and ice covered plateaus, and this dictated where field camps could be placed. In 1997 we established eight camps, and had four and one half days of helicopter support which was used to visit the nunatak region and the central parts of Lyell Land. We also had boat access to Dickson Fjord and Rhedin Fjord, but the working period was cut short by bad weather and engine trouble. Approximately 180 rock specimens were collected (422801–422899 & 423201–423283).

1. Precambrian gneiss complex

The gneiss complexes of Gletscherland, Suess Land and Goodenough Land (Fig. 1) are indistinguishable from each other. The basement complex consists of a variety of lithologies including: orthogneisses (migmatitic gneiss, biotite gneiss, hornblende gneiss, granitic gneisses which are sometimes magnetite-bearing – see Schlindwein 1998, and augen gneiss derived from megacrystic intrusions); rusty-weathering paragneisses, schists (semi-pelitic, pelitic, psammitic and calcareous) and marbles; amphibolites, garnet-amphibolites and ultramafic rocks. We do not recognise the different basement sheets distinguished by Haller (1955, 1971). Nor can we recognise a consistent difference between the two gneissic units shown as "F – migmatite gneiss" (light pink) and "C – synorogenic granite" (dark pink) by Koch & Haller (1971). The components of the orthogneisses listed above are present in variable amounts throughout the study area, and we therefore map only one orthogneiss unit. Koch & Haller's maps accurately show the paragneisses, marbles and amphibolites as separate units within the gneiss complex. They can be compiled onto the final 1:500 000 scale map almost without modification.

Structures in the gneiss complex are complicated owing to the polyphase, intense, penetrative nature of the deformation. Precambrian structures are likely to be present, but it is not possible to distinguish them from Caledonian features. Map-scale, E–W trending, tight to isoclinal folds dominate the region and are impressively displayed along inaccessible fjord walls. Most lithologies are strongly foliated, although low strain lenses do occur. Some of the rocks are L-S tectonites with roughly E–W trending mineral and stretching lineations. The E–W orientations are at odds with the regional, orogen-parallel (N–S) trend of structures in the surrounding basement gneiss complexes (Haller 1971, Higgins et al. 1981). Overprinting by later, upright, NE-trending outcrop scale folds and crenulations are well developed in the western part of Gletscherland, particularly around Buri Søer. No thrusts or other clear tectonic boundaries were discerned within the gneiss complex itself.

The gneiss complex is characterised by medium- to high-grade metamorphism; diagnostic assemblages are best seen in the pelites and mafic rocks. Pelitic schists commonly contain garnet, kyanite or sillimanite, feldspar, muscovite and biotite. Many of the pelites are migmatitic with a gneissic, segregated texture. Leucocratic layers and pods commonly contain kyanite, as well as minor garnet and biotite. Partial melting is also seen in the orthogneisses and mafic rocks, and ranges from cm scale leucosome layers that form part of the banding (i.e. migmatitic gneisses) to larger areas where blocks of gneiss seemingly float in granitic melts (e.g. at Kap Robert and Kap Bayard). Pegmatites that cross-cut gneissic banding are also common. Anomalously lower grade biotite schists, gneisses and quartzites, intruded by granitic sheets, occur in the western part of Gletscherland around Buri Søer.

2. Late Proterozoic cover sequences

Late Proterozoic sedimentary rocks occur to the east (Eleonore Bay Supergroup: EBSG) and west ('Petermann Series') of the gneiss complex. The 'Petermann Series' is formally distinguished as the Petermann Bjerg Group within the EBSG by Sønderholm & Tirsgaard (1993). Both cover sequences structurally overlie the basement gneisses, from which they are separated by faults (discussed below). Vast sections of the cover rocks are unmetamorphosed, and have been studied intensely by stratigraphers and sedimentologists (see Sønderholm & Tirsgaard for full references). Of interest to us is the lower part of the EBSG

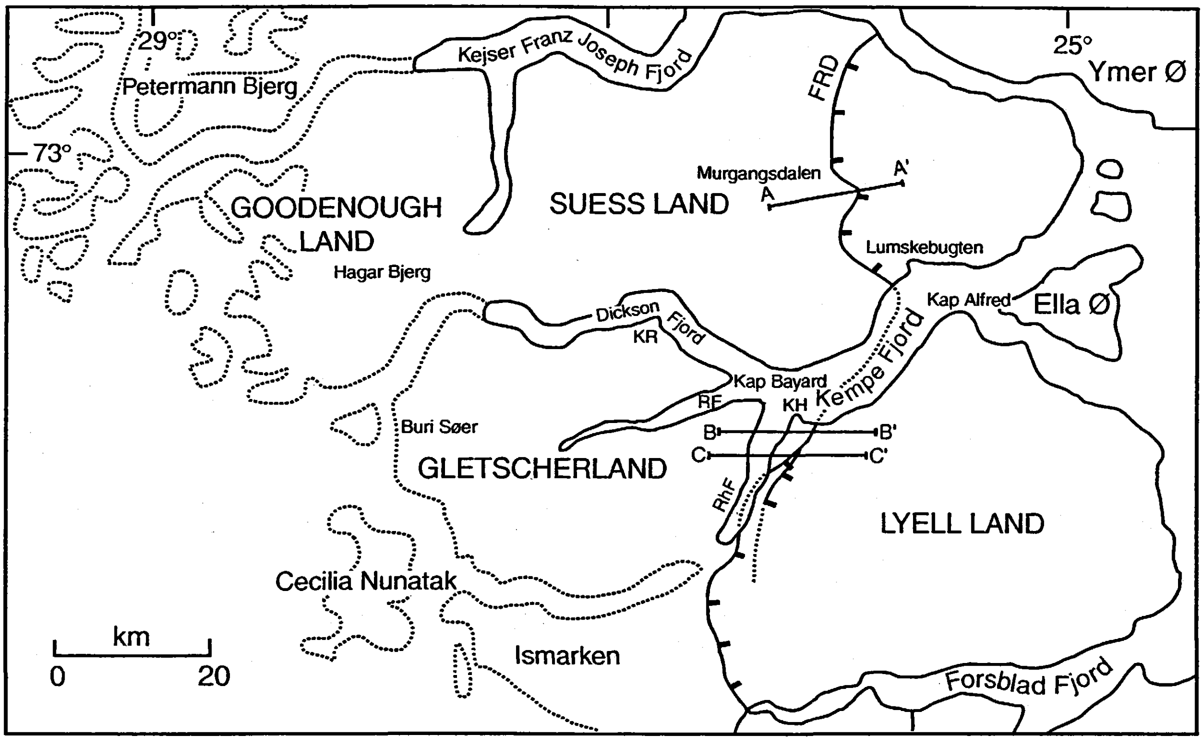

Figure 1. *Map showing place names used in the text and the locations of profile lines (Fig 2). KH – Kap Hedlund; KR – Kap Robert; RF – Röhss Fjord; RhF – Rhedin Fjord; FDR – fjord region detachment.*

section where the rocks are weakly to moderately metamorphosed. Semi-continuous exposures occur in Lyell Land and Suess Land, east of the gneiss complex. We logged one critical 15 km traverse along the south-east side of Kempe Fjord, beginning about 6 km south-west of Kap Alfred and walking south-west to the fault east of Kap Hedlund. The traverse started in unequivocal lower EBSG sandstones, siltstones and shales at chlorite zone with incipient cleavage. Metamorphic grade and fabric development gradually increased as we progressed down section through slates to schists, and across the biotite and garnet isograds, until the units were truncated by the fault. We interpret this entire section as part of the lower EBSG.

Two mysterious metasedimentary units are designated as "K" and "L" on the Koch & Haller (1971) maps. A challenge of our remapping effort is to determine whether these units belong to the lower metamorphosed part of the Late Proterozoic sequences (as is apparently the case along Kempe Fjord), whether they are part of the gneiss complex metasediments, or if they represent a separate sedimentary sequence. We have reinterpreted a number of "L" occurrences in the western nunatak region as basement pelites due to the presence of kyanite-bearing leucosomes in garnet-biotite schists that are characteristic of the basement metasediments. The identification problem is compounded in Goodenough Land because each nunatak mapped as "L" needs to be visited.

3. Granites and the 'migmatite wedge'

A triangular-shaped belt of melted metasediments and granites, which we will call the 'migmatite wedge', is situated in Lyell Land east of the gneiss complex (Fig. 1, Koch & Haller 1971, Higgins *et al.* 1981). The belt begins on the south side of Kempe Fjord and widens southward to Forsblad Fjord. We examined the migmatite wedge from our last camp in a glacial valley east of Rhedin Fjord and by helicopter reconnaissance in the rugged interior of Lyell Land.

The structurally lowest part of the wedge occurs along its western boundary. Migmatitic metasedimentary rocks are neosome-rich with abundant restitic inclusions of quartzite and biotite schist. Primary structures, e.g. bedding and cross-bedding, are found in some quartzite rafts. The neosome is a medium- to coarse-grained two mica granite, marked by a ghost layering defined by biotite-rich stringers that probably represent a former schistosity in the metasediments. The granites also form sheets (a few metres to tens of metres thick) which are both parallel to and cross-cut the relict metasedimentary layering. The eastern margin of the migmatite wedge is in contact with metamorphic equivalents of the EBSG. The boundary between melted metasediments and granites of the migmatite wedge and granite intruded meta-psammites of the overlying EBSG is, however, not easily defined.

We did not see any of the basement gneiss complex lithologies in the migmatite wedge on our reconnaissance stops, contrary to the indications of Koch & Haller on their Nathorst Land map sheet (i.e. patches shown as "F" and "J"). Similar melting and intrusive relations can be seen west of the gneiss complex in Goodenough Land. For example, sheeted granite bodies interleaved with metasediments occur on some nunataks, while other nunataks are comprised almost entirely of two-mica granites with large rafts of metasediments. We believe that the granite-intruded metasediments in Goodenough Land (shown as "L" on Koch and Haller's Nathorsts Land map sheet) can be correlated with the migmatite wedge east of the gneiss complex. More observations are needed in order to define the contact between the Eleonore Bay Supergroup or Petermann Bjerg Group and the melted metasediments in both Lyell Land and Goodenough Land.

4. The fjord region detachment

The eastern border of the Precambrian gneiss complex is in fault contact with the Late Proterozoic sedimentary sequence (EBSG) in Suess Land and the migmatite wedge in Lyell Land. The fault is well-exposed in Murgangsdalen and at Kap Hedlund. We have made detailed observations along three sections (Fig. 1), and visited numerous other exposures. The fault is an east-dipping normal fault which drops low-grade EBSG rocks and the migmatite wedge down over high-grade rocks of the basement gneiss complex. Kinematic indicators present in the footwall show top-to-the-east kinematics. The fault zone is comprised of two parts: (1) a brittle zone of cataclasites, derived from the uppermost surface of the footwall, and (2) an underlying zone of intense plastic deformation that dies out downwards into the footwall. The fault is a regional feature recognised by all previous workers in the region (e.g. Haller 1955; Koch & Haller 1971), and was interpreted as a Devonian extensional fault by Larsen & Bengaard (1991; their 'fjord zone fault'). It has recently been interpreted as a late Caledonian, extensional, detachment zone related to post-orogenic collapse of overthickened crust by Hartz & Andresen (1995). Andresen *et al.* (in press) refer to the fault zone as the 'fjord region detachment' (FRD), and we retain this nomenclature here.

Murgangsdalen section

A stream section in Murgangsdalen, Suess Land, provides complete exposure through the FRD (Fig. 2, section A–A'). The detachment itself is marked by an 80 m thick zone of dark green cataclasite that separates well-bedded, sub-greenschist facies quartzites of the EBSG in the hangingwall from augen gneisses and basement metasediments in the footwall. The cataclasites contain small pink feldspar porphyroclasts that are the clear remains of feldspar augen, indicating that the cataclasites are derived from the footwall gneisses. An 800 m thick zone of strong, plastic deformation occurs beneath the detachment and gradually dies out over an additional 1000 m (structural thickness) before a low strain domain of orthogneiss is encountered.

The rocks within the plastic deformation zone are dominated by augen gneisses and mylonitic versions of the basement metasedimentary sequences. The entire sequence has a flaggy appearance which is the result of a well-developed, east to east-north-east dipping foliation (stereonet, Fig. 3). The east-plunging lineation (stereonet, Fig. 3) is defined by the parallel orientation of rod-shaped and fibrous minerals (i.e. amphibole, sillimanite), elongated aggregates of quartz and feldspar, and pull-aparts of amphibole and sillimanite. The augen gneisses show grain size reduction, with feldspar augen becoming smaller and fewer as the brittle fault is approached. The augen have not developed good recrystallised tails, and are, therefore, poor kinematic indicators. However, biotite-rich shear bands with top-to-the-east kinematics are locally developed in the augen gneisses.

The mylonitic schists, in contrast, have a good S-C fabric. The shear bands become more closely spaced and at a lower angle to the schistosity as the fault is approached. A new set of steeper C' planes form that cut both S and C in the structurally highest mylonitic schists. The shear bands (C and C') consist of biotite and chlorite, and indicate a top-to-the-east sense of shear. Kyanite is found in leucocratic melt pockets in the pelitic metasediments, but is replaced by sillimanite in the upper part of the section. The mylonitic schists here are clearly derived from the typical kyanite-bearing pelitic gneisses and schists found throughout the gneiss complex; retrogression to sillimanite is spatially related to the FRD. The footwall also sustains a brittle overprint in the form of localised pseudotachylites, breccias, and chlorite- and epidote-filled fractures.

Kap Hedlund section

The FRD cuts down section in the hangingwall to the south. At an exposure east of Kap Hedlund (Fig. 2, section B–B'), lower EBSG quartzites are found intruded by granites overlying the gneiss complex. A 1–3 m thick brittle fault zone, again dominated by chlorite-rich cataclasites, separates the quartzites above from the gneisses below. The fault strikes NE–SW and dips south-east here, while lineations are predominantly east-plunging. The underlying zone of mylonitic deformation in the footwall gneiss complex is about 100 m thick, considerably thinner than the plastic deformation zone at Murgangsdalen. Shear bands in mylonitic garnet-biotite-sillimanite schists again yield a top-to-the-east sense of shear. Well-preserved, partially melted, garnet-kyanite basement metasediments are again found in the footwall gneisses about 1000 m beneath the FRD. Our observations are basically in agreement with Vold (1997); because of Vold's recent mapping, and the earlier map of Higgins *et al.* (1981), we did not attempt to remap the Kap Hedlund area.

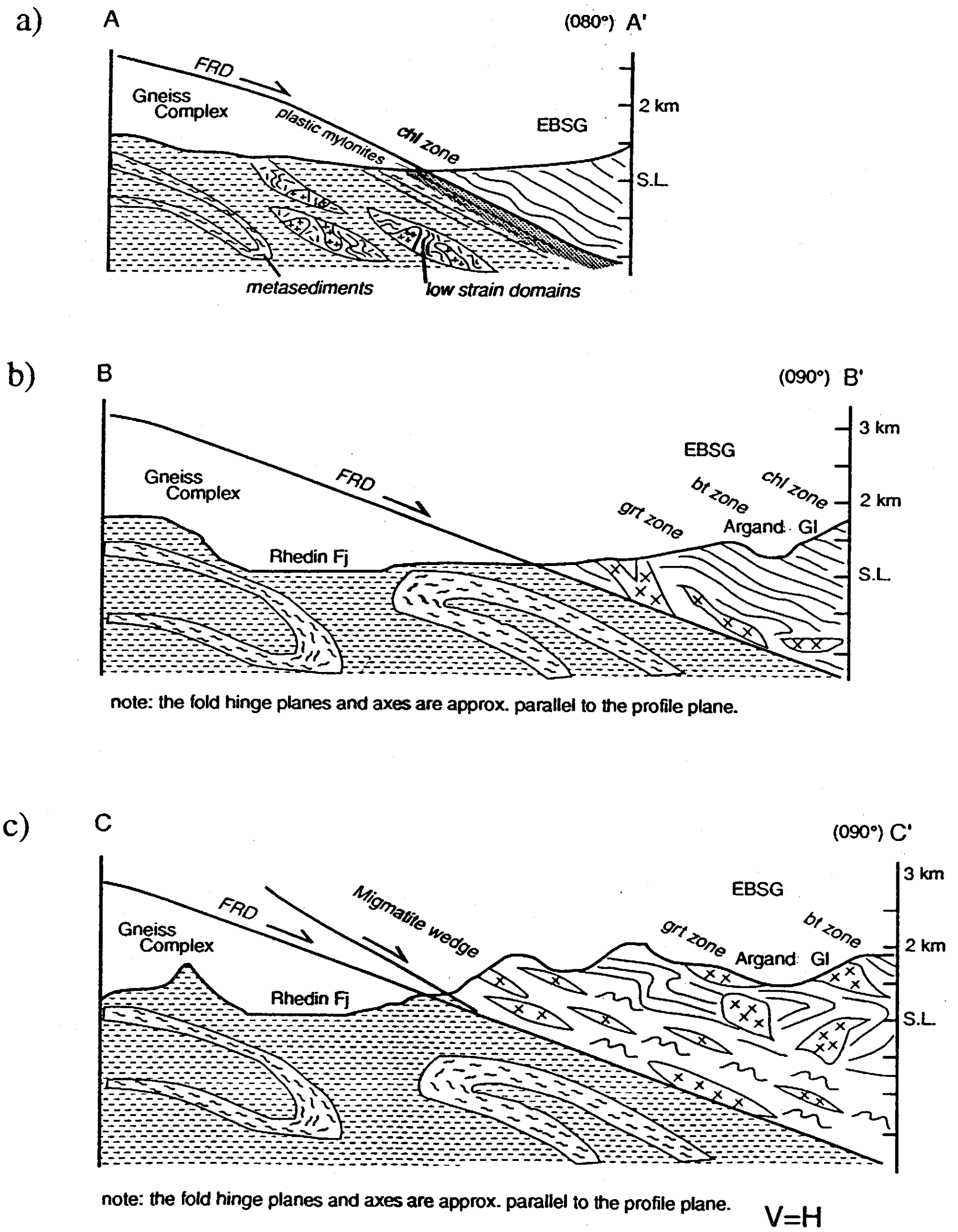

Figure 2. *Diagrammatic cross-sections from (a) Murgangsdalen, (b) Kap Hedlund, and (c) Camp 8 in Rhedin Fjord. Location of profile lines is shown in Figure 1. FRD – fjord region detachment; EBSG – Eleonore Bay Supergroup.*

The camp 8 section

An ESE–WNW profile across the FRD was pieced together along the first glacial valley south of Kap Hedlund and east of Rhedin Fjord (Fig. 2, section C–C'). The FRD fault can be followed along strike from section B–B' to our Camp 8 where it splays into two distinct strands; the splay faults are easily recognized by 1–2 m thick zones of cataclasite. The upper splay separates the lower part of the migmatite wedge from the underlying basement gneisses and metasediments. The lower splay cuts the gneiss complex. A thin zone of mylonitic deformation is also associated with the brittle faults in this section. The Koch & Haller (1971) map shows numerous faults on their Nathorst Land sheet (south of our Camp 8). We were only able to field check a few localities but, in every case, we found brittle fault zones marked by cataclasites. It is planned to gather more structural data in this critical area south-east of Rhedin Fjord in 1998.

Summary of observations along the FRD

The juxtaposition of a younger sedimentary sequence over older gneisses, the very low grade hangingwall above a high-grade footwall, the progressive retrograde metamorphic path indicated by mineral assemblages and a corresponding transition from plastic to brittle deformation in the footwall, coupled with consistent top-to-the-east sense of shear indicators lead us to accept the interpretation of the FRD as an extensional detachment fault (Larsen & Bengaard 1991; Hartz & Andresen 1995; Andresen & Hartz in press). Our along strike observations suggest that displacement dies out from Suess Land to Lyell Land. We have noted that stratigraphic throw decreases southwards, the thickness of both the brittle and plastic deformation zones decreases southwards, and that the fault 'horsetails' south-east of Rhedin Fjord (more map control is required to test this hypothesis). An important

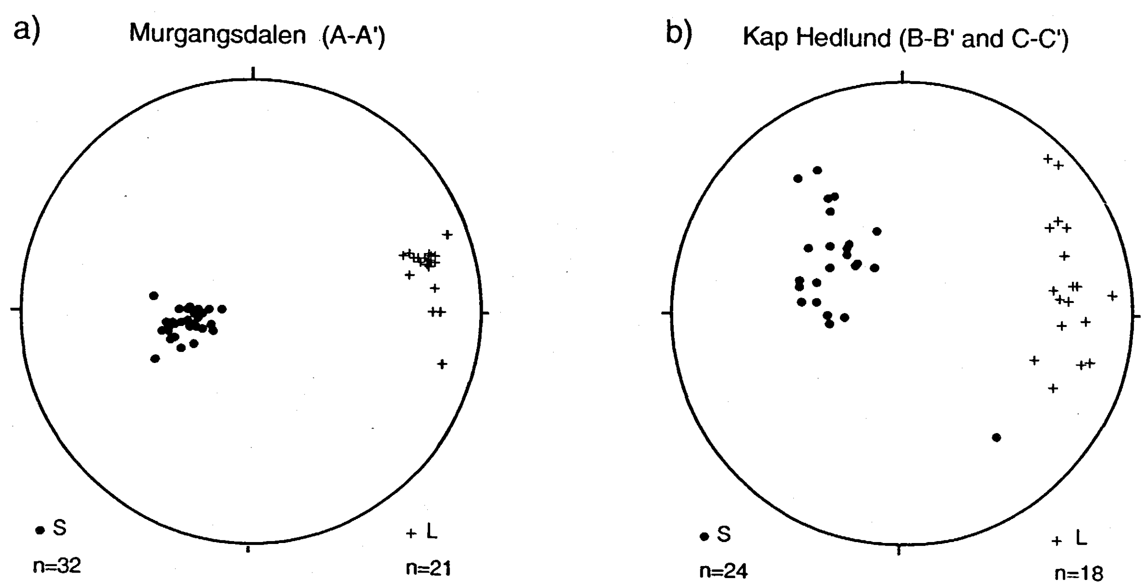

Figure 3. *Stereonet plots of foliations (dots) and plunges of lineations (crosses) for (a) Murgangsdalen and (b) Kap Hedlund.*

consequence of our interpretation is that a single detachment surface does not exist in Forsblad Fjord. Speculation that the FRD continues uninterrupted for another 100 km south to Scoresby Sund (Andresen & Hartz in press) is too simplistic. The FRD is probably better viewed as one segment of a "Late Caledonian" extensional fault system. The exact timing of the FRD is unknown, but the FRD cuts granites and migmatites at Kap Hedlund. Dating of these granites (hopefully by F. Kalsbeek) will provide an important lower limit on the time of extension.

Similar relationships between units, granite generation, and faults were seen on helicopter reconnaissance in the western part of our area. The extension fault recognised by Escher & Jones continues south into the nunatak region on the east side of Nordenskiöld Gletscher in our map area.

5. Metamorphic studies

The general metamorphic grade of the gneiss complexes in this part of East Greenland is known from previous work (e.g. Haller 1971; Thyrsted 1978; Higgins *et al.* 1981). Detailed metamorphic studies and quantification of the metamorphic evolution based on modern principles of phase equilibria have, however, not been carried out. It is well known that tectonic processes are reflected in the style, grade and path of metamorphism in deformed terranes. The primary goal of this project is thus to conduct detailed petrological studies in order to gain a better understanding of the metamorphic evolution of the Caledonian fold belt in East Greenland. The metamorphic pressure-temperature data generated by this study (Elvevold) will be integrated with structural analysis (Gilotti & Elvevold) and geochronology (K. Thrane, F. Kalsbeek & G. R. Watt) to produce a well-constrained model of crustal thickening, subsequent attenuation and exhumation.

Field observations

The metamorphic grade of the gneiss complex is predominantly amphibolite facies, but relicts of possible granulite facies assemblages were found at a few localities (e.g. Kap Hedlund) in 1997. Detailed petrographic analysis will concentrate on the best localities, but the mapping gives us an idea of the regional importance of our results. We know, for example, that metapelitic units contain widespread garnet-kyanite assemblages which are easily identified in the field, and give a quick, fairly accurate, measure of peak conditions. We have so far not detected any regional metamorphic gradients within the gneiss complex, except for variations due to degree of retrogression.

Pelitic metasediments occur both as highly weathered, rusty schists and as more massive gneisses. The common matrix assemblage in the gneisses is quartz + plagioclase + K-feldspar + garnet + biotite + kyanite ± sillimanite ± muscovite. Abundant leucocratic layers and lenses composed of coarse-grained K-feldspar, plagioclase, quartz, kyanite with minor garnet and biotite indicate partial melting of the metapelites. The coexistence of kyanite + K-feldspar + quartz in the anatectic pods suggests that partial melting of the gneisses occurred in the kyanite stability field. The formation of kyanite + K-feldspar

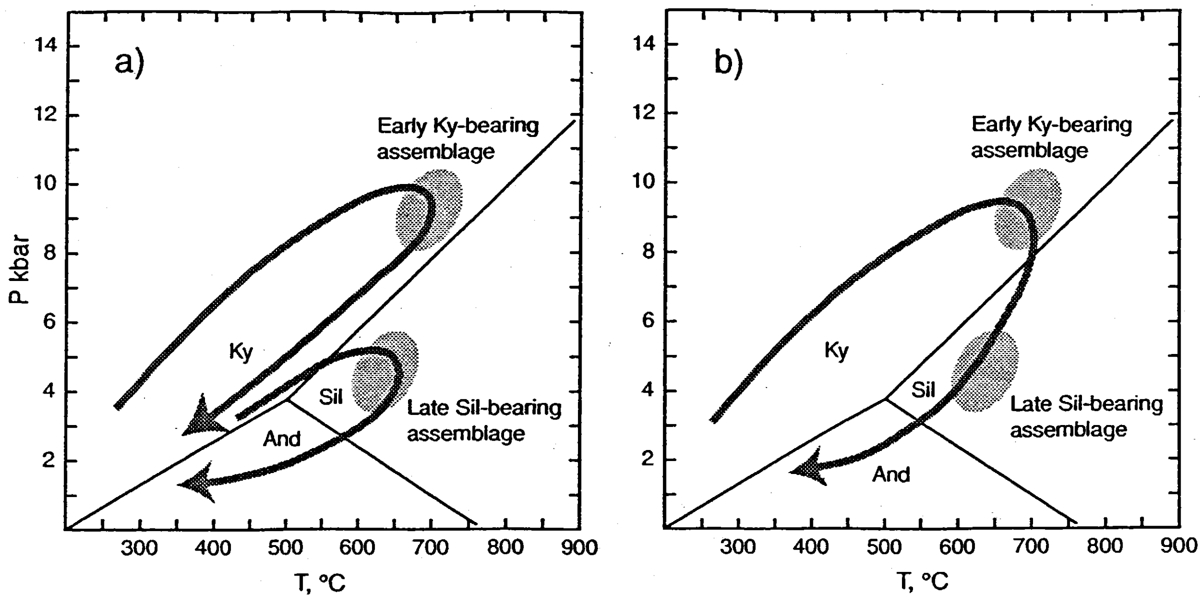

Figure 4. *Two of the several possible P-T evolutions which might result in the observed mineral assemblages in the paragneisses. Shaded ellipsoids indicate approximate equilibrium conditions for the early assemblage garnet + kyanite + biotite + quartz + plagioclase, and the late assemblage garnet + sillimanite + biotite + muscovite + quartz + plagioclase. (a) The early and late mineral assemblages belong to two separate, unrelated thermal events. (b) A continuous P-T path where the high grade kyanite + K-feldspar bearing assemblage is replaced by sillimanite-bearing assemblages during a single thermal event. This is a typical clockwise path which might result from crustal thickening during continental collision followed by unloading and thermal relaxation.*

bearing assemblages is interpreted to be a the result of the fluid-absent melting reaction muscovite + quartz + plagioclase = kyanite + K-feldspar + liquid, which indicates T > 700° C and P > 8 kbars for $a_{H2O} < 1.0$. The absence of orthopyroxene is evidence that the upper stability of biotite + quartz, defined by the reaction biotite + quartz = orthopyroxene + K-feldspar + liquid was not passed. The biotite breakdown reaction provides an upper temperature limit of about 850°C for the peak metamorphism of the pelitic gneisses.

The pelitic gneisses commonly host pods and lenses of garnet-amphibolite. The assemblage garnet + kyanite + alumino-tschermakitic amphibole (characterized by electron microprobe analyses) + quartz has been found in mafic lenses enclosed by paragneisses in Goodenough Land. The assemblage is diagnostic of moderately high pressure conditions.

The granulite facies assemblage garnet + clinopyroxene + amphibole + biotite + plagioclase + quartz + Fe-oxide has been found in the core region of fine-grained mafic lenses hosted by grey orthogneisses east of Kap Hedlund. The lenses display dark, hydrated (retrogressed) margins in contact with the surrounding grey gneisses. Relicts of garnet + clinopyroxene + quartz bearing assemblages have also been found in calc-silicate layers in quartzites from the migmatite wedge in Rhedin Fjord.

The high-grade kyanite + K-feldspar assemblages found in metapelitic gneisses are replaced by sillimanite + muscovite bearing parageneses in areas of high deformation (e.g. along the FRD). This sequence of mineral assemblages can be formed along one continuous, clockwise P-T loop as shown in Figure 4b, or they might belong to two separate and unrelated metamorphic events as illustrated in Figure 4a.

6. Problems and future studies

As mentioned previously, the main goal of this study is to determine the metamorphic evolution of the gneiss complex. A secondary goal is to understand the metamorphism and partial melting of the overlying Late Proterozoic sequences. These data will be used to develop tectonic models for Caledonian deformation in the region. P-T paths will be reconstructed using information from phase equilibria considerations, geothermobarometry, and mineral zoning. Specific sub-objectives of the project include:

- Determination of the prograde P-T path. Metamorphism at elevated temperatures often erases the early history of the rocks. However, relicts of the prograde history can be found as mineral inclusions and as assemblages in low strain lenses.
- An estimation of the peak metamorphic conditions in the gneiss complex. Is there a regional P-T pattern? If so, can the P-T pattern be related to the structural evolution of the area?
- Determination of the physical conditions during the various stages of exhumation. Microstructural analysis of oriented samples collected from the uppermost footwall of the FRD in Suess Land and Lyell Land will be undertaken to further establish kinematics, deformation mechanisms, and the relationship between mineral growth and structural development in the fault zone.
- Due to difficulties of access in Lyell Land and Goodenough Land, we have little hope of establishing isograds in the metamorphosed lower EBSG and its equivalents; however, we should be able to contribute to a better understanding of the metamorphism and melting of these units. Additional mapping will aid in determining the nature of the problematical metasedimentary units of the Koch & Haller (1971) map (i.e. their units K and L).
- Results of the geothermobarometry studies will be integrated with geochronology to establish P-T-t paths. One of the fundamental questions to be solved is the timing of high-grade metamorphism and migmatisation in the gneiss complex. For example, dating the kyanite-bearing leucosomes in the pelitic gneisses will tell us whether or not we are dealing with a single P-T loop.

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Caledonian and pre-Caledonian geology of the crystalline complexes of the Stauning Alper, Nathorst Land and Charcot Land, East Greenland

Johan D. Friderichsen & Kristine Thrane

JDF, KT: *Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark*

This report presents results arising from field work in July and August 1997 within the crystalline complexes of East Greenland between latitudes 72° and 72°30′N; the region includes much of Nathorst Land, the northern Stauning Alper and northern Charcot Land (Fig. 1). This description is based on a subdivision of the region into four structurally defined areas, which from east to west are (see also Fig. 1):

- The area dominated by migmatites and granites around central Forsblad Fjord and eastern Furesø. Within this area the host rocks to the migmatites and granites are the non-metamorphic to low-grade late Proterozoic Eleonore Bay Supergroup (EBS), which is underlain by early or late Proterozoic medium-grade paragneisses. Both rock units were heavily migmatised and partly melted in Caledonian time, and are penetrated by late Caledonian granites.
- The paragneiss area between inner Forsblad Fjord and Furesø. The protolith of this subarea comprises migmatised pelites, semipelites and quartzites which preserve evidence of a polyphase structural and metamorphic history; at least one phase is younger than the migmatisation. The paragneisses are in part folded together with the structurally underlying orthogneisses of the Häsi Bjerge gneiss complex.
- The Häsi Bjerge gneiss complex of Højedal, Tærskeldal, Häsi Bjerge, Jomfrudal and Græensedal. This extensive rock assemblage comprises the basement to the paragneisses, together with which it is locally folded. To the north it is continuous with the Gletscherland complex of Haller (1971), and to the south merges with the Flyverfjord infracrustal complex (Higgins 1982).
- Northern Charcot Land. While south of 72°N the rocks of the Charcot Land window are geologically bounded by a major thrust contact with the Flyverfjord infracrustal complex, the boundary between the Häsi Bjerge gneiss complex and the northern Charcot Land rock units coincides with a major nappe structure which crops out on the north coast of innermost Nordvestfjord.

One of the most important sources of pre-existing information on the geology of the region is the geological map at 1:250 000 covering the region between latitudes 72° and 76°N (Koch & Haller 1971); our region of study makes up the south-west corner. Most previous geological field work carried out in the region was undertaken by John Haller and fellow geologists under the auspicies of Lauge Koch's expeditions up to 1958, in the course of which many of the high alpine peaks were climbed for the first time. This work led

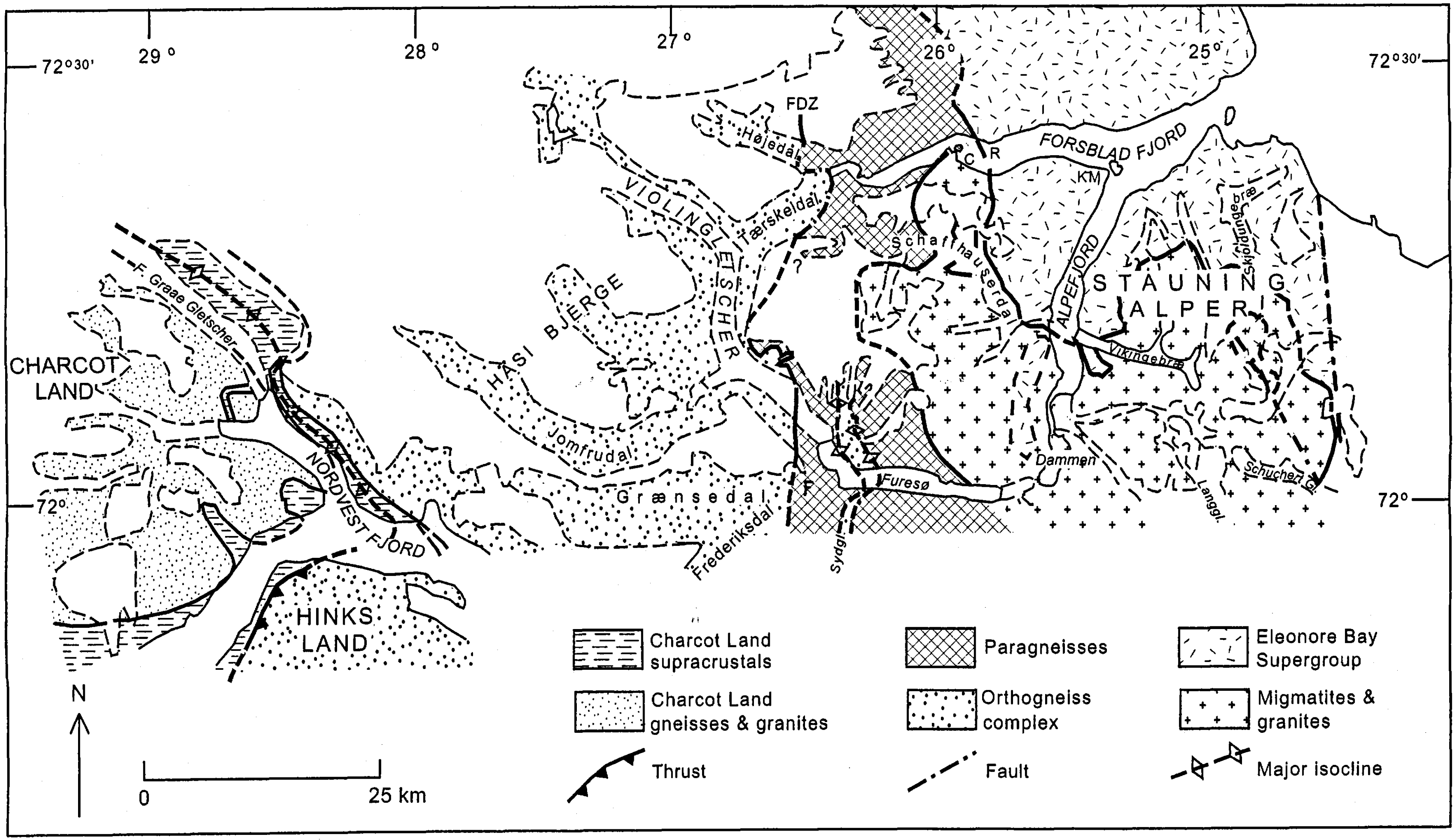


Figure 1. *Geological map of the region between 72° and 72°30′N, west of the Stauning Alper fault.* FDZ – *Fjord region detachment zone.* C – *Caledoniaø.* R – *Randenæs.* KM – *Kap Mæchel.* F – *Filosofbjerg.*

to John Haller's monograph on the geology of the Stauning Alper and Forsblad Fjord (Haller 1958), as well as other regional descriptions (Zweifel 1959; Fränkl 1951, 1953). The high alpine peaks of the Stauning Alper and parts of Nathorst Land have since been visited by numerous climbing expeditions, but in general these produced little in the way of geological observations.

Another important data source is the regional mapping programme undertaken by the Geological Survey of Greenland (GGU) south of latitude 72°N, in Charcot Land, the Frederiksdal region of Nathorst Land and the southern Stauning Alper (in 1968 and 1969). This work resulted in published 1:100 000 map sheets together with map descriptions (Henriksen *et al.* 1980; Higgins 1982). Geological recognaissance work was carried out by GGU between latitudes 72° and 74°N in the mid-1970s, and included some observations in the study region (Higgins *et al.* 1981). Rex & Gledhill (1981) published isotopic age dates on samples collected from some of the rock units. Caby (1976) and Peucat *et al.* (1985) presented observations on various aspects of the geology of the lower part of the Eleonore Bay Supergroup (EBS; formerly the Eleonore Bay Group, and promoted to a Supergroup by Sønderholm & Tirsgaard 1993). In recent years a group of geologists based at Oslo University has studied aspects of Caledonian and post-Caledonian geology, which has included investigations in Forsblad Fjord (see e.g. Hartz & Andresen 1995; Andresen *et al.* in press). Our study, which is supported by funding from the Danish National Science Foundation, forms part of the 1997–98 regional mapping programme by the Geological Survey of Denmark and Greenland (GEUS).

1. Migmatites and granites, and remarks on the Eleonore Bay Supergroup

Eleonore Bay Supergroup (EBS)

According to the maps of Koch & Haller (1971), the lowermost parts of the EBS are to be found along the west side of Alpefjord, in eastern Schaffhauserdalen and at Randenæs. These are referred to the 'bed groups' of the classic terminology (see e.g. Haller 1971), as bed group 3: 'Argillaceous Series, Lower Arenaceous'. The overlying rocks, bed group 4: 'Argillaceous-Arenaceous Series' and the thin intervening bed group 4a: 'Calcareous-Argillaceous Series' are found immediately to the east at the Kap Mæchel peninsular and along the east side of Alpefjord, where bed groups 5 and 6 of the 'Quartzite Series' (upper part of the EBS) are also found.

Only bed group 3 of this sequence was studied lithologically by us in some detail, notably the argillaceous rocks at Randenæs, and the lowermost arenaceous part of the sequence in Schaffhauserdalen. The arenaceous part of the sequence consists of monotonous beds of finely laminated, dark coloured quartzites with thin micaceous partings and occasional thin beds of calc-silicate. Towards the base this sequence becomes increasingly deformed and folded, sometimes by isoclinal and intrafolial folds (see structure section below).

On a small scale the folded quartzites are cut by thin veins and sheets of well foliated granodiorite (possibly equivalent to the granitic migmatite leucosome), which in turn are penetrated by thin quartz-feldspar veins and a late phase of medium-grained two-mica granite without internal fabric.

On a larger scale, steep walls display spectacular late granite veining into these lower EBS quartzites. The same veining is present at Randenæs, where bed group 3 quartzite beds pass upwards to the east into bed group 4 quartzites and phyllites with little granite veining.

There have been various interpretations of the passage down-sequence from the lowermost recognisable EBS beds into higher grade underlying crystalline rocks. Haller (1958, 1971) envisaged the crystalline rocks to be transformed parts of the EBS sequence, in accordance with his 'stockwerke' concept. Higgins *et al.* (1981), who based their interpretations on studies of similar rocks in the Scoresby Sund region south of latitude 72°N, correlated the more or less migmatitic paragneisses immediately below the EBS with supposedly Middle Proterozoic metasediments known as the Krummedal supracrustal sequence (see also Higgins 1988). They inferred the presence of a major structural dislocation (or décollement) dipping shallowly east beneath the EBS. The approximate location of this feature is everywhere obscured by heavy veining and granite emplacement, although at western Randenæs Higgins *et al.* (1981) described a locality where the boundary could be defined 'within narrow limits'. Caby (1976) essentially agreed with Haller's (1958, 1971) interpretation and described the boundary at the same locality as transitional, and Andresen *et al.* (in press) are of the same opinion.

Granitic migmatite

The term granitic migmatite is used here for a rock in which the leucosome granite phase forms more than 50% of the rock volume. Observations indicate that the rock formed by *in situ* melting; initial small sweats increase in size to form veins, eventually breaking up the protolith into inclusions within the flow-foliated leucosome granite. The greater part of the Stauning Alper is composed of granitic migmatite, and it is often possible to characterise the migmatite by its protolith. Thus western and higher parts of the granitic migmatite have an EBS protolith (see the large rafts on both sides of Alpefjord in Fig. 1), while lower and eastern parts have a paragneiss protolith. A large inclusion north of lower Schuchert Gletscher consists of black amphibolite associated with greyish white marble of the paragneiss suite.

The leucosome phase of the migmatite comprises coarse-grained granite, often somewhat foliated but otherwise undeformed, and often with biotite schlieren. We believe that this migmatisation phase is syn-Caledonian.

The granitic migmatite is generally of high metamorphic grade. The grade increases downwards and reaches a peak in the Dammen area, where symplectite developments of cordierite-rimmed quartz-rich nodules replace large garnets. Here further anatexis produced late, light coloured, biotite-garnet-cordierite granite without a distinct fabric, which invaded and rotated inclusions of the granitic migmatite. This we consider to represent a second Caledonian high-grade pulse of migmatisation and melting.

A number of recorded granite types have been tentatively correlated with the early migmatite leucosome. While their anatectic nature and foliated fabric are arguments for this correlation, on the other hand they usually contain few inclusions and in the higher parts of the area in particular form sheets. These granite types include:

- A light-coloured, weakly foliated, medium-grained granite with few scattered metasediment inclusions which is found mainly as veins and irregular blotches; this granite type seems to represent a late stage in the progressive melting, and is mainly seen in the Dammen area.
- Widespread, thick sheets of foliated, coarse-grained to porphyritic (sometimes megacrystic with up to 15 cm long and rectangular K-feldspars) granodiorite to quartz diorite, found In the Dammen region.
- Associated with the foliated, coarse-grained to porphyritic granite are sheets of medium grained versions of the same granitoid with fewer phenocrysts.
- Varieties of 'granular' and often very coarse-grained (but non-porphyritic) granite occur as leucosome in undeformed migmatites along the south coast of Furesø.
- Pegmatitic varieties (with feldspars often 30–40 cm across) occur in a few places; these were not seen as sheets.
- Frequent blocks of a yellow, medium-grained and almost unfoliated cordierite-rich granite, which occurs in the Dammen region; small melanosome inclusions are often present. It probably originated during a late pulse of melting.

Late to post-tectonic granites

A number of granite types are tentatively grouped in this category. The common criterion is the absence of fabric and of later cross-cutting rocks (except for lamprophyre dykes). Late brittle shear along sub-vertical NNW–SSE planes has also been noted (most likely conjugate faults related to the Stauning Alper fault referred to below). The most common type is a two-mica granite which forms numerous veins and sheets. It occurs particularly frequently near the boundary between the EBS and the paragneisses. It also occurs high up in the Stauning Alper as white, cross-cutting bodies in the granitic migmatite. An aplitic version was found in the Langgletscher area, while a coarse-grained type makes up a large part of the north-eastern Stauning Alper around upper Skjoldungebræ.

Lamprophyre dykes

A number of thin (less than 10 m wide), dark lamprophyre dykes with fine-grained matrix and 0.5–1 cm phenocrysts of black clinopyroxene or hornblende occur in the uppermost part of Schuchert Gletscher. One 30 m thick dark coloured dyke, presumed to be a lamprophyre, with a roughly E-W trend and shallow southern dip was seen 8 km further to the east, just north of Schuchert Gletscher.

Metamorphism in migmatites and granites

Relatively high temperature and low pressure metamorphic assemblages characterise the Stauning Alper and eastern Nathorst Land regions. Cordierite-sillimanite-garnet parageneses are found in the Dammen area, which seems to be a high temperature centre approaching (low-pressure type) granulite facies.

Boundaries to the east and west

The easternmost granites are found adjacent to the post-Devonian main fault along the east margin of the Stauning Alper (the 'Stauning Alper fault' of Henriksen *et al.* 1980) which separates Carboniferous sandstones to the east from the Caledonian crystalline terrain to the west. The fault zone is associated with a broad cataclastic zone which affects both granites and granitic migmatites.

To the west the boundary to the paragneiss terrain of Forsblad Fjord and Schaffhauserdal is often obscured by numerous veins and sheets of post-Caledonian granites. In a few places the boundary is well preserved enough to allow conclusions about its nature.

Thus at Randenæs in a small river bed little deformed EBS quartzite and sheared garnet-sillimanite mica schist (paragneiss) were seen stratigraphically only a few metres from each other, separated by coarse, unfoliated granite. Although the lowermost EBS quartzites contain sillimanite nodules (fibrolitic) as well as both garnet and biotite, there is a dramatic up-sequence decrease in metamorphic grade, with low-grade phyllites only about 100 metres upwards. This is probably the locality referred to by Higgins *et al.* (1981).

In Schaffhauserdalen minor faults or isoclinal folds offset the boundary. Unfortunately no way-up criteria were seen to determine if parts of the EBS are inverted here. In lowermost Schaffhauserdalen, however, a major recumbent and ESE-facing syncline inverts lower EBS quartzites, while the corresponding anticline has been obliterated by granitisation.

Further south the boundary between the EBS and the paragneiss area is untraceable in the granitic migmatite, which for purposes of this description forms the west boundary of this area.

We favor an interpretation of the boundary between the EBS and the paragneisses to the west as a highly reworked original unconformity. This boundary is characterised by:

- metamorphic retrogression of the medium-grade, coarse-grained garnet-mica schists below the inferred unconformity;
- pronounced increase of metamorphic grade downwards in the lowermost EBS;
- extensive regional melting and plutonism.

Structure

Large (km scale) flat-lying, isoclinal WNW-verging fold pairs are developed in the lowermost exposed EBS quartzites, one of which has been mentioned above. They have NNE–SSW oriented fold hinges and stretching lineations, and invert and repeat parts of the succession. Late granite veins seem to have been deformed by the same structures, but as they have no internal fabric they may be post-tectonic and were perhaps intruded along pre-existing fold limbs. Presumably this folding is the result of early Caledonian crustal shortening. Late Caledonian top-to-the-east extensional deformation was noted in relation to minor brittle faults.

Small scale fold structures are numerous in the lower part of the EBS quartzites, as parasitic folds on the large flat-lying isoclines and as later upright NE–SW trending structures with shallow plunging fold hinges (Fig. 2). Most granitic migmatite leucosome phases are foliated to some extent, and granite sheets high up in Stauning Alper, e.g. upper Vikingebræ, are gently folded in large flat structures with steep NE–SW trending axial planes and subhorizontal hingelines (Fig. 3).

2. The paragneiss area

The protolith

Micaceous pelitic to psammitic gneisses occur in the area between inner Forsblad Fjord and Furesø. These paragneisses are highly sheared, and have a regular eastward dip near the orthogneiss complex to the west. The flattening of the gneisses decreases gradually going east, so that the deformed migmatitic nature of the rock becomes visible. Along an east dipping zone west of Caledoniaø sheets of younger, little deformed anatectic leucosome granite come in, and further east, close to the boundary with the EBS, intense melting forms the granitic migmatite. This two-fold migmatisation, an early (presumed Proterozoic) phase followed by deformation in the west overprinted by a later (Caledonian)

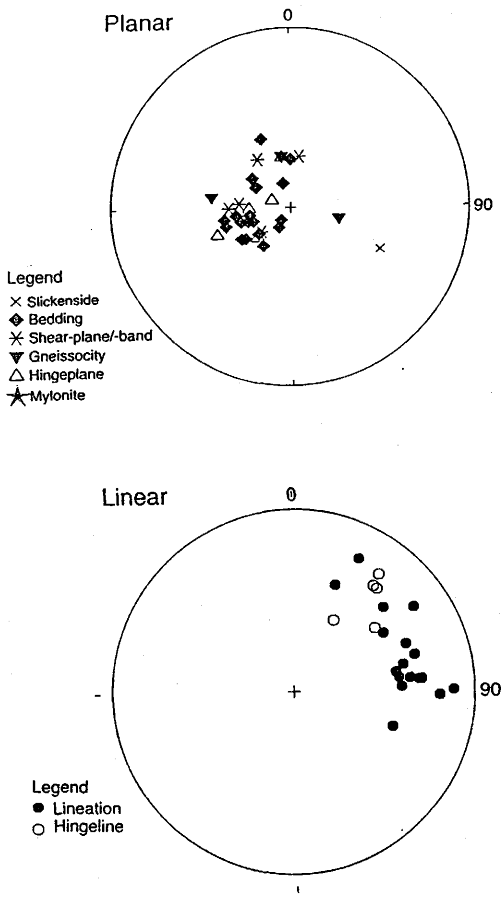


Figure 2. *Stereogram plots (lower hemisphere) of fabric elements in the lowermost EBS at Randenæs and Schaffhauserdal. Planar elements shown as poles to planes.*

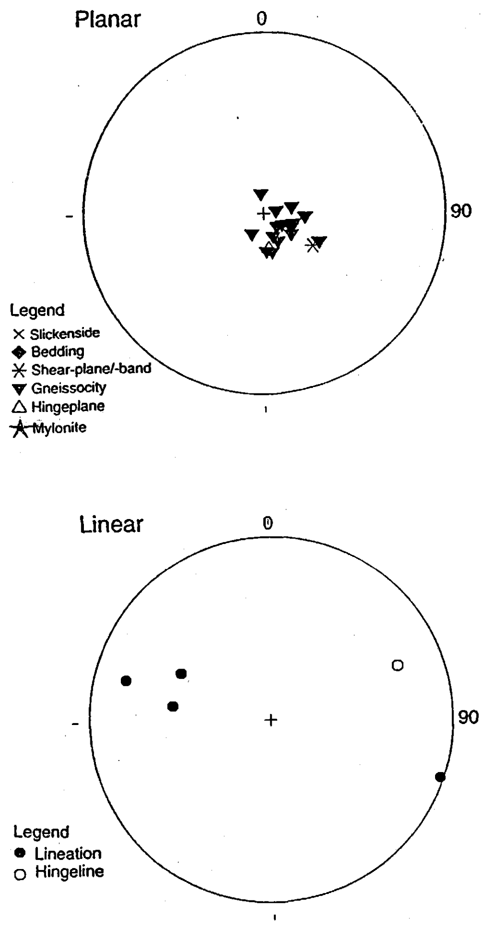


Figure 3. *Sterogram plots (lower hemisphere) of small scale structural elements in the Stauning Alper. Major flat lying folds and upright folds with NE-SW trending sub-horizontal hingelines not represented. Gentle west dips of foliation are conspicuous.*

phase (undeformed) in the east, matches observations from mapping of the 'migmatite and granite zone' south of 72°N in 1968 and 1969 (Higgins 1982; Henriksen *et al.* 1980). For the purposes of this description the Proterozoic migmatite is regarded as the protolith for the paragneiss in order to distinguish it from the undeformed, Caledonian migmatites.

Metamorphism

The high-temperature parageneses with cordierite-garnet-sillimanite-biotite which characterise paragneisses close to the EBS boundary (and central Furesø) change towards lower temperature parageneses with disappearance of cordierite going west towards inner Forsblad Fjord and western Furesø. Here kyanite is found in parageneses characterised by coarse-grained garnet and micas, which indicate relatively higher pressures and medium-grade metamorphism.

Structure

Both large and small scale folds with a wide variety of geometries are found In the central part of inner Forsblad Fjord. In general the linear structural elements plunge to the south-east, while gneissosities and axial planes strike NE-SW with variable dips to the south-east (Fig. 4).

Flattening of the paragneisses near the boundary to the Häsi Bjerge gneiss complex has been noted in many places, and indicates considerable top-to-the-east ductile shear movement. The flattening does not coincide precisely with the boundary, except in the area just north of innermost Forsblad Fjord. In western Furesø large conformable orthogneiss units of the Häsi Bjerge gneiss complex occur within the sheared paragneisses, and east of lower Violingletscher several large flat-lying isoclinal folds of paragneiss contain similar orthogneiss units affected by the folding.

Large brittle faults coincide with the Häsi Bjerge gneiss complex – paragneiss boundary in lowermost Højedal, and are characterised by a shear zone with bands of protomylonite and thin orthomylonites. Massive mylonites at least 10 m thick occur in an outcrop in scree low down in innermost Forsblad Fjord on strike with the Højedal shear zone. This shear zone corresponds to the extensional 'Fjord Region Detachment' of the Oslo University group (Andresen & Hartz 1995; Andresen *et al.* in press). The continuation of this shear zone further to the south has not yet been located, but the following comments can be made.

The massive mylonite zone in innermost Forsblad Fjord seems to disappear to the south into a steep brittle fault trending 025°, on the south side of which it is nowhere to be seen. On a helicopter reconnaisance, devoted to tracing the detachment, the paragneiss – orthogneiss contact cropping out on the south side of Tærskeldal was followed, but very little evidence of shear movement was to be seen. As the detachment need not exactly follow the paragneiss-orthogneiss contact, numerous outcrops further east in the paragneiss terrain were also checked but with no result. At one locality at lower Violingletscher (72°11.12′N 26°35.07′W) a thick mylonite with a shallow east-dipping lineation, a N–S strike and east dipping foliation, does indeed separate paragneiss from orthogneiss, but this mylonite could not be traced along the boundary.

An attempt was also made to locate another important alleged structural contact, the thrust-fault separating units of the 'migmatite and granite zone' from the 'Flyverfjord infracrustal complex' mapped throughout the Scoresby Sund region between 70° and 72°N (Henriksen *et al.* 1980). At the presumed location of the feature west of Sydgletscher at 72°N horizons of rusty brown and highly sheared micaceous schists interbedded with moderately strained basement gneiss were seen, but these very unspectacular shear zones could not be followed northwards across the mouth of Frederiksdal and Græensedal, although the Koch & Haller (1971) map does show a fault at almost the right location. Orth-

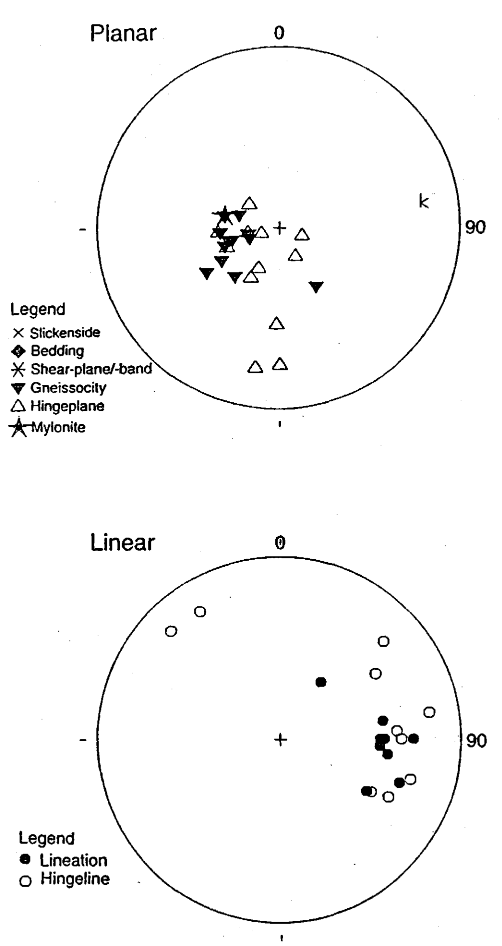


Figure 4. *Stereograms showing structural elements from the paragneiss area.*

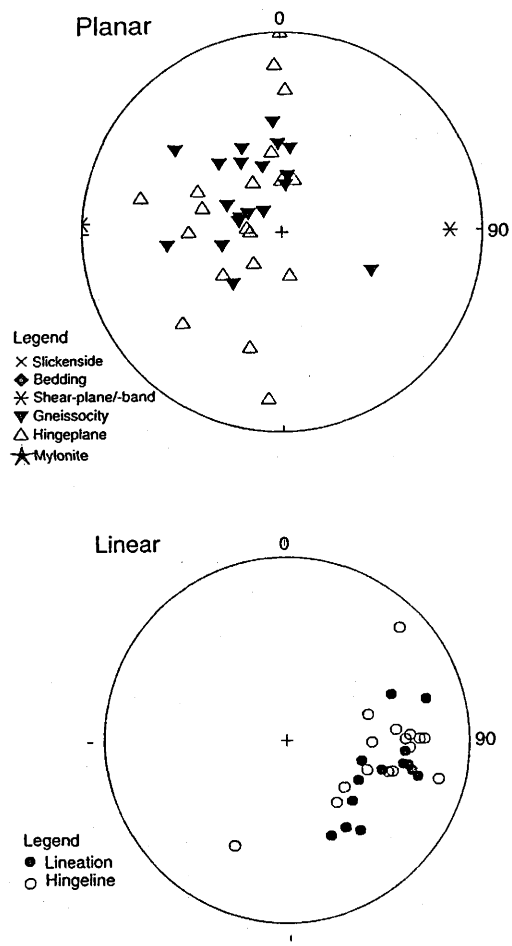


Figure 5. *Stereograms of structural elements in orthogneisses of the Häsi Bjerge complex at and immediately below the contact with the paragneisses. Note strong south-east lineation due to late Caledonian extensional top-to-the-east reactivation.*

omylonite occurs just at the south-east foot of Filosofbjerg, where paragneiss rests on orthogneiss. Here at least 20 m of sheared rocks with thin ductile mylonites are cut by minor east-dipping shear planes with top-to-the-east displacement.

3. The Häsi Bjerge gneiss complex

One of the major problems of our study region was to differentiate between crystalline rock units assigned to the 'Gletscherland complex' to the north, and those of the 'Flyverfjord infracrustal complex' south of latitude 72°N. Archaean isotopic ages were reported from the Flyverfjord infracrustal complex by Rex & Gledhill (1974), whereas gneisses at Kap Hedlund in the eastern part of the Gletscherland complex have yielded early Proterozoic isochron ages (Rex & Gledhill 1981). A number of errorchrons reported by Rex & Gledhill were recalculated by Kalsbeek *et al.* (1993), and qualitative Archaean ages were verified in Tærskeldal and Skræntdal. However, as we cannot at present find convincing reasons to ascribe the rock units outcropping in the extensive region between Nordvestfjord and Gletscherland to one or the other infracrustal complex, we here introduce the 'neutral' name *Häsi Bjerge gneiss complex* for the basement rocks of the western part of our study area.

Gneiss types

By far the largest part of the area is composed of banded grey gneiss. On an outcrop scale the gneisses can be characterised as ranging from homogeneous through veined to augen, nebulitic and agmatitic gneiss. Composition averages granitic. Biotite is the common mafic mineral, but is occasionally dominated by hornblende. The banding which occurs down to millimetre scale is caused by a variable distribution of mafic minerals, and by frequent bands of calc-silicate and amphibolite.

Veining by anatectic quartz-feldspar material is ubiquitous and varies from absolutely concordant to cross-cutting, from millimetre thin to metre thick and from aplitic to pegmatitic. One characteristic type of vein is coarse-grained, conformable and foliated with minute biotite schlieren. The same rock occurs as irregular, diffuse bodies and veins in grey orthogneisses within a large low-strain lens in north-east Tærskeldal (see *structure* below) where it forms the leucosome in locally migmatised orthogneiss.

Mafic horizons

Large scale dark bands are formed by up to several hundred metre thick units of mafic paragneisses and amphibolites. The colour index varies within these horizons. Both para-amphibolites (high magnetic susceptibility, often associated with marbles, in particular in Grænsedal and Jomfrudal) and ortho-amphibolite (low magnetic susceptibility and preservation of gabbroic textures) are present (see also Schlindwein 1998).

Metadolerites

Most of the conformable amphibolites must have originated as dolerite. Concordant amphibolites with relic phenocrysts have been noted, but only in rare cases have cross-cutting relationships been observed, as in low-strain lens in Tærskeldal mentioned above (see also *structure* below). Here it is possible to distinguish at least four characteristic generations of metadolerites. Of these a medium-grained, non-porphyritic NE–SW generation is the youngest, cutting across medium-grained, non-porphyritic NW–SE trending metadolerites, which are in their turn younger than coarse-grained porphyritic E–W trending metadolerites and very coarse-grained and sometimes almost ultramafic, irregular metadolerites.

Ultramafics
In addition to hornblendite in mafic horizons, trains of peridotitic to dunitic pods occur in several places, notably in southern Tærskeldal, where one body is 1000 m by 500 m in size.

Metasediments
Rusty weathering micaceous and psammitic units are often found as very persistent, though often relatively thin (less than 300 m wide) bands in the gneiss. Higgins *et al.* (1981) assumed that these horizons represented deformed shear zones. Their metasedimentary origin has now been confirmed by their association with rare occurrences of marble and quartzite with preserved textures of rust-stained, rounded quartz grains.

Younger granitoids
Only few 'younger' granitoid rocks were encountered within the grey gneisses. One conformable orthogneiss body in Tærskeldal, about 4 × 2 km in size, exhibited a distinctly simpler internal structure than that of the host gneisses. This orthogneiss showed a flaser-like texture, a medium-grain size and slightly undersaturated composition (monzonite-syenite with 0.7% normative nepheline). Another body on the west side of Violingletscher opposite Tærskeldal, about 2–3 km in diameter, comprised light coloured, medium-grained foliated granite, which clearly cross-cuts the surrounding net-veined, mafic gneisses. It is comparitively rich in magnetite, with a high magnetic susceptibility (Schlindwein 1998). This granite is cross-cut by thin pink granite veins, although these were only seen in boulders.

Metamorphism
It was not possible in the field to recognise good metamorphic grade indicator minerals within the gneiss suite. Typical parageneses are quartz + feldspar + biotite + hornblende ± garnet ± sillimanite, roughly indicative of medium epidote-amphibolite grade.

Structure
In most outcrops the foliation in the grey gneiss complex displays simple planar structures on a large scale (i.e. Højedal, west Tærskeldal, along Violingletscher, in Häsi Bjerge and in Jomfrudal and Grænsedal). This is particularly the case near the orthogneiss–paragneiss boundary, where the general dip is eastwards. Linear structural elements in the eastern parts of the area plunge at moderate angles to the south-east (Fig. 5).

In the western part of the area most lineations plunge to the norrth-west. The Caledonian overprint is less conspicuous in the stereograms (Fig. 6), due to a lower strain regime than to the east.

At the north-east end of Tærskeldal the remarkable low-strain lens (mentioned above) appears to owe its existence to a broad low-deformation zone in a very large scale flexure just beneath the boundary between the Häsi Bjerge gneiss complex and the overlying paragneisses (Fig. 7). The gneiss foliation within this low strain lens differs from the surrounding gneisses in that the general south-east plunge seen outside the lens is spread out in ill-defined concentrations in the stereonet plot (Fig. 8). This appears to be due to the flattening of the gneisses up to the boundary with the paragneisses rotating the pre-existing lineations into parallelism.

Two conformable roughly E–W shear zones occur within the banded gneisses in eastern Tærskeldal, one of which is about 300 m wide. The shear zones display ductile shear inhomogeneously across strike, with orthomylonite accounting for up to 10% of the zones. The zones appear to have been partly recrystallised, thus mafic minerals (hornblende, biotite and garnet) seem to grow across the foliation. Both shear zones are deformed together with the host rock, and all primary linear structural elements have been overprinted by the regionally dominant south-east plunging lineation.

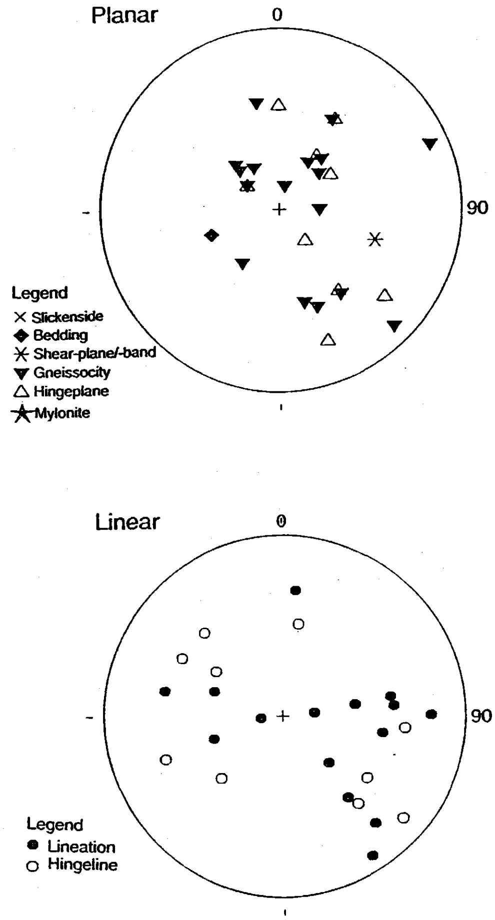


Figure 6. *Stereograms showing structural elements from central and western parts of the Häsi Bjerge gneiss complex. These plots are from a very large area and several structural units.*

4. Northern Charcot Land

From work in southern Charcot Land in the late 1960s, it was known that a major Caledonian thrust displaces the Archean Flyverfjord infracrustal complex over early Proterozoic foreland sequences in Charcot Land exposed in a tectonic window (Steck 1971; Higgins 1982). Steck (1971) observed an increasing northward metamorphic zonation in supracrustal rocks within the window in southern Charcot Land, with E–W trending isograds which

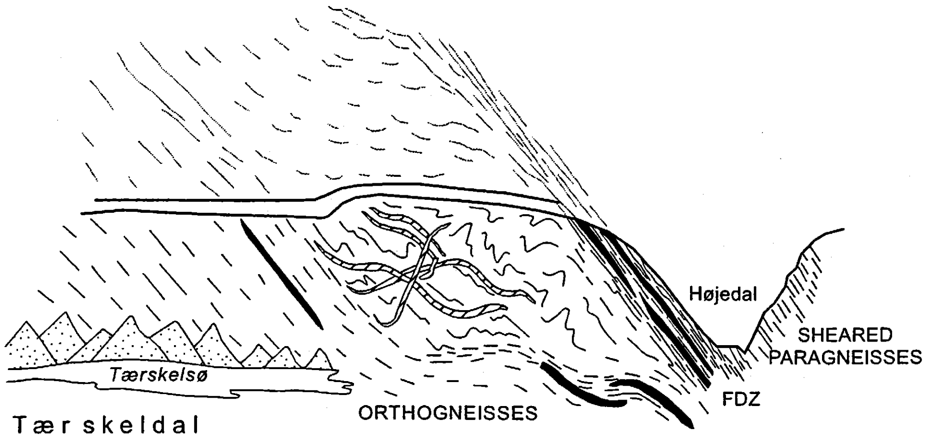
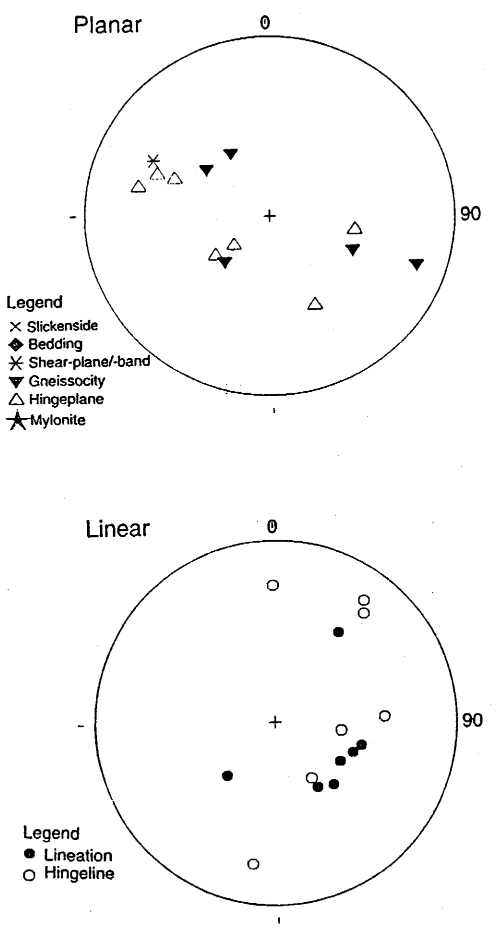


Figure 7. *Sketch illustrating structural setting of the low strain lens in eastern Tærskeldal.*



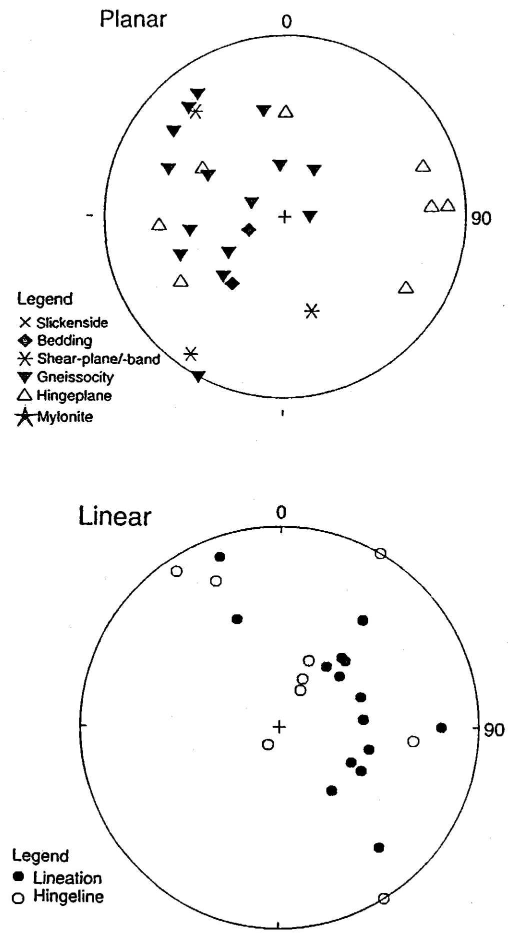


Figure 8. *Stereograms showing structural elements from the low strain lens in eastern Tærskeldal. Although situated just below the orthogneiss-pragneiss boundary there is little evidence of late Caledonian overprinting (cf. Fig. 5).*

Figure 9. *Stereograms showing structural elements from northern Charcot Land. No attempt has been made at subdivision into different structural units.*

were attributed to Caledonian metamorphism. Isotopic age determinations on intrusive bodies yielded ages ranging from 1800–2100 Ma (Steiger & Henriksen 1972; Hansen *et al.* 1972, 1973, 1980; Hansen 1976), implying that the metamorphic zonation observed by Steck was in fact early Proterozoic. Several mica mineral ages from within the window testify to a minor Caledonian metamorphic overprint.

Orthogneisses

The grey gneisses of northern Charcot Land are more homogeneous in structure than their Flyverfjord infracrustal complex and Häsi Bjerge gneiss complex counterparts, but otherwise they have some of the same general characteristics. They contain light coloured veins (conformable as well as cross-cutting), mafic units such as mafic gneisses and amphibolites are present, but ultramafic sheets and lenses were not seen. Veins and thin sheets of medium to fine-grained (in places aplitic) quartz granodiorite were found with concordant relationships to the host gneiss. The quartz granodiorite contains deformed inclusions of the gneiss, and is usually foliated.

Supracrustal rocks

In southern Charcot Land the Charcot Land supracrustal sequence comprises psammites, semipelites, pelites, marbles, gabbros and various extrusive volcanic rocks, apparently resting directly on the basement gneisses (Steck 1971). In northern Charcot Land similar supracrustal rocks occur as units that are apparently folded into the basement gneisses without distinct difference in metamorphic grade or deformation intensity. On the north side of F. Graae Gletscher there is a thick sequence of supracrustal rocks with similar lithologies to those described above, which are overlain by a very thick sequence of dark grey low-grade pelite or phyllite. The relationships of this phyllite series to the somewhat higher grade supracrustal rocks below is currently uncertain. However, the possibility exists that they correlate, and that the increase in metamorphic grade up to 72°N noted by Steck (1971) decreases again further to the north.

Charcot Land muscovite granite

Light coloured coarse to pegmatitic (sometimes with pink K-feldspar megacrysts) muscovite ± garnet granite makes up large portions of northern Charcot Land. It forms an irregular batholith cross-cutting and net-veining the surrounding orthogneisses in a very spectacular fashion. The granite has no internal fabric and seems to have a replacive relationship to its host rock. Veins of the granite are frequently seen to cut the supracrustal units, and seem to post-date their main metamorphic fabric.

Tertiary dykes

About 4–5 late (presumably late Mesozoic or Tertiary) dolerites with roughly N–S trends and sub-vertical orientation transect the central part of northern Charcot Land. Their thickness varies between 50 cm and 10 m, and they seem to be very persistent although often displaying en-echelon structures.

Metamorphism

As mentioned above, the present somewhat limited number of observations indicate a decreasing grade of metamorphism going northwards from latitude 72°N. It is possible that the sequence of phyllites found near F. Graae Gletscher is simply a reflection of a rapid decrease in grade, comparable to the gradient described by Steck (1971) in southern Charcot Land.

Structure

Stereonet plots of structural elements in Charcot Land (Fig. 9) reveal a completely different pattern from those of the Häsi Bjerge gneiss complex. Foliations in the gneisses generally dip at shallow angles to the east and south-east, and lineations plunge moderately to the east, falling in a north-east group and a south-east group. Minor scale folds, however, are much more varied in direction, and form several discrete groupings, not unlike the pattern of minor structures in the low strain lens of north-east Tærskeldal.

One serious problem facing us in northern Charcot Land was to define the continuation of the major thrust which so clearly defines the Charcot Land window south of 72°N. The thrust seems to dematerialise north of its last outcrop in north-west Hinks Land, and the obvious solution of drawing it up the fjord and the middle of F. Graae Gletscher leaves one with the problem of explaining why there are thick deposits of Charcot Land supracrustal rocks on the east side of F. Graae Gletscher. In 1934 Eduard Wenk had discovered and drawn a very large scale flat-lying, west-verging isocline on the north coast of innermost Nordvestfjord (Wenk 1956), with a closure some 25 km north-west of its first appearance opposite the snout of Daugaard-Jensen Gletscher. However, the isoclinally folded white marbles that Wenk measured from fjord level account for less than half of the magnitude of this fold or nappe, and over its entire length the fold could easily accomodate a translative movement of proportions necessary to form the Charcot Land window (a minimum of 40 km displacement; Hansen *et al.* 1980). We consider that the thrust movement is taken up by the nappe, and hence that there is lateral correlation between the thrust hangingwall and footwall rocks; this would imply that the Charcot Land gneisses correlate with the Flyverfjord infracrustal complex and that the Charcot Land supracrustal sequence equates with the Krummedal supracrustal sequence. There are, however, serious problems with this interpretation: notably that the metagranite cross-cutting the Charcot Land supracrustal sequence has been dated to about 1800 Ma (Hansen *et al.* 1980), while the Krummedal sequence is thought to be about 1200–1800 Ma old. This enigma may be resolved by a critical review of existing and planned isotopic age analyses.

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Granites in the Caledonian fold belt of East Greenland

Hans F. Jepsen & Feiko Kalsbeek

HFJ, FK: *Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark*

Our task during the 1997 season of the Geological Survey of Denmark and Greenland regional mapping project in East Greenland was to study the Caledonian granites in the area between 72° and 74°N. Most of the work will consist of geochronological and (isotope-) geochemical investigations, and the conclusions and suggestions expressed in this field report are preliminary and may have to be revised or abandoned when analytical data become available.

Planning of the project – selection of sample sites etc. – was based on earlier investigations, especially those of Haller (1953, 1958), Higgins *et al.* (1981), and Rex & Gledhill (1981).

Field work was carried out from 12 camps, scattered between 72° and 74° N so as to obtain information from as large a part of the area as possible (Fig. 1). Helicopter reconnaissance was used extensively in areas that were difficult of access on foot. Unfortunately, most granites are exposed in steep cliffs or along steep scree slopes. Only very rarely was it possible to study the granites in detail over extended exposed surfaces.

1. Regional geology

Stratigraphically the area studied consists of three main divisions:

(1) Archaean and Early Proterozoic basement complexes;
(2) Middle Proterozoic to Early Palaeozoic metasedimentary sequences (see below);
(3) Post-Caledonian deposits.

The granites that are the topic of this study occur in unit (2).

The Precambrian metasedimentary rocks of unit (2) have been subdivided into an older part, correlated with the Middle Proterozoic 'Krummedal supracrustal sequence' in the Scoresby Sund region to the south (Higgins 1988), and a younger part, the Late Proterozoic 'Eleonore Bay Supergroup' (e.g. Higgins *et al.* 1981; Sønderholm & Tirsgaard 1993). This distinction has been questioned by, among others, Caby (1976) who thought that the metasediments of Forsblad Fjord belong to one continuous sedimentary sequence. In the areas we have visited both units are dominated by quartzites and mica schists, and we have not been able to differentiate the older and younger sequences in the field. Therefore, for the purpose of this report, we treat them as one unit, which we informally term 'KR-EBS' (KRummedal and Eleonore Bay Supergroup).

2. Granites

The only *certain* Caledonian granites are those that intrude the Late Proterozoic Eleonore Bay Supergroup (EBS). Typically they are homogeneous, white, medium-grained biotite-muscovite granites or, less commonly, biotite granites. Such granites occur, for example, in Grejsdalen and at Randenæs (Forsblad Fjord), where they intrude pelitic and quartz-rich psammitic rocks of the EBS, and contain large rafts of those.

Lithologically similar granites ('Grejsdalen type' granites) that do not cut the EBS may be older, some possibly of Grenvillian age (~1000 Ma). Evidence to support an older age for some of the granites has been provided by Rex & Gledhill (1981) from Rb-Sr whole-rock data (see below).

Some granites are clearly deformed and exhibit a tectonic fabric. However, this feature cannot be used with confidence to distinguish between Caledonian and older granites, because some granites cutting EBS lithologies are clearly foliated. On the other hand, we have seen many instances where granites are strongly boudinaged, but where the granite itself does not show any tectonic fabric.

Granites of 'Grejsdalen type' are very common as sheets in the deeper parts of KR-EBS. Their thickness varies from less than 1 metre up to 100 metres or more. Locally granites and pegmatites contain biotite-rich schlieren, and at many places it is evident that at least some of the granite is the product of partial melting of pelitic mica schists, leaving biotite-rich schlieren as restite. Such granite sheets (often discordant in detail to the foliation in their country rock) are common, for example, in Djævlekløften, Snestormdal, Eremitdal (all in Andrée Land) and Knækdalen (Frænkel Land).

Very large granite bodies of certain Caledonian age occur in north-west Louise Boyd Land, Goodenough Land, and the Stauning Alper. Vertical dimensions may be of the order of 500–1000 m, whole mountains being built up of massive, homogeneous granite. Such granites may contain large rafts of metasediments of the EBS, up to 100 m in size. Commonly the rafts lie in an orientation that shows that they have hardly been rotated during inclusion in the granite, suggesting that the granite was emplaced in sheets rather than as plutonic masses. Rafts that are clearly rotated also occur, but they are exceptions.

We have not found any 'Grejsdalen type' granites within the basement complexes we studied in Murgangsdalen, Knækdalen, Kap Hedlund and Skræntdal (Gletscherland).

The evidence of granite formation by partial melting of KR-EBS lithologies, together with the absence of similar granites in the crystalline basement complexes, is strong evidence that all Caledonian granites (and similar granites of possible older age) formed by anatexis of KR-EBS mica schists, and that they did not come 'from depth' through the crystalline basement.

Anatexis by dehydration melting of micaceous metasediments may take place at temperatures of 650–750°C, much too low to start melting of the much dryer orthogneisses that build up most of the basement complexes. A clear illustration of this feature was seen at Kap Hedlund, where there are layers of mica schist interleaved (perhaps tectonically) with the orthogneisses of the basement (Higgins *et al.* 1981). These mica schists contain a large proportion of granite and pegmatite as veins and sheets; the orthogneisses have none.

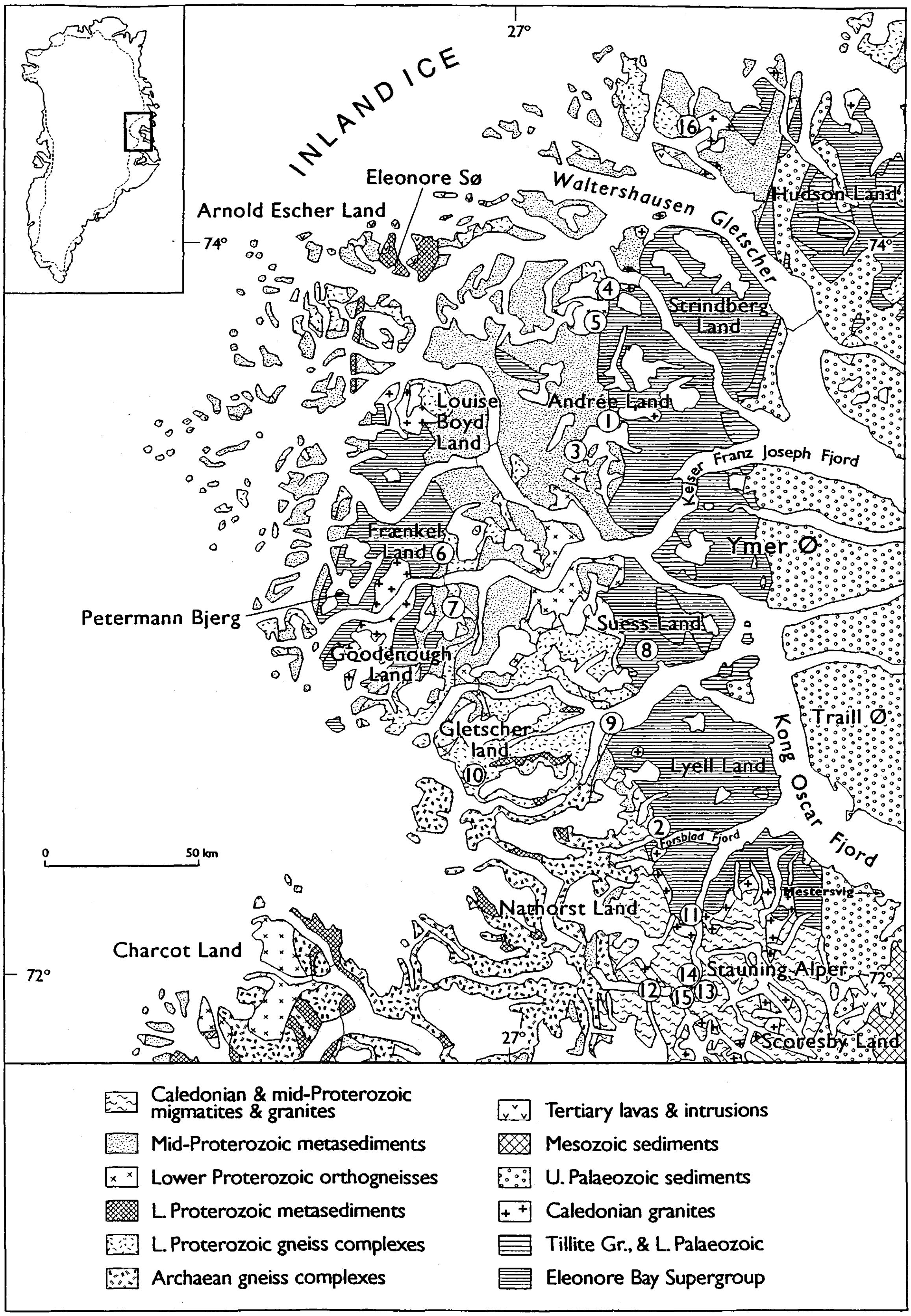

Figure 1. *Map showing place names and granite sampling sites. 1: Grejsdalen, 2: Randenæs, 3: Djævlekløften, 4: Snestormdal, 5: Eremitdal, 6: Knækdalen, 7: Goodenough Land, 8: Murgangsdalen, 9: Kap Hedlund, 10: Skræntdal, 11: Alpefjord, 12: Fureso, 13: Dammen, 14: Damslottet, 15: Spærregletscher, 16: Korsgletscher.*

The nature of the granites themselves supports an origin by melting of metasediments: felsic two-mica granites (our 'Grejsdalen type') are generally regarded as 'S-type' granites, formed by partial melting of metasediments, as contrasted to 'I-type granites' which form by anatexis of more mafic magmatic rocks (Chappell & White 1974).

Formation of the granites in this manner would fit well with the idea of crustal collapse towards the end of the Caledonian orogeny (Hartz & Andresen 1995). During extensional tectonism the crust is thinned, mantle rocks (or mafic magmas coming from the mantle) rise and may provide the necessary heat to cause melting at relatively high levels in the crust.

3. Stauning Alper

Large parts of the Stauning Alper and the area west of Alpefjord between Forsblad Fjord and Furesø consist of migmatites. Here (we think) the process of granite formation – generation, extraction, transport, and intrusion – can be followed within the extent of a few mountains, less than 4000 m vertically from the level of generation to the level of intrusion.

The area around Dammen, at the head of Alpefjord, contains beautiful exposures of migmatites (see Watt & Kinny 1998). The leucosome consists of non-deformed white biotite granite, full of remnants of mica schists in variable stages of digestion. Often the latter are very dark and biotite-rich, commonly with conspicuous garnet. Apparently they represent restite material after removal of a granitic fraction. Up to 75% of individual outcrops may consist of granite. Partly rounded blocks of quartzite lie randomly scattered within the migmatite. They have been little affected by the melting.

White, biotite-poor granite occurs both as the granitic parts of migmatites, as well as in sheets, up to ~10 m wide, with irregular borders towards the migmatite and with local migmatite inclusions. White granite also occurs as metre-size patches, free of inclusions, surrounded by migmatite. The field observations strongly suggest that the white granite was formed *in situ* and locally collected into larger patches and sheets. Commonly the granites contain aggregates with cordierite, suggesting melting took place at moderate to low pressures.

Apart from white granite, darker biotite-rich granite is also present. This commonly has centimetre-sized feldspar augen and many small (~5 cm) biotite-rich inclusions. Biotite-rich granite often occurs as decimetre-wide layers between screens of partly molten mica schist, but also as larger units, up to tens of metres or more wide. The field observations suggest that in this case much of the restite biotite was dispersed into the granite melt, making it darker than the white granite which left most restite material behind. This would be in agreement with a suggestion of Chappel *et al.* (1987) that much of the variation in granites may be due to variations in the extent to which restite material is expelled from the granitic magma.

The migmatites at Dammen also contain large inclusions (up to ~10 m) of homogeneous amphibolite, biotitised along their margins with granite-rich migmatites, and sometimes broken up into pieces by granite and pegmatite veins.

Near the coast at Dammen the migmatites do not show a clear tectonic fabric. Metasedimentary remnants, including quartzitic inclusions, have random orientations. Higher up, from ~100 m altitude, the migmatites become more organised with layering in the restites dipping 20–30° to the north-west. Up to ~500 m altitude the migmatites have a large proportion of restite, but this is very variable, and granite-dominated layers are also present. Higher up the proportion of restite decreases, and from ~700 m upwards most of the rock is granite.

White granite dominates the upper 1500 m of the mountain Damslottet. At 850 m it is distinctly foliated, but at 2050 m (helicopter locality) the granite is massive. On the south-facing inaccessible walls of Damslottet large angular rafts of metasediments (tens of metres in size) are exposed. These are full of concordant granite sheets. In the mountains further north the granite has large rafts of metasediments that belong to the lower part of the Eleonore Bay Supergroup. The latter appear hardly to have been affected by the intruding granite.

Further north in the region we have not seen migmatites similar to those exposed at Dammen. We think that this is due to a much deeper level of exposure in the south. Supporting evidence for this view is: (1) The deepest parts of the Eleonore Bay Supergroup are exposed in southern Alpefjord; and (2) Mountains around western Furesø and further north-west are topped by a peneplain at ~2000 m. The rugged mountains of the Stauning Alper, with altitudes of up to >2800 m do not show remnants of this peneplain, suggesting late differential uplift of the Stauning Alper region of the order of 1 km or more relative to the western and north-western parts of the region. The rocks at Dammen and Spærregletscher have numerous joints with slickensides which may be related to this period of uplift.

It would seem likely that migmatites, similar to those at Dammen, are present beneath other areas with large amounts of granite, such as in Louise Boyd Land and Goodenough Land.

4. Sampling and analytical programme

Most of our samples are from 'Grejsdalen type' granites, from KR-EBS mica schists, and from granitoid rocks from the older crystalline basement. The most immediate aims of the analytical work will be:

1. To date the granites with the help of ion-probe zircon analyses or other means, and to see whether or not some of them are of Grenvillian age. Dating by SHRIMP U-Pb zircon data may be difficult because it is likely that zircons of different generations will be present, and it may not be easy to decide which generation dates the emplacement of the granite. Low-temperature S-type granites commonly only have small proportions of new magmatic zircon, sometimes only as rims that may be too narrow to be analysed.
2. To compare the zircon-age distribution in the granites with that of detrital zircons from KR-EBS mica schists, to test the model that the granites formed by melting of the metasediments. Moreover we aim at obtaining Sr and Nd isotope data on the granites and the metasediments as a further test of this model.
3. If the results of the analyses support the general model we will use major and trace element data on granites, mica schists and restite material to obtain mass balance estimates – how much granite can be extracted from a given quantity of metasediment?

Furthermore, since in our case the characterisation of the granites as S-types is based on their field occurrence – independent of geochemistry – it will be interesting to see how far the geochemical criteria will agree with the field evidence.

4. With the help of age determinations on detrital and metamorphic zircons from mica schists it may be possible to obtain information on the time of deposition. This may have implications for the tectonic history of the region. For example: if the mica schists that are embedded in Early Proterozoic gneisses at Kap Hedlund contain detrital zircons of Grenvillian age (cf. Strachan *et al.* 1995), then they must have been tectonically emplaced into the gneisses, a possibility suggested by Higgins *et al.* (1981).
5. More generally, we hope with the help of our analytical data to be able to obtain a better understanding of the relative importance of Grenvillian *vs.* Caledonian events in the region.

5. Postscript – the evidence for Grenvillian metamorphism and granite formation

Isotopic evidence for Grenvillian metamorphism and granite formation has been presented for the Scoresby Sund region to the south of the present study area by, for example, Hansen *et al.* (1978) and Steiger *et al.* (1979). To the north Strachan *et al.* (1995) report SHRIMP U-Pb data for zircons from a metasedimentary gneiss from the Smallefjord sequence (75°–76°N), and suggest that these rocks have experienced metamorphism around 950 Ma ago. It would therefore appear likely that the area between 72° and 74°N has also undergone Grenvillian metamorphism, but evidence that this is indeed the case is as yet less certain.

Rex *et al.* (1977) and Rex & Gledhill (1981) report Rb-Sr whole rock data for granitic and metasedimentary rocks from the area covered by the present study. Many of the investigated sample suites did not yield useful age information, but for a number of data sets isochron (or errorchron) ages were calculated. A few of these suggested Grenvillian ages in the range of 1000–1200 Ma. However, most of the 'isochrons' are poorly fitted and should be regarded with great reservation. We have analysed a number of Rex & Gledhill's data sets with help of the 'bootstrap' method (an alternative to the usual isochron calculations to determine the precision of ages and initial Sr-isotope ratios; Kalsbeek & Hansen 1989). Two examples are given below.

Quartzitic gneisses from Forsblad Fjord

Rex *et al.* (1977) analysed 12 samples of metaquartzitic gneisses from a locality in inner Forsblad Fjord and (after rejecting one of the analyses) calculated an errorchron age of 1245±100 Ma. This result was used by Higgins *et al.* (1977) to challenge the view of Caby (1976) that the metasedimentary rocks in inner Forsblad Fjord represent the lower part of the Eleonore Bay Group. Figure 2A shows the distribution of 10 000 ages obtained by the bootstrap method. This distribution encompasses dates between 1000 and 2000 Ma with a peak at about 1500 Ma, and does not support the age given by Rex & Gledhill (1976). We do not believe the isotopic data in question can be interpreted in terms of age of deposition

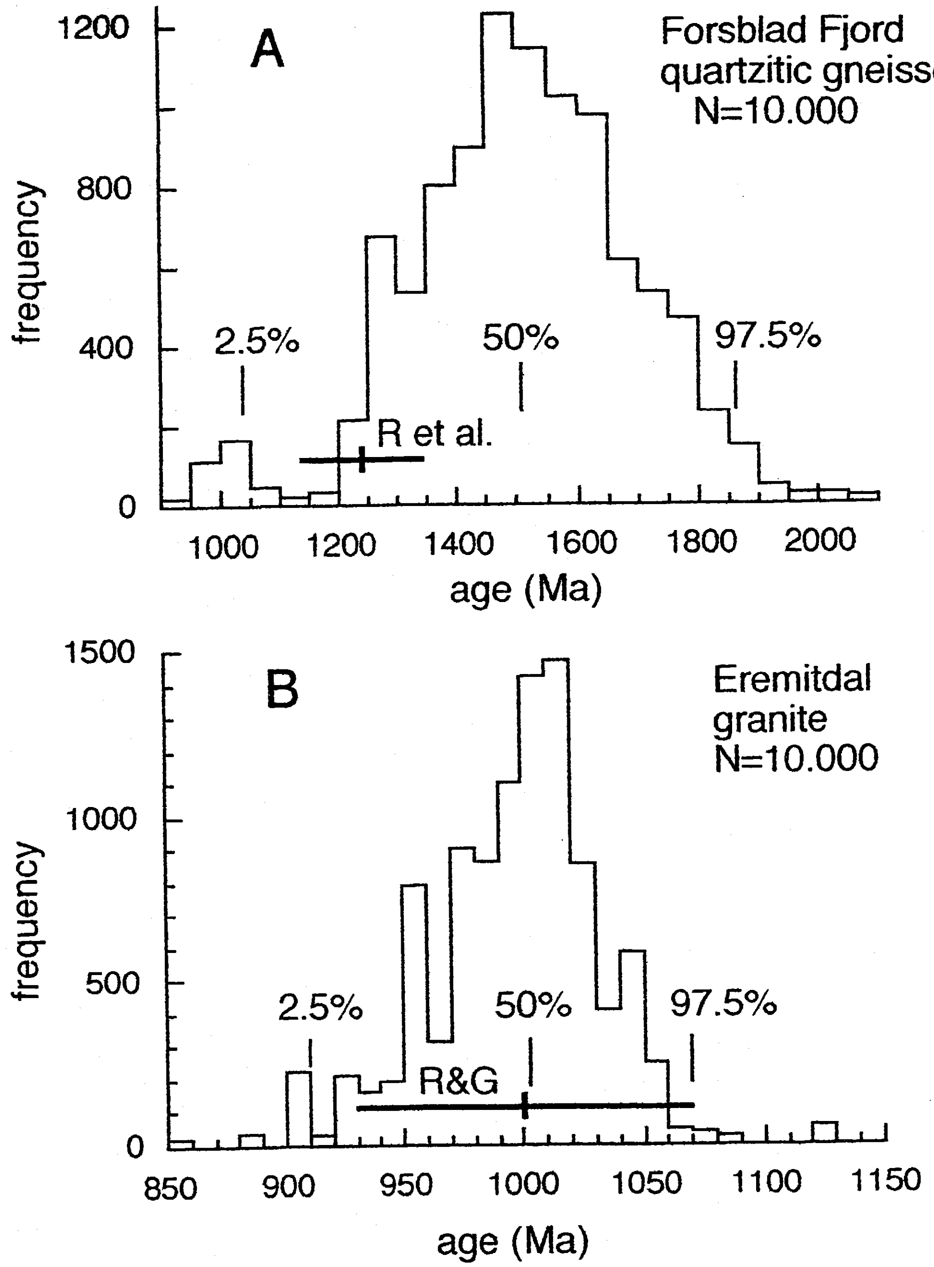

Figure 2. *Bootstrap analysis of Rb-Sr data from Rex et al. (1977) and Rex & Gledhill (1981) compared to the ages reported by these authors.*

or metamorphism of the rocks. The same is true for data sets obtained for other collections of metasedimentary rocks.

Eremitdal granite

Rex & Gledhill (1981) obtained a 1000±70 Ma Rb-Sr whole rock isochron age for a foliated muscovite granite from Eremitdal (8 samples, one not used in the isochron calculation). This is a reasonably well fitted isochron (MSWD 2.8), and the age calculation is confirmed by bootstrap analysis (Fig. 2B) which yields ages of 1000 +70/-90 Ma (2σ). Although linear arrays in isochron diagrams can in some cases be interpreted as mixing lines without chronological significance (see e.g. Faure 1986, p. 147), such pseudoisochrons are rarely as well defined as the isochron obtained by Rex & Gledhill (1981) for the Eremitdal granite. We therefore regard the 1000 Ma age of the Eremitdal granite as strong evidence for Grenvillian granite formation, although, as Rex & Gledhill (1981) point out, further confirmation is needed.

None of the other 'older granites' investigated by Rex & Gledhill (1981) has yielded reliable isochrons, and all ages in the range of 500–800 Ma should be regarded with reservation unless confirmation by independent means is obtained.

Zircon U-Pb data for foliated muscovite granite 344986 from Korsgletscher

A sample from this granite was obtained in 1990, and Rb-Sr whole rock data yielded a model age of ~1050 Ma (Kalsbeek *et al.* 1993). Zircons from this sample were analysed by SHRIMP at the Australian National University, Canberra, by one of us (F. K.) under the direction of A. P. Nutman. Most zircons are water-clear with somewhat irregular shapes. A number of brown grains are also present; some of these have distinct cores and rims. Fifteen spots were analysed. Eleven of these (10 on clear grains, 1 on a brown grain) gave near-concordant data with $^{206}Pb/^{238}U$ ages ranging between 780 and 950 Ma (Fig. 3).

Four analyses were made on a large (300 μm) brown grain, one on the core and three on the rim. They yielded much younger ages, 540, 442, 411, and 350 Ma. These four spots are characterised by very low Th/U ratios (0.01–0.05, compared to 0.16–0.69 for the other grains, Table 1). Such low Th/U ratios are characteristic for zircons grown during high-grade metamorphism (Williams & Claesson 1987); accordingly we interpret this grain as a

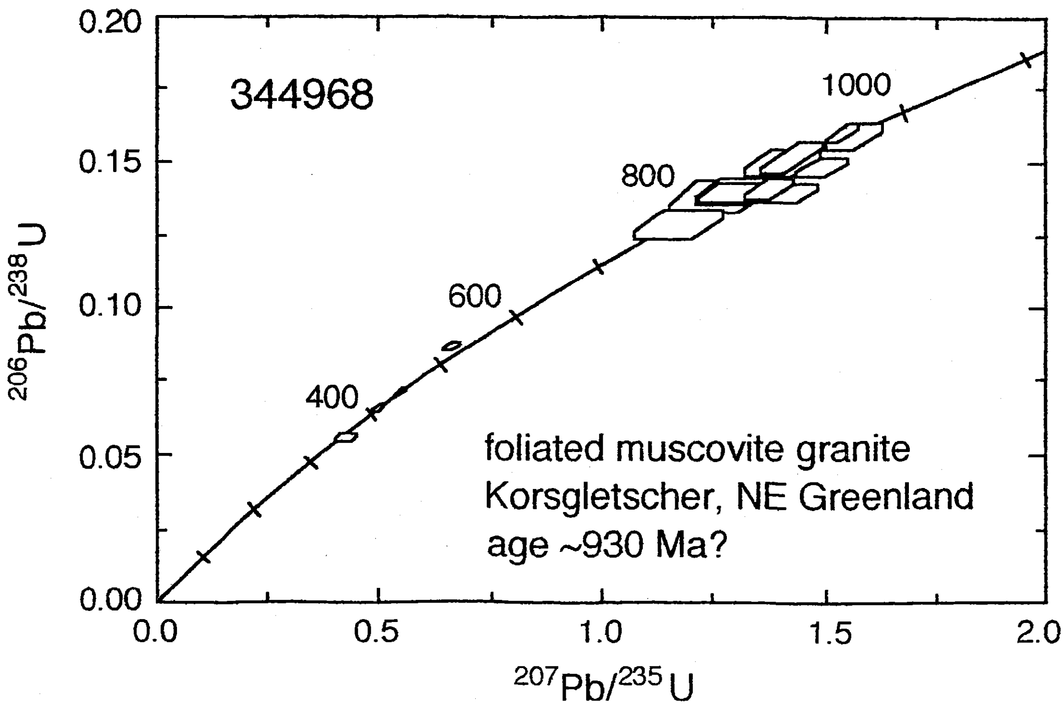

Figure 3. *Concordia diagram for SHRIMP zircon data on zircons from GGU 344968, a foliated muscovite granite from Korsgletscher (74°19.2'N, 25°13'W).*

Table 1. Summary U-Th-Pb data for zircons from metagranite 344968, North-East Greenland

Spot	U (ppm)	Th/U	f_{206} (%)	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	age*	disc. (%)
1.1	152	0.66	0.01	0.1396±35	0.0674±34	842±20	-1
2.1	90	0.39	0.02	0.1378±55	0.0664±49	832±31	2
3.1	89	0.69	0.03	0.1287±53	0.0661±45	780±30	-4
3.2	81	0.57	0.01	0.1398±44	0.0673±35	843±25	0
4.1	270	0.26	0.00	0.1487±35	0.0729±20	893±20	-12
5.1	303	0.23	0.00	0.1411±38	0.0707±19	851±22	-10
6.1	333	0.01	0.08	0.0559±13	0.0552±27	351±08	-16
6.2	4880	0.02	0.03	0.0659±12	0.0549±07	412±07	1
6.3	4474	0.02	0.03	0.0711±15	0.0558±04	442±09	0
6.4	11,808	0.05	0.02	0.0868±17	0.0551±10	537±10	29
7.1	184	0.18	0.01	0.1590±43	0.0714±20	951±24	-2
8.1	569	0.56	0.02	0.1394±35	0.0732±35	841±20	-17
9.1	104	0.49	0.02	0.1499±48	0.0680±33	900±27	4
10.1	251	0.34	0.01	0.1519±57	0.0682±17	912±32	4
11.1	2218	0.16	0.00	0.1601±32	0.0698±08	957±18	4

f_{206} is the proportion of ^{206}Pb that is not radiogenic; age * is the apparent $^{206}Pb/^{238}U$ age; disc. is the degree of discordance between the $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages. All errors quoted at 1 σ level.

metamorphic zircon formed during Caledonian metamorphism. Unfortunately the data are too scattered for further interpretation of these four analyses.

The scatter in apparent ages observed for the other zircons is most plausibly intepreted as the result of variable loss of radiogenic Pb. If this interpretation is correct the oldest ages obtained from this group (~930 Ma) should refer most closely to the time of emplacement of the granite.

We conclude that there is indeed strong evidence for the presence of Grenvillian (*sensu lato*) granites in the region. Consequently, parts of the supracustal KR-EBS sequences have to be older than ~1000 Ma. However, as pointed out by Leslie & Higgins (1998), there is no evidence for Grenvillian deformation or the presence of an angular unconformity between the older group of metasediments and the Eleonore Bay Supergroup.

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Field observations and preliminary sedimentary interpretations of the marine shallow-water platform and slope carbonates of the Upper Proterozoic Andrée Land Group, East Greenland

Kasper S. Frederiksen & Lorraine E. Craig

Abstract: Various sedimentary lithologies and structures of the Upper Proterozoic Andrée Land Group in Andrée Land, Strindberg Land, Ymer Ø, Suess Land, Ella Ø, and Scoresby Land, East Greenland are described. These include various types of intertidal and/or subtidal stromatolites, oolitic/pisolitic shoal/barrier complex limestones, tidal channel dolomite breccias and conglomerates, limestone tempestite couplets and shaly limestone turbidites. Based on sedimentary and stratigraphic evidence it is suggested that the Andrée Land Group represents a carbonate ramp, probably distally steepened. Part of the Andrée Land Group is dolomitised. At least two generations of dolomitisation are recognised, an early selective dolomitisation which picked out stromatolites, breccias and conglomerates, and a later dolomitisation associated with faults and folds.

KSF: *Geological Survey of Denmark and Greenland, Thoravej 8, 2400 Copenhagen NV, Denmark*
LEC: *Royal Geographical Society, 1 Kensington Gore, London SW1 2AR, U.K.*

Field work in July–August 1997 was focused on collection of data for a sedimentological and stratigraphic analysis of the Upper Proterozoic Andrée Land Group (Eleonore Bay Supergroup) in East Greenland.

Six localities were visited (Andrée Land, Strindberg Land, Ymer Ø, Suess Land, Ella Ø, and Scoresby Land) between latitudes 72° and 74°N (Fig. 1). These six localities represent the widest range of palaeoenvironments in the study area, and may thus form the basis for the most complete picture of the Late Proterozoic palaeogeography of the East Greenland Basin. For logistical reasons the easternmost outcrops of the Andrée Land Group in Steno Land, Ole Rømer Land, and Hudson Land were not visited in 1997, and a planned locality in Lyell Land was omitted because of lack of time; these will be studied in the 1998 field season.

This study of the carbonates of the Andrée Land Group is funded by the Danish National Science Foundation. It forms a part of the 1997–1998 project of geological investigations in the southern part of North-East Greenland undertaken by the Geological Survey of Denmark and Greenland.

1. Stratigraphy

The Andrée Land Group (originally “Die Kalksten-Dolomit Serie” of Teichert (1933) and commonly known by its English translation as the “Limestone-Dolomite Series”, e.g. Haller 1971) was formally redefined by Sønderholm & Tirsgaard (1993). It is the uppermost group of the Eleonore Bay Supergroup (Fig. 2). The Nathorst Land, Petermann Bjerg, Lyell

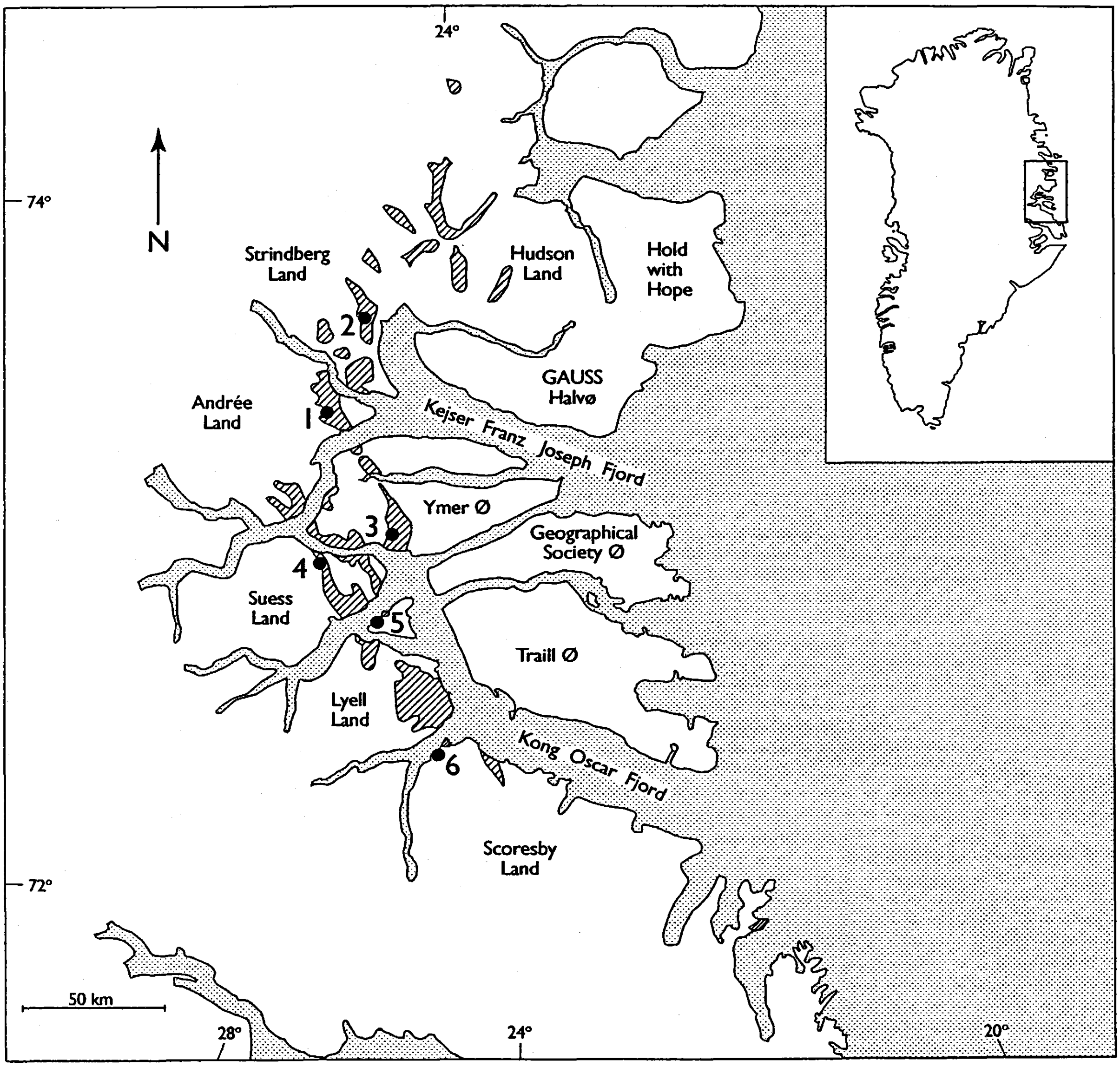
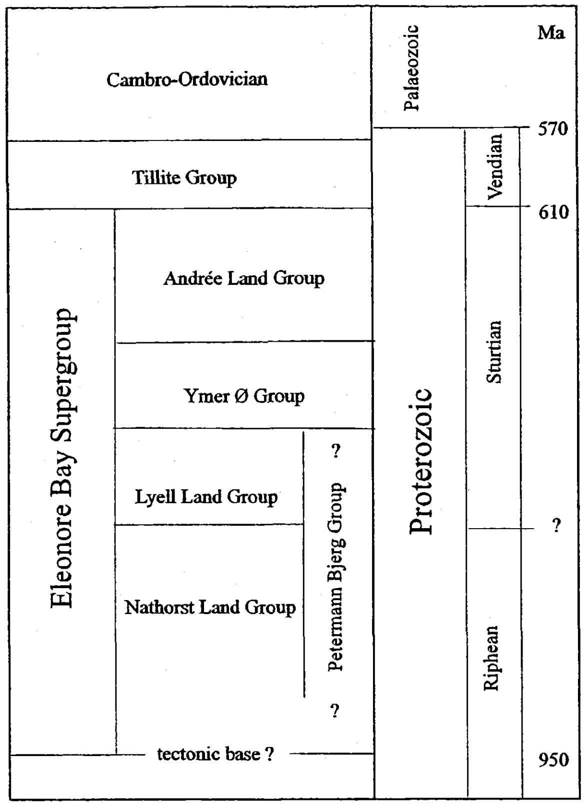


Figure 1. *Map showing the distribution of the Andrée Land Group, and the positions of localities 1–6 described in the text.*

Land and Ymer Ø Groups make up the lower and middle parts of the Eleonore Bay Supergroup, which is in general characterised by an upwards evolution from coarse siliciclastic deposition through mixed siliciclastics to carbonate deposition at the top (Katz 1952; Fränkl 1953; Caby & Bertrand-Sarfati 1988; Herrington & Fairchild 1989; Sønderholm & Tirsgaard 1993). The Andrée Land Group comprises limestones, dolomites and shales; no coarse siliciclastic sediments occur. The lower boundary with the Ymer Ø Group is sharp, and is placed by Sønderholm & Tirsgaard (1993) at the abrupt change from yellow and red, recessive interbedded dolomite and siliciclastic mudstone (top of Ymer Ø Group) to cliff-forming yellow-weathering dolomite. The upper boundary with the Tillite Group may be sharp or transitional, and in some places is a thrust. The boundary is easy recognisable as

Figure 2. *Present lithostratigraphic scheme for the Eleonore Bay Supergroup, slightly modified after Sønderholm & Tirsgaard (1993).*



it is marked by the transition from carbonate to diamictite. The Andrée Land Group is divided into seven formations AL1–AL7, which from bottom to top correspond to "bed-groups 14–20" of earlier workers (see Sønderholm & Tirsgaard 1993). These formations are not yet formally defined because of unresolved problems concerning both the stratigraphy and the nature of the dolomitised horizons.

2. Description of localities

Andrée Land (Locality 1)

Locality 1 (Fig. 1), the type locality of the Andrée Land Group, is situated in Andrée Land, north-east of the mouth of Grejsdalen (73°29.16'N, 25°05.66'W). The Andrée Land Group crops out in an E–W trending stream section between sea-level and 900 m altitude, ending at a prominent, white dolomitic cliff-forming layer. The inaccessible dolomitic cliff is formed by the upper formation of the group and is continuous to an altitude of 1175 m, where the boundary to the overlying Tillite Group is exposed. The lower part of the formation AL1 and the lower boundary of the Ymer Ø Group are not exposed. The outcrops of the Andrée Land Group at this, the type locality, are extremely good.

Strindberg Land (Locality 2)

Locality 2 is situated in Strindberg Land on the west-facing slopes of Blokken (73°45.75'N, 24°40.31'W). The Andrée Land Group crops out north-east of Brogetdal in a series of small cliffs and dip slopes between 580 m and 1240 m altitude. The boundary between the Andrée Land Group and the underlying Ymer Ø Group is well exposed. The upper boundary with the Tillite Group is inferred to occur in a snow-covered gully concealing an estimated maximum 30 m of the section. Local easterly plunging minor folds and NE–SW trending faults were observed to the east of the measured section. A complete section exists at this locality, although formation AL2 could not be identified, and hence the boundaries of formations AL1 and AL3 were not determined. The total thickness of the measured section is 990 m. In general the quality of the outcrops is poor.

Ymer Ø (Locality 3)

Locality 3 is situated in south-eastern Ymer Ø, south-east of Margerie Dal (73°06.26'N, 24°51.54'W). The lower and upper boundaries of the Andrée Land Group with respectively the Ymer Ø Group and the Tillite Group are excellently exposed. The total thickness is 897 m. The exposures of this section typically occur in cliff-forming ridges and are of high quality.

Suess Land (Locality 4)

Locality 4 is situated in northern Suess Land on the north-west facing slopes of Trugbjerg (73°06.69'N, 25°45.69'W). Both upper and lower boundaries of the Andrée Land Group are well exposed. The sequence crops out in a gorge on the western side of Nanortalik Dal and in cliff-forming ridges on Trugbjerg. The total thickness of the section was measured at 1042 m. Exposures are of low quality, comparable to those in Strindberg Land (Locality 2).

Ella Ø (Locality 5)

Locality 5 is situated on Ella Ø at Kap Oswald (73°52.92'N, 25°08.08'W). Only a part of formations AL5 and AL6 are exposed at this locality, with the boundary to the Tillite Group observed in a smaller stream section just north-west of Ella Ø Station. The total thickness is 891 m. The rocks occur as small ridges folded into a anticline. The quality of the outcrops is excellent.

Scoresby Land (Locality 6)

Locality 6 is situated in northern Scoresby Land, west of Kap Petersséns (72°25.00′N, 24°51.30′). The succession at this locality contains formations AL1–AL6. The lower boundary of the Andrée Land Group with the Ymer Ø Group is excellently exposed in a steep cliff-section. The total thickness of the measured sequence, which crops out in a series of small and large ridges, was 855 m. The upper 20 m of the succession were too deformed to be logged, and the upper boundary of the group is not exposed.

3. Methods

At each locality a detailed sedimentological section was measured on a scale of 1:200 in order to establish a facies division. In some cases a more detailed log was made to record sedimentary changes. A summary log for each locality is presented in this report based on the 1:200 scale logs (Fig. 3). Detailed data on lithology, structure, texture, grain size, grain composition, bed thickness, boundaries, rock type associations etc were collected. At all of the localities samples of the different rock types were collected, mainly for thin section studies and rock slab preparation.

4. Sedimentology

A range of limestones and dolomites with variable sedimentary features were identified. The colour of the limestones ranges typically from medium grey to very dark grey, while the dolomites of formations AL2 and AL4 may be white, yellow, or light grey. The dolomitised rocks of formation AL1 are yellow to buff-coloured. In formation AL6 the dolomitised rocks range in colour from chocolate-brown, red-purple, green or yellow to buff, which may be caused by variable contents of clay or micrite. The limestones and dolomites are typically very fine to medium-fine sand, whereas breccias and conglomerates are usually composed of very coarse sand to pebbles. Each lithology, and most of the structures occur in different grain size fractions. Poorly exposed rocks were logged as 'structureless dolomite or limestone', and are not described below. The deposits and structures characteristic of the Andrée Land Group are:

- Stromatolites, which are mostly dolomitised, are white, grey, cream or black in colour. They occur in a wide range of varieties, as subhorizontal laminae, wavy laminae, domal, columnar (up to 25 cm) and bulbous (up to 20 cm) forms. Branching forms with up to 8–10 branches on a single individual are seen, but simple bifurcated forms are most common. Occasionally the stromatolites form mounds up to 3.5 m high and 10 m wide (e.g. on Ella Ø and in Scoresby Land). The sediment infill between the stromatolites comprises mostly slumped breccias with a very high density of stromaclasts (20–60% dependent on morphology of the stromatolites) in a grey, white, purple, or brown muddy carbonate matrix. In Scoresby Land, in formation AL1, lenses of blue-greyish fining upward limestone up to 40 cm thick occur between the stromatolitic mound structures. They have curved erosional bases containing minor amounts of clast material.
- Dark grey, moderately to poorly sorted, oolitic to pisolitic limestones usually have ooids/pisoids from 1 to 4 mm in diameter, but pisoids as large as 12 mm have been observed. The concentric growth laminae in the ooids and pisoids was thus often clearly visible without a hand-lens. Oolitic to pisolitic limestones occur in beds up to *c.* 1 m thick. They are often cross-bedded and may form lenses up to 3–4 m long with erosional bases. The lenses are usually coarser-grained than the surrounding fine-grained non-oolitic/pisolitic limestones. Beds of oolitic or pisolitic limestones are commonly normally or inversely graded.
- Breccias or conglomerates, which are mostly dolomitised, are usually white or grey in colour. Three main types have been recognised: (1) Slumped breccias with flat pebble

clasts, either stromaclasts (typical 6–8 cm long, 0–2 mm wide needle-like clasts) or clasts of broken laminae or beds (typically 10–12 cm long); (2) slumped poorly sorted breccias of very coarse angular clasts (up to 10–20 cm in diameter) commonly with a large content of ooids or pisoids; and (3) conglomerates, either cross-bedded (planar or trough), fine-grained or structureless very coarse pebble to cobble conglomerates (up to 20–25 cm clasts). The breccias and conglomerates usually have erosional bases, which may be channel-shaped. In Scoresby Land, some conglomerate bases are irregular with a relief of up to 40 cm. Partly eroded domal stromatolites are commonly attached to the bases.

- Couplets of dark grey, fine-grained, structureless 10–30 cm thick limestone beds which are overlain by dark grey, very fine-grained, horizontal or wavy-laminated limestone beds 1–15 cm thick. The boundary between the fine-grained structureless and very fine-grained laminated part is usually sharp. The couplets occur as sheets, but sometimes also as lenses because of erosion between the individual couplets. The couplets, usually 10–40 cm thick, are arranged in stacked cycles, typically 2.5 m thick with distinctive erosional bases. Couplets form the most common deposit type in the Andrée Land Group.
- Normally graded, very fine-grained limestones occur in a wide range of colours including grey, green, red-purple, chocolate-brown, yellow and cream. The normally graded beds are characterised by a basal part with clasts up to 1 cm in diameter, a middle structureless part, and an upper horizontal or ripple-laminated part. Beds are between 3 cm and 2 m thick. Commonly, beds lack the basal parts or the upper parts due to erosion.

The Elisabeth Bjerg Formation, the uppermost formation of the Ymer Ø Group and directly overlain by the Andrée Land Group, is interpreted as representing a siliciclastic-carbonate ramp system (Tirsgaard 1996). Sedimentary data from the present field work support a carbonate ramp system setting for the Andrée Land Group. Sedimentary features such as channel incision, widespread cyclic deposits, widespread structureless limestone-laninated limestone couplets and widespread wave-agitated limestones, which according to the definition of Read (1982, 1985) are very characteristic of carbonate ramps (both homoclinal and distally steepened ramps), have all been recorded in the Andrée Land Group.

It is envisaged that the shelf during Andrée Land Group time was a distally steepened carbonate ramp with a back-ramp lagoon sheltered behind an inner shallow ramp barrier or shoal. On the seaward side of the barrier or shoal a deeper ramp and deep basin is presumed to have existed.

The stromatolites probably represent an intertidal back-ramp lagoon environment sheltered behind an inner shallow ramp barrier or shoal complex. Their structural morphology clearly shows variable energy conditions during growth caused by either intrinsic or extrinsic factors. The close association between stromatolites, sometimes slumped, and breccias with stromaclasts suggests periodic unstable conditions, and with common erosion of the shallow marine areas. However, it cannot be excluded that stromatolites grew in a subtidal environment on the seaward side of the inner shallow ramp barrier or shoal complex. The cross-bedded, fining-upward conglomerates commonly found in close association with lenses of oolitic limestone probably represent channel fill from tidal channels cutting through the inner shallow ramp barrier or shoal complex. The irregular conglomerate bases described above may represent palaeokarst surfaces. Such palaeokarst surfaces are formed during long-lived periods of subaerial exposure, due to reaction between soluble carbonate minerals and rainwater (e.g. Tucker & Wright 1990). It is therefore more likely that the conglomerates represent the inner shallow ramp than the slope environment. Ooids and pisoids are usually formed in very shallow marine settings, generally at depths of less than 2 m (Tucker & Wright 1990). The cross-bedding, grading, and lensing of the oolitic and pisolitic limestone beds suggest that they represent tidally influenced channel bars within the inner shallow barrier or shoal complex itself. The limestone couplets are probably the result of the cyclic accumulation of sediment on the deeper ramp. Although no hummocky cross-bedding has yet been identified, the limestone couplets are interpreted as transported from the inner ramp to the deeper ramp during storm events (e.g. Dott & Bourgeois 1982; Tucker & Wright 1990). The normally graded limestones are interpreted as turbidites as they display a number of the characteristic features of Bouma T_{abcde} sequences (e.g. Stow 1986). They were deposited on the slope from the deeper ramp to the deep basin.

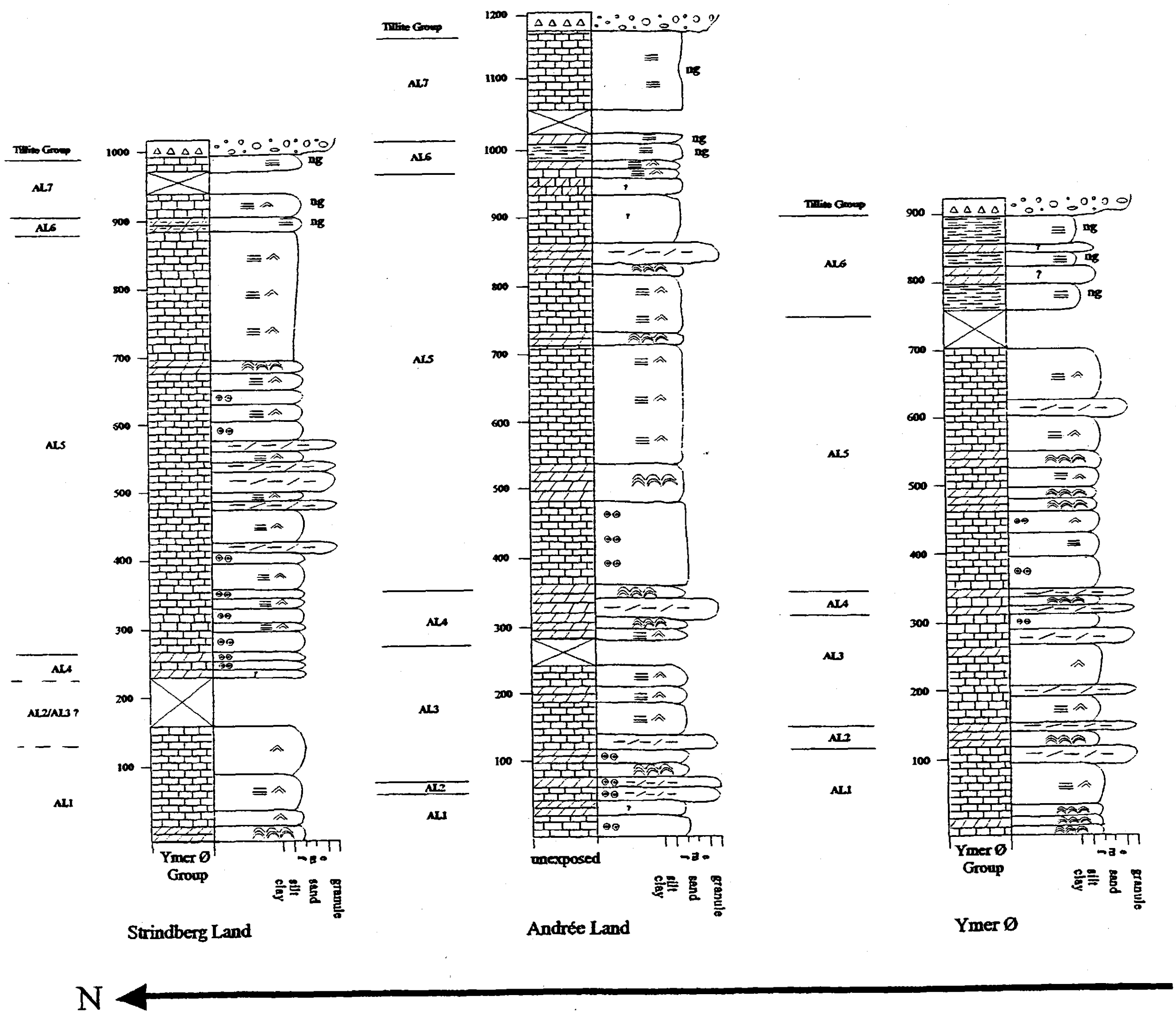
The summary logs (Fig. 3) show a distinct vertical sedimentary development at all localities reflecting a large-scale deepening upwards trend. For example, the log of the Ymer Ø section shows from 0–550 m deposits from the inner ramp lagoon and barrier/shoal complex interbedded with deposits from the deeper ramp, and from 550–900 m deposits from the deeper ramp interbedded with deposits from the slope and deep basin. Similar trends can be identified at the other five localities. Numerous smaller scale deepening-upwards trends have been recognised on the 1:200 logs at all localities: e.g. stromatolites (inner ramp lagoon) are overlain by oolitic/pisolitic limestones (inner ramp barrier/shoal) which are overlain by limestone couplets (deeper ramp). Occasionally this smaller scale deepening-upwards trend is followed by a shallowing-upwards trend; i.e. stromatolites (the inner ramp lagoon) are followed by oolitic/pisolitic limestones (inner ramp barrier/shoal).

North–south and east–west variations between the localities can be discerned. Thus, the southernmost locality in Scoresby Land has a high proportion of cross-bedded limestones and cross-bedded channel-formed limestone conglomerates compared to the five other, more northern, localities. Similarly, a higher proportion of shallow ramp deposits has been observed in the west than to the east. However, these variations may be caused by differences in the occurrence of gaps in the section logs.

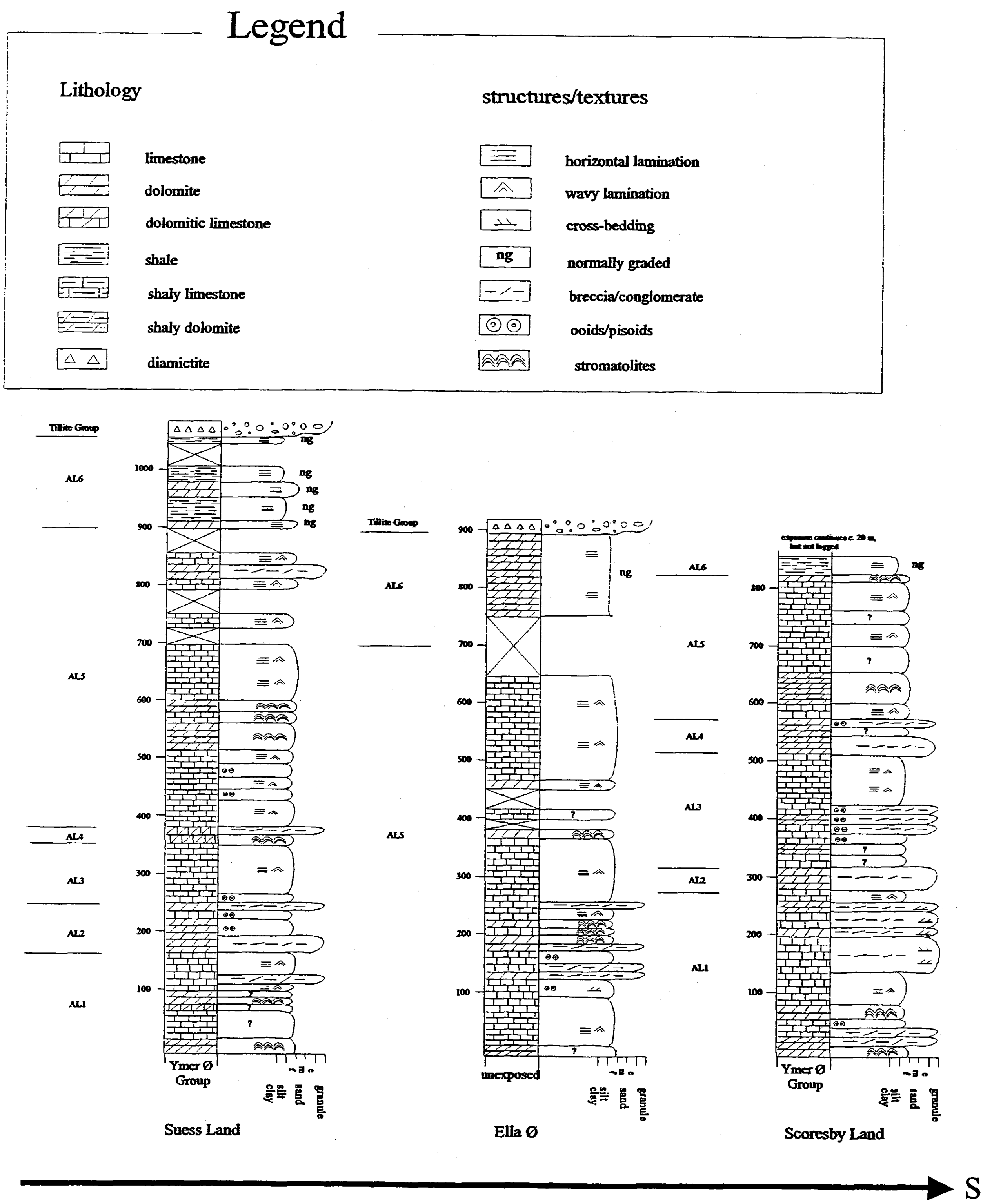
5. Diagenesis

Dolomitisation of the limestone has been recorded throughout the Andrée Land Group. The dolomitisation appears as units up to 50–100 m thick. Some of the dolomitised units (formations AL2, AL4 and AL6) have been given formation status in the present lithostratigraphic subdivision of the Andrée Land Group (Sønderholm & Tirsgaard 1993), while other thick dolomitised units, such as the base of formation AL1 and AL5, have not been assigned as formations. The boundaries between the limestone and dolomite units are in places very sharp and abrupt, and in other places gradual over 1–3 m. Examples have

Figure 3. *Section logs from the six localities studied in 1997. From north to south: Strindberg Land, Andrée Land, Ymer Ø, Suess Land, Ella Ø and Scoresby Land. The inferred lithostratigraphic subdivision (formations AL1–AL7) is also shown.*



been noted where dolomitisation cuts across bedding and forms laterally discontinuous units. On Ella Ø and in Scoresby Land the thickness of dolomite units may thus vary by up to 10–15 m over a lateral distance of 500–600 m. Field observations show several gen-



erations of dolomitisation in the Andrée Land Group. Most of the stromatolites and breccias are dolomitised, which suggests an early, selective dolomitisation. However, dolomitic veins, often highly crystallised, associated with minor folds and post-sedimentary faults indicate later dolomitisation. Dolomitisation may also be associated with other diagenetic mineralisations such as iron formation (crystals of pyrite and pyrotite were found in Andrée Land and Suess Land) and chert formation.

Lithostratigraphic description and subdivisions of the Andrée Land Group have been presented in a number of studies from East Greenland (e.g. Katz 1952; Fränkl 1953; Eha 1953; Sommer 1957; Herrington & Fairchild 1989). The formation subdivision of the Andrée Land Group is essentially based on the transitions between limestone and dolomite.

It is not the aim of this report to discuss the lithostratigraphic subdivision of the Andrée Land Group in detail. However, it may be noted that are several problems with the present lithostratigraphic subdivision because of the scale of the irregular, and commonly cross-cutting dolomite units. Since north–south and east–west variations in lithologies caused by highly irregular dolomitisation and depositional environments are now known to exist, the nature of the formations AL1–AL7 also varies, which makes them sometimes difficult to identify. The presently recognised formations are indicated on the summary logs (Fig. 3).

6. Concluding remarks

The 1997 field work was very successful. Fortunately, the majority of outcrops are of a reasonably good quality, which will make detailed sedimentary and stratigraphic analysis possible in the remaining years of this study. Dolomitisation and weathering are present throughout the Andrée Land Group, but neither have obliterated all the primary sedimentary textures and structures. Future thin section work should provide important information on the morphologies of the coated grains in the oolitic and pisolitic limestones, and on the nature of the clast assemblages of the breccias and conglomerates. The 1997 field work clearly suggests that the Andrée Land Group provides an excellent opportunity to analyse the sedimentary, tectonic, and climatic development within a sequence stratigraphic framework. These initial interpretations of the sedimentary depositional system are preliminary, and may be revised several times during the duration of the project. Furthermore, the dolomitisation provides many interesting problems, although it is likely that a detailed study of the dolomitisation is beyond the scope of this project. In addition to the locality in Lyell Land and the easternmost regions of Ole Rømer Land, Hudson Land, and Steno Land which it is planned to visit in 1998, it may be worth revisiting some of the 1997 localities.

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Mineral resource investigations in the Caledonian crystalline complexes between Andrée Land and Lyell Land, East Greenland

Henrik Stendal & Maj B. Wendorff

HT, MBW: *Geological Institute, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark*

The aim of the field work in 1997 was to delineate the mineral potential of different geological scenarios within the Caledonian crystalline complexes of East Greenland (Fig. 1). The chosen targets were major tectonic lineaments in the crystalline metamorphic complexes and granites. The field work was carried out within the scope of the 1997–1998 regional mapping programme of the Geological Survey of Denmark and Greenland which centres on the region 72° to 75°N.

Our field work was carried out in: Andrée Land – five camps (Grejsdalen, Junctiondal, Jomsborgdal, Djævlekløften and Luciagletscher); Suess Land – one camp (Murgangsdalen); Lyell Land – two camps (Kap Hedlund and west of Randenæs); additional sampling was carried out using a helicopter in Suess Land and on Ymer Ø.

1. Sampling and analysis

The sample collections consist of stream sediments (90), heavy mineral concentrates (56) and rocks (grab and chip samples, 113). Most of the samples will be analysed for their metal contents by a variety of methods (INAA, ICP, XRF and AAS) mainly by commercial laboratories. At present chemical data is only available for the < 100 μm fractions of the stream sediment samples analysed by INAA and ICP. For the ICP analyses, values from total digested samples are used.

2. Background

Mineralisation patterns in the East Greenland Caledonides have been reviewed by Stendal & Ghisler (1984), on the basis of investigations carried out during the decade 1974–1984 by the University of Copenhagen in collaboration with the former Geological Survey of Greenland and Nordisk Mineselskab A/S (The Northern Mining Company Ltd.). These investigations were mainly concentrated on the Late Proterozoic Eleonore Bay Supergroup and were focused on copper (Ghisler *et al.* 1980; Stendal & Hock 1981), arsenic (Stendal 1982a) and tungsten (Hallenstein & Pedersen 1983; Pedersen & Stendal 1987). In 1979 a geochemical exploration program for scheelite in a 100 000 km^2 area of East Greenland was undertaken by Nordisk Mineselskab A/S as a part of the project "A study of scheelite mineralisation in East Greenland" with the support of the Commission of the European Communities (Hallenstein *et al.* 1981). A general framework of mineralisation in East Greenland has been given by Harpøth *et al.* (1986), and Thomassen (1990) has delineated some targets for gold exploration.

3. Present study

The investigations carried out during the present study can be conveniently described in terms of their settings: those related to a major detachment zone, vein-related mineralisation, and other types of mineralisation.

Detachment zone

The tectonic zone between the Neoproterozoic sediments (Eleonore Bay Supergroup: EBS) and the underlying Palaeoproterozoic to Mesoproterozoic crystalline metamorphic complexes has been studied in Junctiondal on Andrée Land, in Murgangsdalen on Suess Land and at Kap Hedlund in Lyell Land. This zone has been named the "Fjord Region Detachment" zone by Andresen *et al.* (in press). Hartz & Andresen (1995) and Andresen *et al.* (in press) interpret this feature as a late Caledonian detachment zone related to orogenic collapse. In Andrée Land the fjord region detachment as depicted by Hartz & Andresen (1995) and Andresen *et al.* (in press) follows the base of the EBS, but the most conspicuous tectonic lineament is the NW–SE trending structure which Haller (1953) denoted as the "Junctiondal Fault", and which lies within the metamorphic complexes. In southern Lyell Land the detachment zone also diverts away from the EBS contact and lies within the metamorphic complexes. Our investigations on the detachment are in broad agreement with the conclusions of Hartz & Andresen (1995) and are observed especially well in the Junctiondal area.

The detachment zone is a semi-brittle extensional fault with top-to-east downthrow dipping 20°–30° E, with well preserved E–W stretching and mineral lineations. In the Junctiondal area it is 10–20 m wide, comprising cataclastic quartzite, limestone, dolomite and shale. The zone is strongly silicified, dolomitised and sulphidised and contains a few quartz veins. Mineralisation in the detachment zone is often found in cataclastic rusty quartzite. The ore minerals are iron sulphides, often less than a few vol.%.

The metamorphic complex (west of the detachment zone in Andrée Land and Suess Land) is dominated by quartzitic gneisses alternating with mica schists and mica gneisses. White quartz veins up to a half metre wide occur but they are not mineralised. Within the metamorphic complex several shear zones up to a few metres wide occur; they are rusty, sulphide-bearing, silicified and altered.

In Suess Land the detachment zone is characterised by extensional faulting with several N–S striking faults. The fault zones have a distinct E–W trending lineation plunging east. The cataclastic rocks of the fault zones are heavily silicified and in some places also metasomatised. One rust coloured fault zone is 13 m thick and has up to a few vol.% iron sulphides. The zone is silicified and the main rock type is a quartz-rich muscovite schist.

Vein related mineralisation

These are mineralisations found in close connection to quartz-, granite-, aplite- and pegmatite-veining in the Palaeoproterozoic to Mesoproterozoic crystalline metamorphic complexes, and were especially investigated in Andrée Land. Quartz-veining in a grey, banded quartzitic mica schist or gneiss, structurally above a calc-silicate sequence, dominates in a triangular area south of Jomsborg Dal and east of Rendalen. The white quartz veins vary in thickness from a few centimetres to one metre, and in length from one metre to fifty metres. Many of the veins are rust coloured and contain up to one vol.% sulphides; arsenopyrite is the common sulphide, but in addition, pyrrhotite and pyrite and more rarely chalcopyrite form part of the sulphide assemblage.

The contact between the quartz veins and the host rock is sharp and shows no sign of alteration. The quartz veins are found both concordant and discordant to the schistosity of the rocks. The discordant veins are dilatation veins formed as a result of dextral shear which gives a prominant 60° jointing in the host rock. A few shear zones up to 1.5 m wide occur striking 040°. The dilational veins are typically from 10 to 50 m apart from each other. A loose block, not found *in situ,* but clearly derived from the shear zone contained arsenopyrite on the shear planes.

Caledonian intrusive activity in the region is seen in the form of aplites, pegmatites, granite bodies and veins and quartz veins. In the metamorphic crystalline complex these veins are numerous, and some areas are more extensively veined than others. Iron sulphides are often associated with the veining and Harpøth *et al.* (1986) have reported gold-bearing boulders from Luciagletscher and west of Randenæs. At Luciagletscher one 5 cm thick quartz vein with a total of 10% pyrite and galena in red granite was located. In general, the granite is a light two-mica rock which in many places has considerable amounts of tourmaline. The pegmatite also contains tourmaline, as well as beryl, green mica and pyrrhotite. The pegmatites occur both as concordant and discordant lenses to the schistosity: the discordant veins strike more or less N–S and dip steeply towards the west.

Other types of mineralisation

In the Jomsborg Dal – Rendalen area a yellow-brown coloured 5 m thick quartz-muscovite schist containing up to 5 vol.% pyrite occurs. The horizon occurs in the transition zone between a calc-silicate sequence and the quartzitic mica gneisses. In Suess Land numerous semi-massive and disseminated pyrrhotite-bearing boulders were found in Murgangsdal. The boulders are banded with up to 5 cm thick pyrrhotite layers in a hornblende calc-silicate rock, and are thought to be derived from the calc-silicate sequence.

4. Results from stream sediment data

The stream sediment analyses for gold (INAA), copper (ICP), lead (ICP), zinc (ICP) and arsenic (INAA) are shown on Figures 1–5, respectively.

Figure 1. *Gold (ppb) in stream sediments. The detachment zone is indicated by the full line with triangular symbols on the downdip side. AL = Andrée Land; LL = Lyell Land; SuL = Suess Land; YØ = Ymer Ø. D = Djævlekløften; G = Grejsdalen; Jo = Jomsborg Dal; Ju = Junctiondal; KH = Kap Hedlund; M = Murgangsdalen; R = Randenæs.*

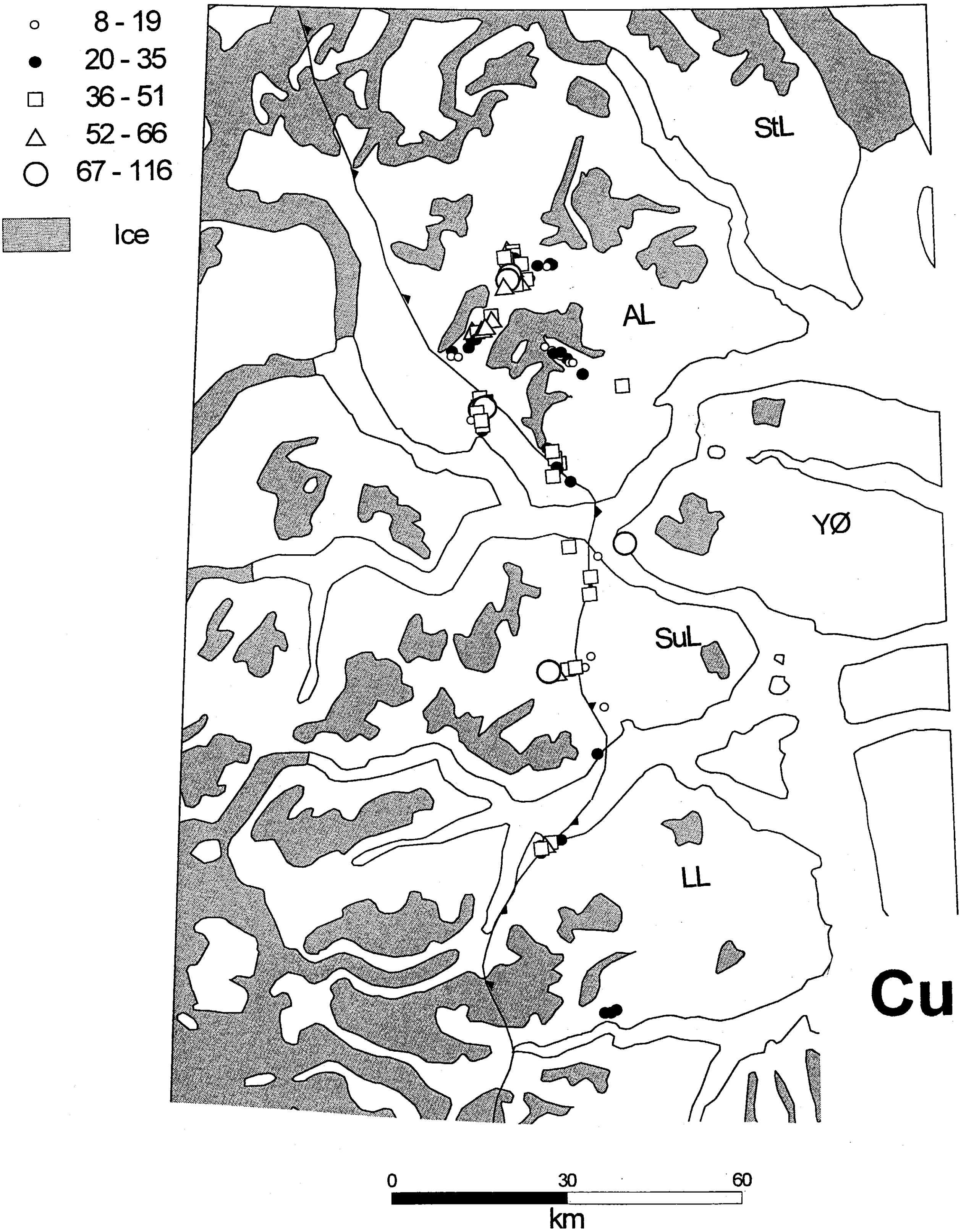

Figure 2. *Copper (ppm) in stream sediments. The detachment zone is indicated by the full line with triangular symbols. AL = Andrée Land; LL = Lyell Land; SuL = Suess Land; YØ = Ymer Ø.*

Gold (Fig. 1)

The gold content varies from below the detection limit of <2ppb to 39 ppb. Seventy out of ninety samples were below the detection limit, sixteen samples had values from 2 to 9 ppb gold and four samples were found with 10 ppb gold or higher values. Three of the highest four values were closely related to the detachment zone, while the fourth sample is from Grejsdalen, located in rusty gneisses (Palaeoproterozoic to Mesoproterozic crystalline metamorphic complex) associated with Caledonian granites. No gold seems to be present in Jomsborg Dal where arsenopyrite mineralisation is common. The previously known gold anomalies at Luciagletscher and the Randenæs were not detected in the stream sediment data.

Copper (Fig. 2)

The copper content of the <100 μm fractions of the stream sediment samples ranges from 8 to 116 ppm. Especially low values were seen in the Luciagletscher and Randenæs areas. The enhanced copper values occur throughout the sampled area.

Lead (Fig. 3)

The lead content of the <100 μm fractions of the stream sediment samples ranges from 8 to 66 ppm. The enhanced lead areas occur where granite veining comprises a major part of the metamorphic complexes, e.g. Luciagletscher, Grejsdalen and Djævlekløften.

Zinc (Fig. 4)

The zinc content of the <100 μm fractions of the stream sediment samples ranges from 13 to 125 ppm. Individual areas show almost the same full range of variation, which probably reflects the natural variation between the different rock types rather than any anomalous sites.

Arsenic (Fig. 5)

The arsenic content of the <100 μm fractions of the stream sediment samples ranges from below 0.5 ppm to 28 ppm. All samples below 6 ppm are classified as one group. It is anticipated that this level represents the normal background for the area. It is noticeable that the known arsenic mineralisation in Jomsborg Dal is not reflected in the stream sediment samples. The clearly anomalous area is Djævlekløften, an area with abundant Caledonian granites. Two single anomalies were found in the western part of Murgangsdalen and west of Randenæs.

Scheelite

Of 56 heavy mineral concentrates studied, scheelite grains were found in 27 concentrates. The number of grains seen ranged from 1–130 grains of scheelite, with the largest number found in Jomsborgdal at a locality dominated by Caledonian granite.

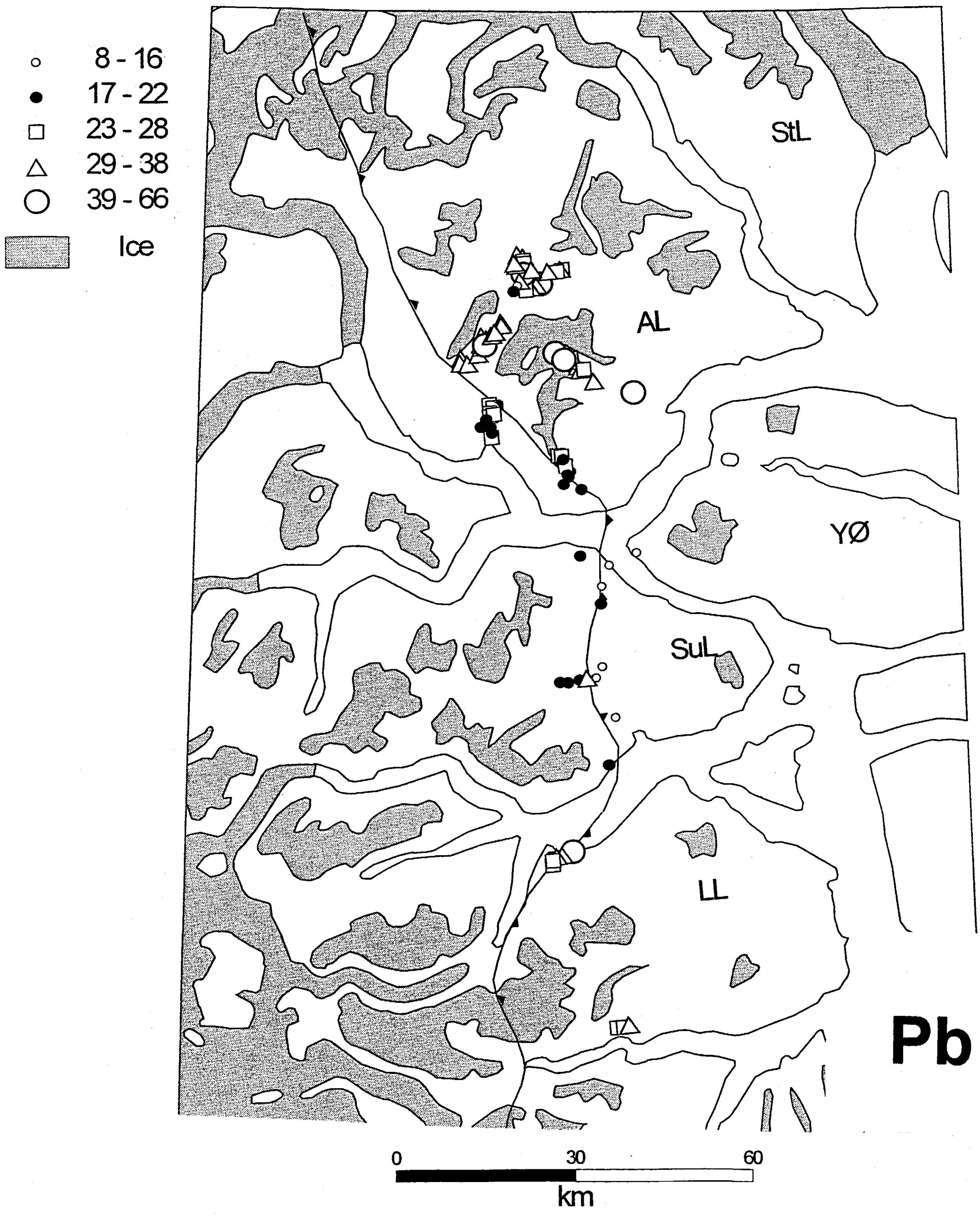

Figure 3. *Lead (ppm) in stream sediments. The detachment zone is indicated by the full line with triangular symbols. AL = Andrée Land; LL = Lyell Land; SuL = Suess Land; YØ = Ymer Ø.*

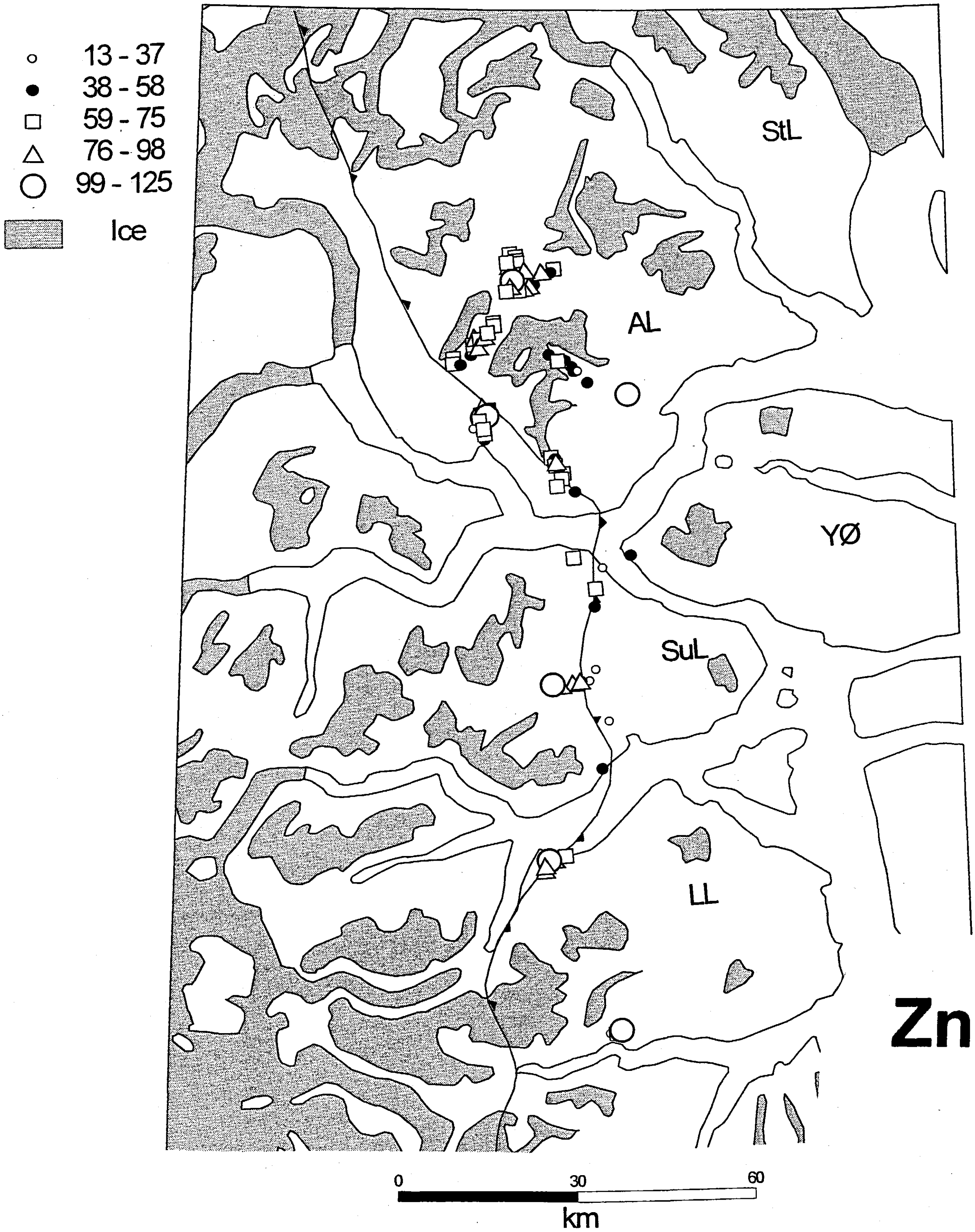

Figure 4. *Zinc (ppm) in stream sediments. The detachment zone is indicated by the full line with triangular symbols. AL = Andrée Land; LL = Lyell Land; SuL = Suess Land; YØ = Ymer Ø.*

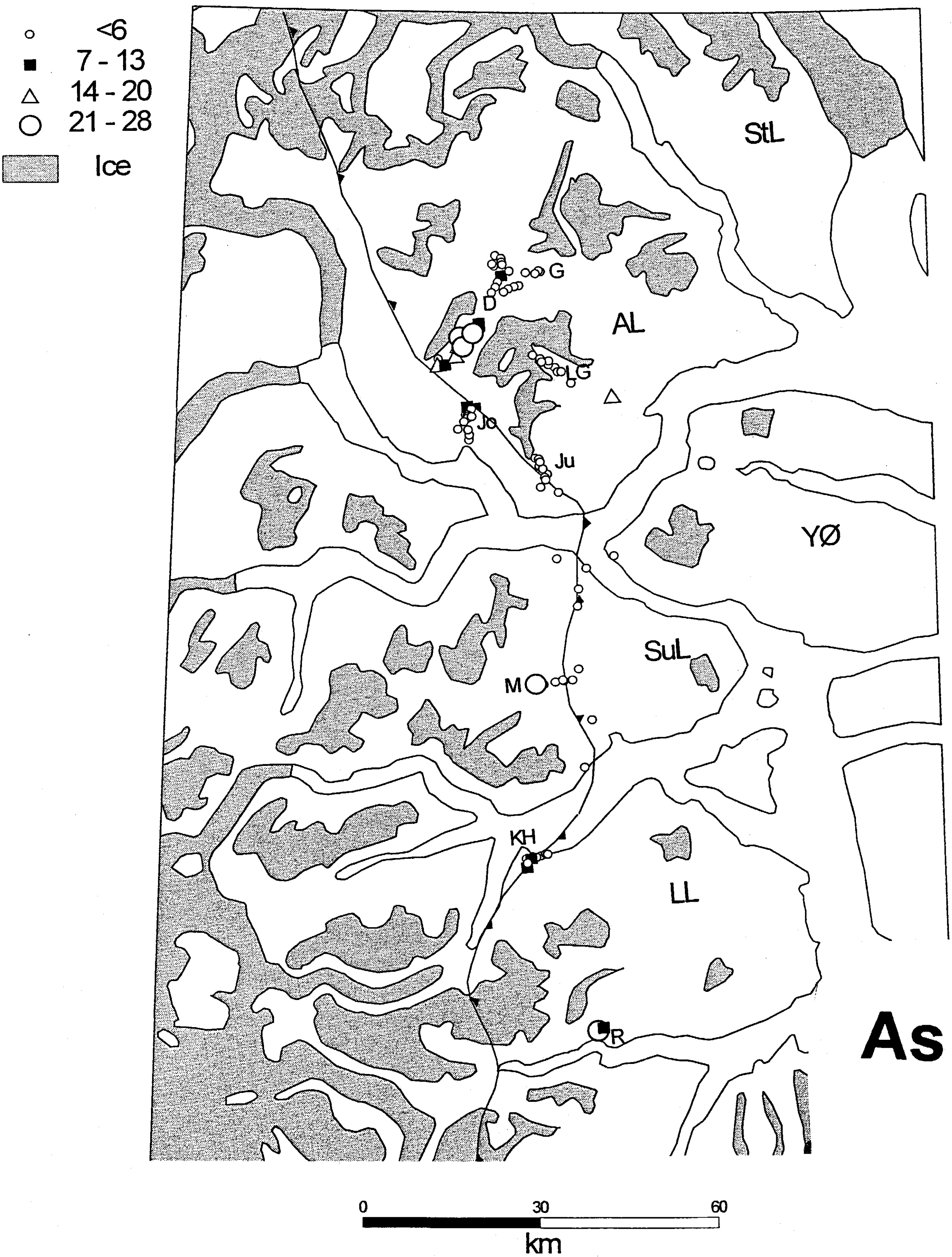

Figure 5. *Arsenic (ppm) in stream sediments. The detachment zone is indicated by the full line with triangular symbols. AL = Andrée Land; LL = Lyell Land; SuL = Suess Land; YØ = Ymer Ø. Jo = Jomsborg Dal; Ju = Junctiondal; KH = Kap Hedlund; M = Murgangsdalen; R = Randenæs.*

5. Concluding remarks

The field work has revealed mineralisation in several settings, e.g. along the detachment zone between the Eleonore Bay Supergroup and the Palaeoproterozoic to Mesoproterozoic crystalline metamorphic complexes, most notably in Junctiondal.

- The arsenic anomalies known in Jomsborg Dal and Rendalen can be explained by mineralised quartz veins, but were not detected in the <100 μm fractions of the stream sediment samples. Djævlekløften, however, seems to be a surprisingly interesting area with respect to arsenic, lead and gold.
- The previously known gold anomalies in the Randenæs and Luciagletscher areas have not yet been satisfactorily explained.
- In general, the <100 μm fractions of the stream sediment samples do not at this stage seem to reveal the observed mineralisations of the area particularly well. This may be because the stream sediments only reflect the general lithologies, or that the grain size fractions of the stream sediment samples do not match with the grain sizes of the mineralisation (see discussion in Stendal 1979, 1982b).

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Metamorphism and migmatisation in the Gletscherland complex, northern Suess Land, East Greenland

Gordon R. Watt

Abstract: The Gletscherland complex is a lithologically varied orthogneiss terrane bounded to the west by the Hagar sheet and to the north by granitic gneisses and augen gneisses of the Niggli Spids dome. A major Caledonian extensional contact (fjord region detachment: FRD) cuts the eastern margin of the Gletscherland complex. Boudins of relatively undeformed orthogneisses and paragneisses are preserved in low strain areas for several kilometres west of the FRD. Early fabrics and metamorphic assemblages in garnet-amphibolites, granitic gneisses and migmatitic biotite-rich gneisses within these boudins suggest a substantial pre-Caledonian history of high grade metamorphism followed by N–S compression. In northern Suess Land the early E–W fabrics resulting from this compression are progressively reworked eastwards by a series of shallow, east-dipping extensional shear zones with top-down-to-the-east displacement. These shear zones may be related to the Caledonian FRD and perhaps reflect gravitational collapse of the orogen, manifest at deeper crustal levels by extensive partial melting and late to post-tectonic granite emplacement. No evidence for the early Caledonian crustal shortening reported by J.C. Escher, K.A. Jones and others in the basement gneisses was found, but large NW directed folds in the metasedimentary sequence overlying the basement gneisses in Upper Murgangsdalen may be related to early Caledonian compression.

GRW: *School of Applied Geology, Curtin University of Technology, GPO Box U1987, Perth, WA 6001, Australia*

As part of the 1997–1998 field mapping programme by the Geological Survey of Denmark and Greenland (GEUS) in the East Greenland Caledonides, three areas in northern Suess Land (referred to here as lower Murgangsdalen, upper Murgangsdalen and Payer Gletscher: Fig. 1) were sampled with the broad objective of constraining the timing and significance of anatexis in the Gletscherland complex and relationships with adjacent areas. The Gletscherland complex is a large, lithologically varied orthogneiss terrane, bounded to the west by the Hagar sheet and to the north by granitic gneisses and augen gneisses of the Niggli Spids dome. These three infracrustal units constitute the "Central Metamorphic Complex" of Haller (1971), which isotopic work (e.g. Rex & Gledhill 1981) has shown is dominated by Precambrian crystalline basement rocks variably reworked during the Caledonian orogeny.

In the east the Gletscherland complex is structurally overlain by lower grade metasediments of the Upper Proterozoic Eleonore Bay Supergroup, the boundary between the two units being defined by a major eastwards dipping extensional shear zone referred to as the "Fjord Region Detachment" (FRD) by Andresen *et al.* (in press). In the Murgangsdalen region of northern Suess Land the dominantly amphibolitic orthogneisses contain large areas of variably migmatised and deformed biotite gneiss, and show E–W trending structures and upright fabrics which are reworked eastwards by a series of low angle exten-

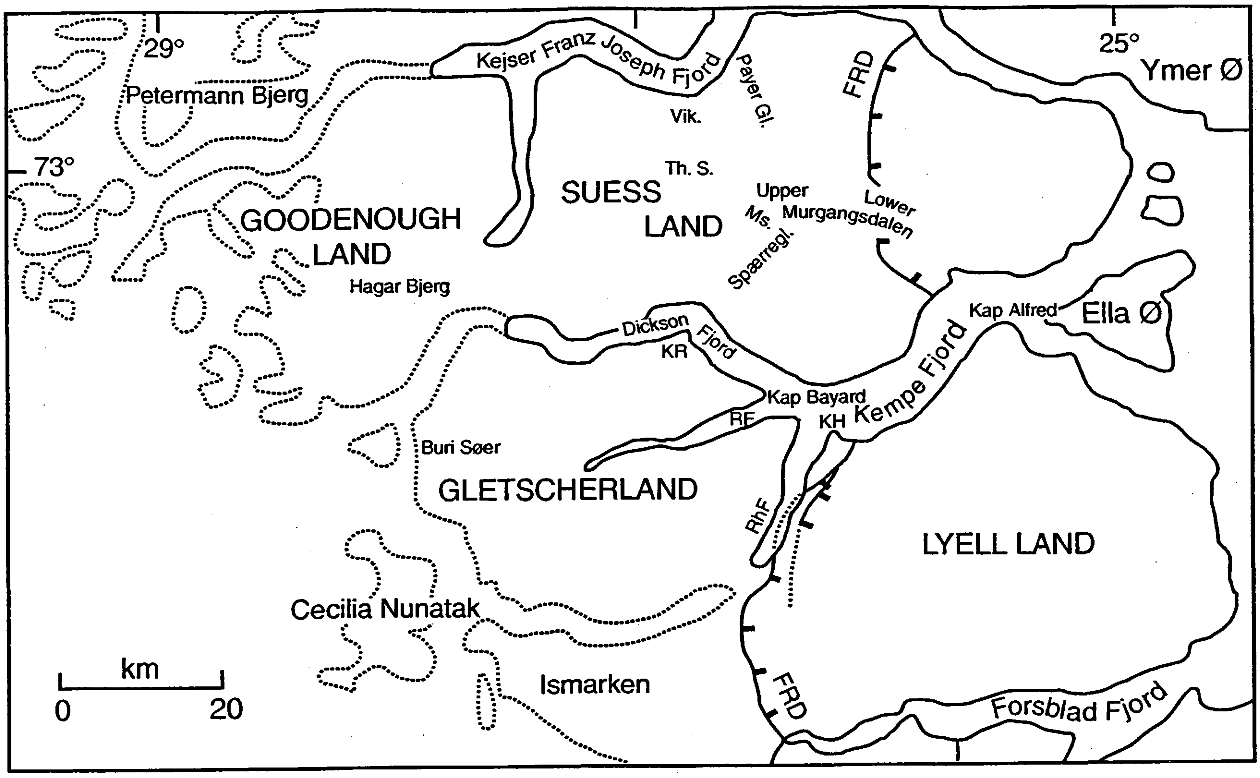

Figure 1. *Map of Suess Land with localities mentioned in the text and the location of the fjord region detachment (FRD). Areas west of the FRD comprise crystalline complexes, areas east of the FRD are dominated by the Eleonore Bay Supergroup. KH: Kap Hedlund. KR: Kap Robert. RF: Röhss Fjord. RhF: Rhedin Fjord. Payer Gl.: Payer Gletscher. Vik: Vikingeborg. Th. S. : Thun Søer. Ms: Murgangsø. Spærregl.: Spærregletscher.*

sional shear zones which we interpret as being related to the FRD. The main objective of the migmatite studies in the Gletscherland complex was to determine whether the paragneiss enclaves within the dominantly amphibolitic orthogneiss succession represent infolded younger metasediments (Mesoproterozoic Krummedal supracrustal sequence or Neoproterozoic Eleonore Bay Group), or a series of older metasedimentary gneisses. Some comments regarding relationships with the adjoining Hagar sheet and Niggli Spids dome are made in the light of new field data (Escher & Jones 1998).

1. Field observations

1.1 Gletscherland complex – lower Murgangsdalen

The extensional shear zone (FRD) at the east border of the Gletscherland complex is excellently exposed in a series of deep gorges and water-washed slabs eastwards from the edge of Spærregletscher. A schematic cross-section from NW to SE across the area is shown in Figure 2. Steeply foliated E–W trending orthogneisses and paragneisses (D1$^{(pre-Cal)}$) which have been folded (D2$^{(pre-Cal)}$) are cut by granitic and pegmatitic veins. Boudins of relatively undeformed orthogneisses and paragneisses are preserved in low strain areas several kilometres west of the FRD (Elvevold & Gillotti 1998). Here amphibolite sheets and foliated biotite gneisses commonly contain several generations of cross-cutting granitic veins and tourmaline-bearing pegmatites. These veins vary in width from 2 cm to more than 1 m, clearly post-date $D1^{(pre\text{-}Cal)}$, and are reworked in Caledonian extensional shear zones (Ext^{Cal}). Contacts between amphibolites and paragneisses in these low strain zones are now parallel to $S1^{(pre\text{-}Cal)}$ and are interpreted as transposed igneous contacts – relict igneous layering appears to have been preserved in rare amphibolite gneiss boudins several hundred metres west of the FRD in lower Murgangsdalen. Biotite gneisses within low strain areas are often migmatitic, preserving syntectonic melt segregation structures. This melting may have occurred syn- or post-$D1^{(pre\text{-}Cal)}$, is folded by $D2^{(pre\text{-}Cal)}$ and is deformed by Ext^{Cal}. Calc-silicate horizons within the biotite gneisses are also boudinaged by Ext^{Cal} and may represent either original sedimentary horizons or dismembered and strongly metamorphosed ultrabasic layers.

Basement gneisses with early structures are reworked progressively eastwards by a series of eastwards dipping, low angle, extensional shear zones (Ext^{Cal}) which are interpreted as being related to the FRD. The margins of larger low strain boudins are characterised by a realignment of fabrics and cross-cutting veins into the dominant eastwards dipping foliation. The size and number of low strain boudins decreases eastwards and fabrics and cross-cutting relationships become transposed in the high strain region adjacent to the FRD itself. Detailed work by Elvevold & Gilotti (1998) has shown that the fjord region detachment separates augen gneisses and strongly deformed metasediments of the Gletscherland complex in the footwall from bedded EBG quartzites in the hangingwall. The upper part of the gneiss section is comprised of L-S tectonites with an east-plunging lineation, while metapelites have well developed S-C fabrics with top-to-the-east shear sense. These ductile fabrics have been overprinted by late, brittle, top-down-to-east normal faults. Similar late faults have been described by Escher & Jones (1998) further north. Elvevold & Gilotti (1998) recognised kyanite-bearing migmatites within the metasedimentary part of the footwall series. This implies that the early melting (pre-Caledonian extension) occurred at relatively high pressures, presumably in response to thickening, in contrast to most of the melting elsewhere in the East Greenland Caledonides which appears related to extension (Watt & Kinny 1998).

1.2 Gletscherland complex – upper Murgangsdalen

The rocks exposed west of Spærregletscher in upper Murgangsdalen show no evidence for eastwards directed Ext^{Cal} extension. They are dominated by garnet amphibolites and granitic gneisses, with steep E–W trending foliations and a strong, steeply westwards plunging lineation. We interpret these rocks as the undeformed precursors of the gneisses reworked further east by the FRD. Apparent partial melting textures are preserved in several areas of the garnet amphibolites, suggesting that relatively high grade metamorphic conditions may have been reached. Structurally above these gneisses are a series of horizontally foliated metasediments with large scale folds suggesting westwards directed thrusting. A schematic cross-section is shown in Figure 3.

Garnet amphibolites

Variably migmatised amphibolitic gneisses comprise the main part of the upper Murgangsdalen gneiss assemblage. These contain large (up to 2–3 cm diameter) garnets, often with a narrow rim of plagioclase in leucosomes of finer grained, banded garnet and garnet-biotite amphibolites. Several samples show garnets with plagioclase-amphibole rims reflecting decompressive excavation histories. Small early ($F1^{(pre\text{-}Cal)}$?) isoclinal folds develop a strong axial planar fabric along which patch leucosomes containing garnet are commonly found. Leucosomes are often irregular in shape, up to 20 cm long and flattened along $S1^{(pre\text{-}Cal)}$. Rare leucosome patches contain green, prismatic crystals which may be orthopyroxene, overgrown by rims of dark amphibole. The main foliation in the amphibolites is defined by numerous pale plagioclase-rich layers, and is folded by large, steeply plunging tight $F2^{(pre\text{-}Cal)}$ folds with axial planes dipping steeply north (Fig. 4). These large E–W trending folds were interpreted by Higgins *et al.* (1981) as early Proterozoic in age, while earlier workers (Haller 1971) considered the E–W folds to be inherited structural trends from pre-existing basement preserved within completely remobilised Caledonian rocks. In the nose of one of these major $F2^{(pre\text{-}Cal)}$ folds, these plagioclase-rich layers clearly cut early patch leucosomes emplaced along $F1^{(pre\text{-}Cal)}$ axial planes.

On the northern slopes of the Murgangsø valley, banded amphibolites, felsic gneisses and biotite gneisses contain syn-extensional melt migration textures. Melt migration into boudin necks, extensional shear zones and incipient boudin neck structures indicate that anatexis was accompanied by a major dextral shearing event which boudinaged early fold structures. The timing of this event is uncertain – it clearly post-dates $D1^{(pre\text{-}Cal)}$ but it is difficult to determine how it relates to other deformation events in the area. If we assume that the melting occurred before $D2^{(pre\text{-}Cal)}$ (and therefore remove the effects of $F2^{(pre\text{-}Cal)}$ folding) then the sense of movement is approximately top-to-the-east, and this anatexis may then relate to extensional collapse of the early Caledonian west-directed thrusting of Escher & Jones (1998). Alternatively, if the dextral shearing occurred during $D2^{(pre\text{-}Cal)}$ then melt movement may have been controlled by differential movements and non-homogeneous shortening on the limbs of large $F2^{(pre\text{-}Cal)}$ folds.

A thick sequence of brownish metasedimentary gneisses are exposed above the basement gneisses of the Murgangsø valley. The rocks show large folds with top-to-the-west and north-west displacement. The relationship of these rocks to the underlying basement is uncertain – it is possible that the folds reflect either early E–W crustal shortening or later extensional collapse. Both these models imply a structural discontinuity between these metasedimentary gneisses and the orthogneisses of the basement below. Further work to constrain the origin and structural history of these lithologies is required.

Granites

Numerous pegmatitic and fine-grained granitic sheets up to 20 m thick occur interfolded with the amphibolites – these sheets cross-cut $S1^{(pre\text{-}Cal)}$ but are folded by major $F2^{(pre\text{-}Cal)}$ folds and have a well developed westwards plunging $L2^{(pre\text{-}Cal)}$ lineation. These sheets appear very similar to felsic veins cutting early fabrics in the amphibolitic gneisses in low strain boudins in lower Murgangsdalen. High on the northern side of upper Murgangsdalen a prominent granite sheet intrudes amphibolites and biotite gneisses. Contact relationships

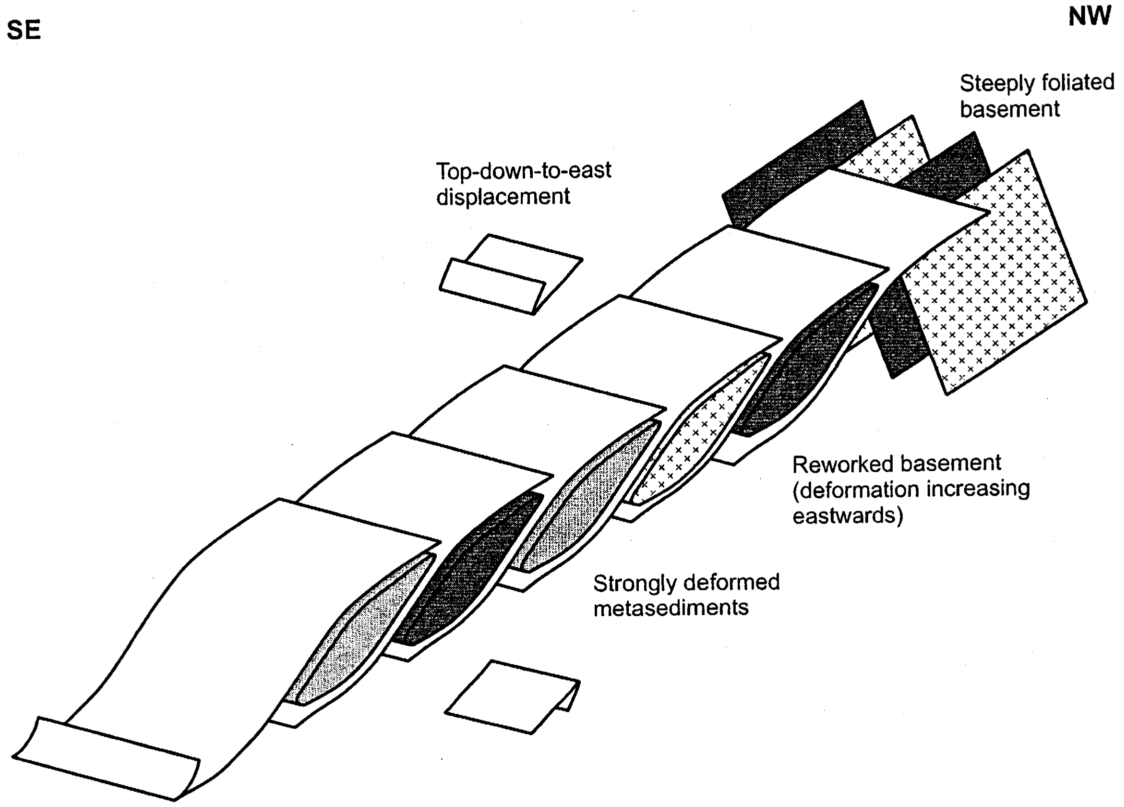

Figure 2. *Schematic cross-section of lower Murgangsdalen west of the fjord region detachment (looking SW). Steeply foliated basement rocks (including amphibolites and granitic veins) are progressively reworked eastwards by a series of gently dipping shear zones with top-down-to-the-east displacement. Towards the FRD metasedimentary gneisses become interleaved with the basement gneisses.*

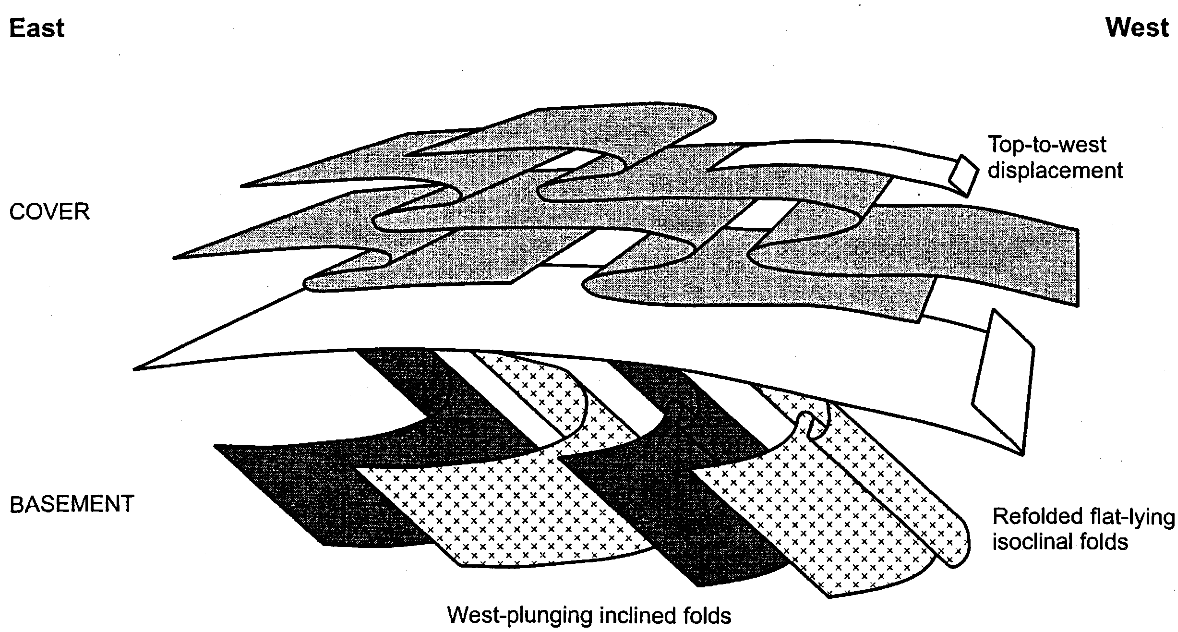

Figure 3. *Schematic cross-section through upper Murgangsdalen showing basement cover relationships (looking south).*

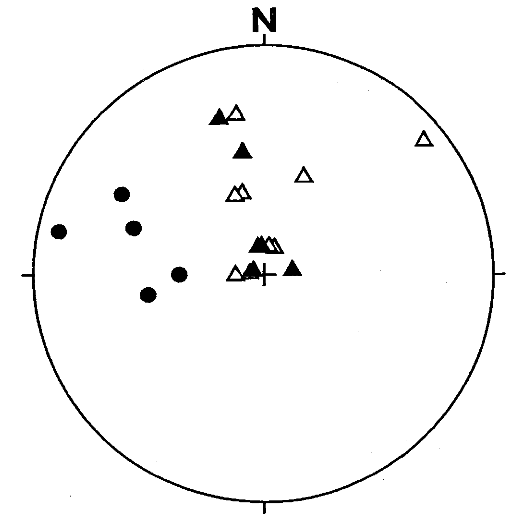

Figure 4. *Stereonet showing major structural trends in Upper Murgangsdalen basement gneisses. Symbols: open triangles – poles to main foliation; filled triangles – poles to axial planes of small folds; filled circles – poles to F2$^{(pre\text{-}Cal)}$ fold hinges.*

are preserved and fingers of granite can be seen intruding along the foliation within biotite gneisses. This granite, like the felsic sheets elsewhere in upper Murgangsdalen, is itself foliated and folded. While many Caledonian granites in the region show evidence for deformation (e.g. Jepsen & Kalsbeek 1998; Watt & Kinny 1998), these fabrics are more typically related to the Ext^{Cal} event. The granites of the upper Murgangsdalen area are, however, unaffected by the development of the fjord region detachment further east and it is therefore suggested that they are pre-Caledonian in age.

Migmatites

Migmatitic biotite gneisses within the orthogneiss succession are folded by open upright F2$^{(pre\text{-}Cal)}$ folds whose north-dipping axial planes and west-plunging hinges clearly post-date anatexis. At the eastern end of the Thun Søer, well developed migmatitic textures are preserved. Leucosomes are 3–10 cm wide and contain excellently developed biotite-rich melanosomes. Relict melt segregation textures (e.g. leucosome-filled small scale shear zones) are present, indicating that these migmatites did not form by subsolidus segregation. Deformation increases westwards (towards Vikingeborg) and upwards and the migmatites merge with more typical banded biotite gneisses similar to those described in lower Murgangsdalen.

1.3 Niggli Spids dome – Payer Gletscher

The Niggli Spids dome (NSD) is a large, relatively homogeneous mass of well-foliated augen orthogneisses and K-feldspar megacrystic granitic and granodioritic gneisses located to the north of the Gletscherland complex. Overlying the orthogneisses and granites of the dome are a thick succession of metasedimentary rocks (Niggli Spids sequence of Escher & Jones 1998) which dip off the dome to the west, north and south (Higgins *et al.* 1981). These metasediments appear structurally above gneisses of the Gletscherland complex in upper Murgangsdalen.

Table 1. Tentative correlation of pre-Caledonian and Caledonian events in the northern Suess Land/Kejser Franz Joseph Fjord region, East Greenland (Caledonian events in lower part of table).

Lower Murgangsdalen		Upper Murgangsdalen		KFJ Fjord (Escher & Jones 1998)	
Timing	**Structure/Event**	**Timing**	**Structure/Event**	**Timing**	**Structure/Event**
$D1^{(pre\text{-}Cal)}$?	Main foliation	**$D1^{(pre\text{-}Cal)}$?**	Main foliation		
$D2^{(pre\text{-}Cal)}$?	N–S compression and folding	**$D2^{(pre\text{-}Cal)}$?-**	N–S compression and folding		
	GRANITE EMPLACEMENT		GRANITE EMPLACEMENT		
???	???	**$D1^{(Cal)}$**	Thrusting of metasediments over basement?	**$D1^{(Cal)}$**	E-W crustal shortening Westwards thrusting
					GRANITE EMPLACEMENT
				$D2^{(Cal)}$	NNW-SSE extension
					GRANITE EMPLACEMENT
				$D3^{(Cal)}$	N-S trending major folds
Ext^{Cal}	E-directed extension (at depth) related to FRD.	**Ext^{Cal}**	E-directed extension (at depth) related to FRD	**$D4^{(Cal)}$**	E–W extension Brittle normal faults

The contact between the Niggli Spids dome orthogneisses and overlying metasediments is a spectacular feature which can be traced for many kilometres. It is well exposed on the eastern side of Payer Gletscher on the south side of Kejser Franz Joseph Fjord (see Fig. 6 in Higgins *et al.* 1981). Homogeneous well-foliated granitic gneisses (with aligned K-feldspar megacrysts defining a weak south-easterly plunging lineation and a top-to-the-south shear sense) form the top part of the "dome". Deformation increases strongly in the top 5 m of the gneisses, and at the contact it becomes a strongly foliated granitic schist with elongate quartz ribbons parallel to foliation. The granitic schists are overlain by mylonitic psammites and psammitic schists containing very tight, flat-lying isoclinal folds indicating top-to-the-south-east displacement. Above the psammites a 10 m section of strongly deformed leucocratic diopside gneisses and interbedded psammitic and semi-pelitic schists passes upwards into a thick succession of biotite-muscovite gneisses and rusty brown flaggy semi-pelitic schists. Escher & Jones (1998) interpret the NSD-metasediments contact as a tectonised unconformity on the basis of pegmatitic veins which cut the granitic gneisses of the dome but do not occur in the metasediments above.

The thick series of biotite and biotite-muscovite schists above the NSD contains large tectonic slices of upper amphibolite facies migmatitic biotite gneisses, which appear very similar to the migmatites exposed in upper Murgangsdal. One distinguishing characteristic of these migmatites is the occurrence of huge (up to 25 cm in diameter) purple-red garnets. Leucosomes are narrow (typically less than 10 cm wide) and folded. A weak lineation defined by amphibole plunges gently south-east, similar to the lineation in the augen gneisses and parallel to hinges of minor folds developed on the NSD-metasediment contact.

2. Discussion and concluding remarks

2.1 Structural relationships within the central metamorphic complex

The fjord region detachment in lower Murgangsdalen is interpreted as a crustal scale detachment which has brought relatively low grade metasediments (EBG) into contact with high grade basement rocks of the Gletscherland complex. Dominantly E–W fabrics reflecting an early, probably pre-Caledonian event are progressively reworked eastwards in a series of shallow, east-dipping extensional shear-zones with top-down-to-the-east displacement (Elvevold & Gillotti 1998). Extensional collapse after crustal thickening (Sandiford 1989) is now recognised as a major tectonic process in large scale fold belts. Extension may be initiated by a reduction in horizontal compression or by detachment of the thickened lower boundary layer during convergence. Extensional features (flat-lying foliations, large recumbent folds, late to post-tectonic leucogranites) are common throughout the East Greenland Caledonides. Escher & Jones (1998) have noted large scale extension (directed NW) in areas north of Murgangsdal, and attribute this to extensional collapse of the Caledonian mountain pile. Watt & Kinny (1998) suggest that extensive melting related to decompression accompanied extensional collapse in the south-eastern part of the study area, and other workers (notably Andresen *et al.* in press, and Hartz & Andresen 1995) have stressed the importance of extension in juxtaposing low grade metasediments on high grade gneisses throughout the East Greenland Caledonides. Extension is predominantly eastwards directed, and occurs in response to collapse of the orogen following E–W crustal shortening in the early Caledonian. Escher & Jones (1998) have recorded D2 NW-directed extension in much of Frænkel Land and southern Louise Boyd Land. Northwest directed extension may be a result of collapse on the "western" side of the orogen, or perhaps may represent a "ramp" type deflection of the overall extensional fabric at the northern margin of the central metamorphic complex.

Little or no work has been done on the nature of the contacts between the individual components of the central metamorphic complex (Gletscherland complex, Hagar sheet and Niggli Spids dome). The Hagar sheet/Gletscherland complex contact has been remapped by Escher & Jones (1998) who suggest that it results from early Caledonian westwards thrusting of the Hagar sheet over their Niggli Spids metasedimentary unit. Large scale westwards-facing recumbent folds have been noted in the metasediments (Niggli Spids metasedimentary unit?) structurally above the migmatitic metasediments and orthogneisses of upper Murgangsdalen and may be related to the aforementioned westwards-directed thrusting. Escher & Jones (1998) suggest that this westwards thrusting and thickening event occurred at an early stage in the Caledonian orogeny. If this correlation is correct, and the rusty-brown metasediments found at structurally high levels at the western end of Upper Murgangsdalen correlate with the Niggli Spids metasediment unit of Kejser Franz Joseph Fjord, then the N–S compressional event which gave rise to the widespread E–W folding in the basement amphibolite gneisses of the Gletscherland complex must represent a pre-Caledonian event. If this is the case then the upper Murgangsdalen area records a significant amount of pre-Caledonian history (Table 1).

The contact between the northernmost Gletscherland complex rocks and the granitic gneisses of the Niggli Spids dome (NSD) has not yet been identified. Interpretation is hampered by an insufficient understanding of the origin of the NSD itself – evidence for large scale repetition (e.g. the symmetrical thickness of sheets of granitic gneiss within the dome on the eastern side of Payer Gletscher) may imply that it was involved in a large scale thickening event. Large westwards-directed folding of the Niggli Spids metasedimentary sequence over the Niggli Spids dome can be seen on the southern side of Kejser Franz Joseph Fjord and at the western end of Murgangsdalen, suggesting that the metasediments were tectonically emplaced over both the Niggli Spids dome and Gletscherland complex. As noted above, however, the Niggli Spids metasediments have been mapped by Escher & Jones (1998) as sitting unconformably above the Niggli Spids dome. This observation implies that the dome-shaped structure of the Niggli Spids dome cannot be related to ballooning during emplacement. As yet no geochronological work has been done on the age of emplacement of the Niggli Spids dome. Without this data it is difficult to determine whether the Niggli Spids metasediments are of "Krummedal sequence" affinity, or whether they represent a previously unrecognised metasedimentary package.

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Caledonian migmatisation and granite formation in the northern Gåsefjord–Stauning Alper migmatite and granite zone, East Greenland

Gordon R. Watt & Peter D. Kinny

Abstract: The migmatites and granites of the Alpefjord, Dammen and Furesø areas of eastern Nathorst Land form the northernmost extension of the Gåsefjord–Stauning Alper migmatite and granite zone (GSMZ), an extensive tract of high grade metasediments and granites in the southern part of the East Greenland Caledonian fold belt. All degrees of migmatisation, from small-scale patch leucosomes in metasediments to schlieren-rich granitic migmatites, are present. Diatexites and gneissic migmatites have the characteristic assemblage garnet-cordierite-sillimanite-spinel-biotite, common in many granulite facies migmatite terranes. Initial stromatic migmatites most probably formed under water-saturated conditions. As temperature increased vapour-absent melting reactions began to dominate, resulting in the formation of syn-extensional cordierite-rich leucosomes by decompression melting. Field observations are consistent with a two-phase migmatisation along a single P-T path characterised by early compression and crustal thickening and subsequent extensional collapse. Metamorphic textures in pelitic migmatites from the Dammen area suggest that footwall decompression accompanied the development of extensional structures. Dehydration melting under granulite facies conditions can generate large volumes of mobile granitic magma, especially when accompanied by syn-anatectic deformation, and may be responsible for the production of the abundant leucogranite sheets which are widespread throughout the region. These large (300–600 m thick) late- to post-tectonic leucogranite sheets occur near the top of the GSMZ, and were emplaced after the development of extensional fabrics in the GSMZ and overlying Eleonore Bay Supergroup (EBG) quartzites. The location of these leucogranites shows strong stratigraphic control – emplacement depths occur frequently at or just above the GSMZ–EBG contact. Ascent may have been via extensive net-veining and dyking networks or along shear-controlled extensional features. Rafts of EBG quartzite in granites suggest stoping was an important process at emplacement levels. The source rocks for the Caledonian leucogranites are, as yet, unidentified; if the Caledonian granites were formed by decompression melting under granulite facies conditions then it is possible that their protoliths are not exposed at the present surface, since water-undersaturated melts can ascend large distances before crystallisation. In contrast, many of the anatectic granites, concordant granite sheets and syn-tectonic cordierite-rich leucosomes within the migmatites of the GSMZ are of local origin and are expected to yield both zircon protolith ages and information regarding the timing of anatexis.

GRW, PDK: *School of Applied Geology, Curtin University of Technology, GPO Box U1987, Perth, WA 6001, Australia*

Detailed field mapping and sampling of migmatites and granites in the Nathorst Land and Suess Land regions of East Greenland (72°–73°N) was carried out as part of the 1997–1998 field mapping programme by the Geological Survey of Denmark and Greenland (Danmarks og Grønlands Geologiske Undersøgelse: GEUS). The study area lies in the northern part of the Gåsefjord–Stauning Alper migmatite and granite zone (GSMZ) (Fig. 1), a continuous N–S zone of paragneisses, migmatites and granites which extends for more than 200 km through the Scoresby Sund region (70°–72°N).

The East Greenland Caledonian fold belt is a N–S trending, 1200 km long zone of interleaved polyorogenic gneisses, granites and paragneisses ranging in age from Archaean to Late Proterozoic, assembled during the Caledonian orogeny (Henriksen 1985; Higgins 1995). Haller (1958, 1971) and co-workers considered the high grade basement gneisses to represent new crustal material formed in the deep-seated root zone of Caledonian metamorphism, and envisaged the overlying, lower grade paragneisses as a simple, relatively undeformed "superstructure". Subsequent mapping and isotopic dating in the southern part of the East Greenland fold belt showed that many of the basement rocks involved in the Caledonian orogeny have a pre-Caledonian origin, and that significant reworking of older rocks has occurred (Higgins 1995; Rex & Gledhill 1981).

Our field work in the region was carried out as part of the Australian Research Council funded research project "Geochemical and geochronological studies of partial melting". The project aims to investigate the mechanisms and rates of extraction of granitic melts from migmatites formed under granulite facies conditions, to compare granulite facies migmatites with migmatites formed under water-saturated conditions, and to assess the validity of current models for granite formation which require anatexis under anhydrous lower-crustal conditions. The close spatial association of granites and migmatites, the range in granite emplacement environments (including diatexitic leucosomes, restite-rich anatectic granites and thick sheets of leucogranite hundreds of metres thick emplaced in brittle quartzites) and the excellent 3D exposures over wide areas make this part of East Greenland an ideal place to study granite formation, ascent and emplacement. Much of the field information which was collected is directly relevant to the Survey mapping, and follow-up work at Curtin University, Australia (notably SHRIMP geochronological analysis) will provide constraints on the timing of metamorphism, granite emplacement and source rocks for the Caledonian granites as well as the basement gneisses of the so-called "Central Metamorphic Complex".

Detailed field work objectives were as follows:

(1) *Mapping and logging of migmatite structures at a variety of scales in an attempt to trace granite pathways through the crust from sites of formation to emplacement levels*. The generation, extraction, coalescence and ascent of granitic magmas is the single-most effective large-scale mechanism for chemical re-organisation of the earth's crust. Current models for crustal differentiation invoke high temperature anatexis under relatively dry conditions (Clemens 1990, 1992). Upper crustal, water-saturated melting, is thought to give rise to less mobile granitic melts, often rich in partially disaggregated source material. In many parts of the GSMZ granitic and migmatitic rocks merge with one another, but there are also large volumes of granite emplaced at a structurally higher level which apparently contain little or no entrained source material. If these granites are derived locally from the migmatitic supracrustal succession then it is clear that a range of extraction efficiencies may be possible from a single migmatite terrane, and that current models of granite formation (which require granite genesis to occur solely in the lower crust) cannot explain the generation of all granites.

(2) *Sampling of migmatites and granites for geochemical and geochronological studies.*
The main aim of these studies is to determine the influence of melt-extraction mechanisms

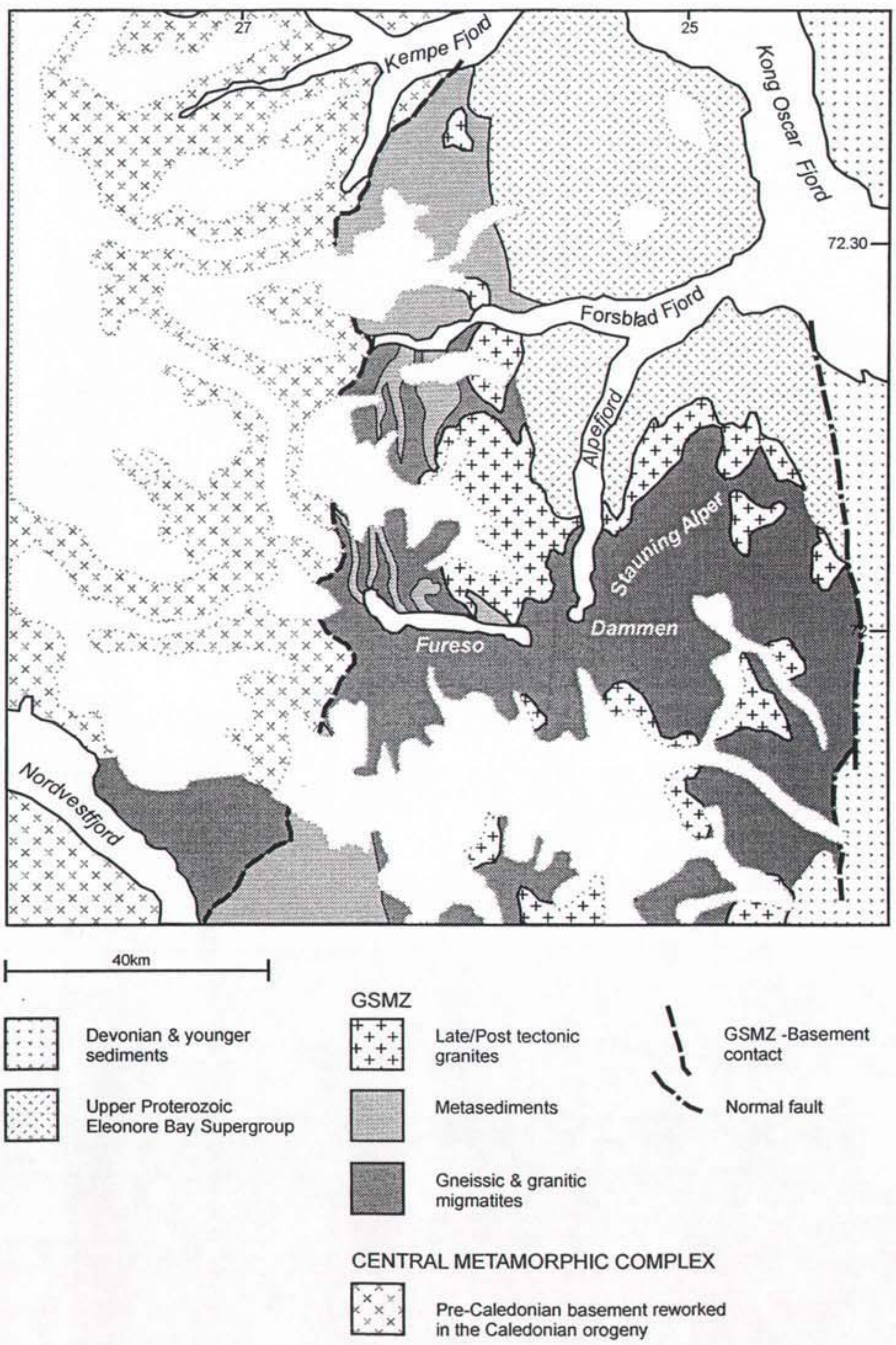

Figure 1. *Location map showing study area and main geological subdivisions (after Higgins 1995). GSMZ: Gåsefjord–Stauning Alper migmatite and granite zone.*

and rates on melt chemistry and granite segregation processes. One of the key developments of our understanding of partial melting processes has been the discovery that melt segregation may occur over geologically short time scales (10 000–100 000 years) due to deformation-enhanced melt segregation (the rapid movement of melt into low pressure sites across deviatoric stress gradients) (Brown 1994; Watt *et al.* 1996). The efficient extraction of melt during anatexis means that accessory phases such as zircon and monazite (important minerals for U-Pb isotopic dating) do not have time to completely dissolve. Migmatites may therefore contain partially dissolved protolith zircons as well as newly crystallised grains formed during anatexis. Dating these composite grains enables us to place geochronological constraints on both protolith ages and the timing of high grade metamorphic events.

1. Geological setting

The anatectic granites and variably migmatised paragneisses of Forsblad Fjord, Dammen and Furesø (Fig. 1) form the northernmost part of the Gåsefjord–Stauning Alper migmatite and granite zone (GSMZ). The western boundary between the pre-Caledonian basement gneisses of the central metamorphic complex and the overlying supracrustals of the GSMZ (Fig. 1) is a major east-dipping shear zone, interpreted as a thrust (resulting from westwards movements of large supracrustal nappes onto the basement) by Henriksen & Higgins (1976; see also Higgins *et al.* 1981), and as a large scale extensional detachment with an eastward displacement by Hartz & Andresen (1995). The nature of the eastern margin of the northern GSMZ is also uncertain. In the Forsblad Fjord region of eastern Nathorst Land (72°–74°N) the variably migmatised paragneisses which comprise the main part of the GSMZ were considered by Haller (1958) as the lower part of the Upper Proterozoic Eleonore Bay Group (EBG: promoted to a Supergroup by Sønderholm & Tirsgaard 1993). The EBG comprises a thick (c. 16 km) succession of shallow water marine shales, quartzites and limestones. Peucat *et al.* (1985) described an E–W section through Alpefjord and Schaffhauserdalen in which they recognised a continual increase in metamorphic grade downwards through the Eleonore Bay Supergroup into the migmatitic paragneisses of the GSMZ (see also Caby 1976). In contrast, Higgins *et al.* (1981) suggested that a tectonic contact related to westwards thrusting of the EBG over older, migmatitic paragneisses was present in Forsblad Fjord. These older paragneisses were thought by Higgins *et al.* to represent the northern equivalents of a thick succession of psammitic to pelitic paragneisses – the Krummedal supracrustal sequence – which forms a large part of the southern GSMZ. Mapping and isotopic work by the Survey in the southern part of the GSMZ (in the inner fjord region of Scoresby Sund) showed that Krummedal paragneisses had been affected by both Proterozoic and Caledonian metamorphism and migmatisation (Higgins 1988, 1995). Augen granites intruding migmatitic Krummedal supracrustals yielded a U-Pb zircon age of 1053 ± 40 Ma and a Rb-Sr whole rock age of 987 ± 23 Ma (Steiger *et al.* 1979). Two phases of migmatisation were recognised by Chadwick (1975), but in most of the study zone it is impossible to determine the age of migmatitic structures on the basis of field evidence alone. Attempts to date Krummedal-like paragneisses in the northern part of the GSMZ have been unsuccessful. Foliated muscovite granites within Krummedal-like paragneisses in Eremitdal, Andrée Land (73°50′N) have, however, produced Neoproterozoic whole rock Rb-Sr ages; one suite of these "older granites" (a strongly foliated muscovite-garnet granite and associated co-genetic dykes) gave a reasonably good isochron with an age of 1000 ± 70 Ma (Rex & Gledhill 1981). If the variably migmatised paragneisses of the GSMZ in the Dammen area represent the northern equivalent of the mid-Proterozoic Krummedal succession, a simple upwards transition into the Late Proterozoic Eleonore Bay Supergroup cannot exist, and a major tectonic contact must exist at the base of the EBG succession (Higgins *et al.* 1981). The exact nature of the GSMZ–EBG contact and the time at which it formed is therefore crucial to our understanding of the tectonic evolution of the area, not least because many Caledonian granites are emplaced along this boundary.

Several generations of late- to post-kinematic plutonic rocks have been recorded in the Stauning Alper region and to the south in the Scoresby Sund region. Granitic bodies within the GSMZ tend to be more or less concordant and restite-rich, containing large partially disaggregated rafts and xenoliths of metapelitic material, whereas near the GSMZ–EBG contact and in the EBG they occur as clean, often discordant, two-mica leucogranites and quartz-monzonite sheets. The majority of these granitoids are Caledonian in age and range in size from thin centimetre-scale veins to sheet-like bodies up to 10 km long and 600–800 m thick. In the northern part of the GSMZ the emplacement of large granite bodies shows a strong stratigraphic and structural control; often leucogranite sheets are located at or just above the contact between the GSMZ and the EBG. Most ages (recorded by U-Pb multigrain zircon and Rb-Sr whole rock methods) fall in the range 450–350 Ma – e.g. a leucogranite from the south side of Forsblad Fjord which intrudes the EBG yielded a Rb-Sr age of 445 Ma (Rex & Gledhill 1981) – but several older granites have also been recorded (up to 550 Ma) on the basis of Rb-Sr data. One sample of a foliated biotite granite from the south side of Forsblad Fjord gave an Rb-Sr "errorchron" of 750 ± 130 Ma (Rex & Gledhill 1981) which may record a mixed age resulting from Caledonian melting of older paragneisses.

2. Migmatititic rocks

2.1 Field observations

The best developed (and highest grade) migmatites of the areas studied were found in the Dammen and Stauning Alper areas, closely associated with large volumes of granitic rocks (Fig. 2). Dammen lies south of Forsblad Fjord, at the western margin of the northernmost Stauning Alper region, and appears to be structurally lower than most of the granites and migmatites exposed further west and north. All degrees of migmatisation, from banded patch and stromatic migmatites through to leucogranites with little or no entrained material, are present, typically with gradational contacts. The paragneisses of the northern part of the GSMZ, notably around Forsblad Fjord, are less migmatitic and are simply foliated biotite gneisses cut by granite veins rather than true *in situ* partial melts. This northwards decrease in the degree of migmatisation has previously been noted by Higgins *et al.* (1981). In certain areas, however, which are characterised by a weakly developed shearing

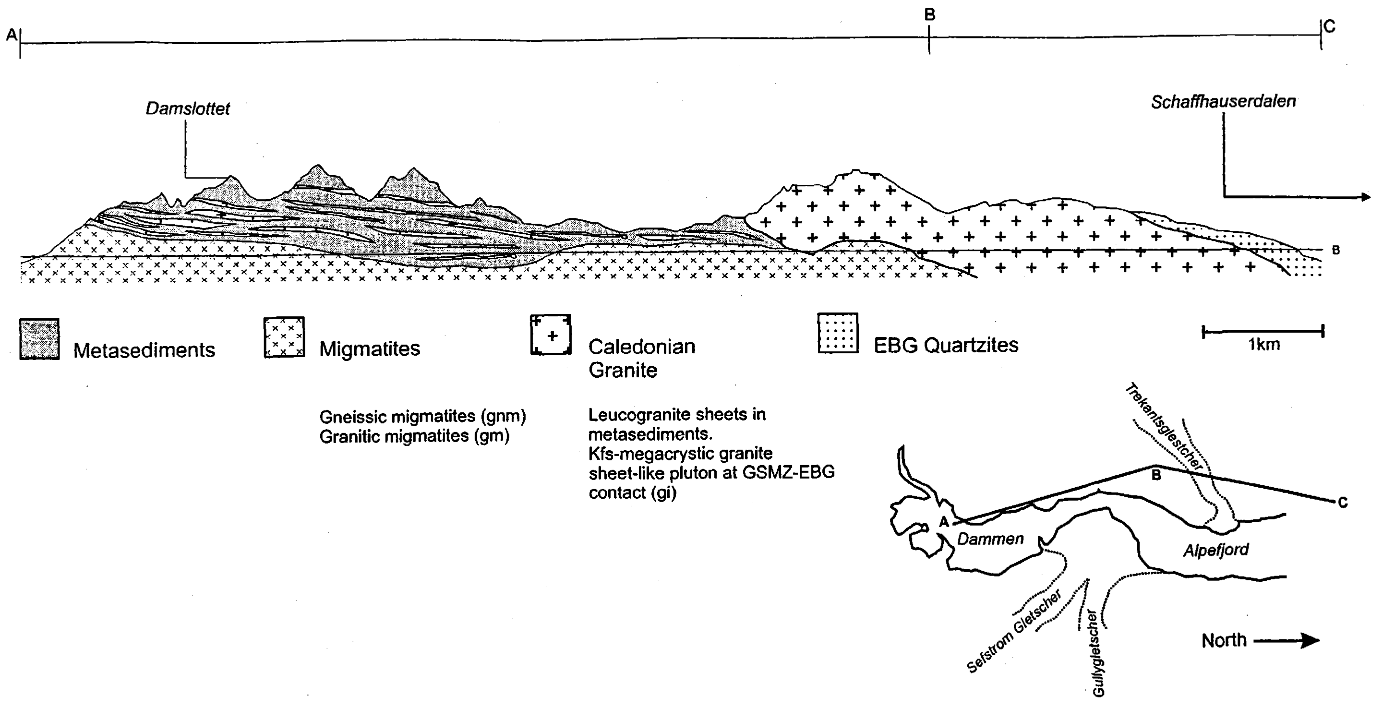

Figure 2. *Approximate S–N cross-section through the Dammen area and the southern end of Alpefjord.*

and disaggregation of metapelitic schlieren within leucocratic granite melts, good migmatitic fabrics have developed. These areas reflect the close interplay between melt and deformation – deformation is focused into areas where granite veining has been extensive enough to disrupt the coherence of the paragneisses, thus resulting in a migmatitic appearance.

In order to minimise confusion regarding migmatite terminology, the following migmatitic and granitic 'facies' are used here (equivalent names are given in italics):

Veined paragneisses (gn)

Biotite gneisses and schists, cut by granitic or leucogranite sheets but without any *in situ* development of partial melts. These paragneisses form a large part of the northernmost GSMZ, and their exact age is unknown – they may represent either the northern extension of the Krummedal sequence paragneisses or the lowest parts of the EBG succession.

Gneissic migmatites (gnm)

Metatexites, stromatic migmatites. These are the most widespread migmatite type, but vary greatly from paragneisses with incipient patches of melt formation, through stromatic and banded migmatites with layer-parallel leucosomes, to strongly migmatised gneisses with abundant leucosomes and granite veins but which still retain a metamorphic foliation and preserve relict structures which often constrain melt migration.

Granitic migmatites (gm)
Diatexitic migmatites, anatectic granites, schlieren-rich granites. These generally have no metamorphic fabric, but contain rafts, xenoliths and schlieren of variably disaggregated metasedimentary material.

Granites (gi)
Restite-poor or restite-free leucocratic veins, sheets, dykes, sheets and plutons on a variety of scales, either intruding migmatitic rocks (and thus showing gradational contacts) or unmigmatised paragneisses (with sharp intrusive contacts).

High grade cordierite+garnet+sillimanite+spinel gneissic migmatites form the base of the exposed section at Dammen. Garnet is common, typically subhedral and often closely associated with cordierite. Coarse-grained cordierite-rich leucogranites form sub-vertical dykes that cross-cut a flat lying earlier stromatic migmatite fabric, which is probably extensional in origin (suggested by the boudinaging of unmelted psammitic xenoliths). On the east shore of Dammen these sub-vertical leucogranites appear to coalesce upwards and pond in horizontal (foliation parallel) leucogranite sheets. Where melts accumulate into anatectic granites and more diatexitic areas, xenoliths of pelitic material comprise very coarse-grained cordierite+garnet gneisses, similar in appearance to melanosomes of both the earlier migmatites and the subvertical leucogranite dykes. Excellently exposed syntectonic melt segregation structures are preserved on the northern margin of Fureso, where cordierite-rich melts can be seen migrating into extensional structures such as boudin necks and small shear zones. The majority of deformation witnessed in the migmatites of the GSMZ around Dammen and Furesø appears to have been synchronous with melting. On the north side of Furesø, gneissic migmatites show folded leucosomes with steep axial planes indicating dextral shearing. Larger, coarse cordierite-bearing leucosomes which merge with the folded leucosomes show no consistent orientations, and occur in boudin necks and shear zones and as patches which appear to cut across these earlier migmatite leucosomes in some areas. Folding of xenoliths within more melt-rich areas shows no consistent sense of orientation The cores of these patches are often choked with coarse, almost monomineralic cordierite – these textures have been interpreted by White & Chappell (1991) as evidence for flushing of large volumes of melt. If this interpretation is correct, then the amount of melting that has occurred in the GSMZ may be much greater than previously suspected, and these patch migmatites may represent relict pathways along which granitic melts have ascended (e.g. Petford *et al.* 1993).

2.2 Metamorphic conditions

The abundance of cordierite throughout most of the Stauning Alper region of the GSMZ suggests that metamorphism occurred under relatively low pressures (Hensen & Green 1973; Holdaway & Lee 1977). Cordierite occurs in three main associations in the Dammen migmatites. Most commonly it is found as granoblastic grains up to 5 mm in diameter in migmatitic melanosomes, intergrown with garnet, sillimanite and spinel. This assemblage is consistent with decompression of high grade granulite facies assemblages, and occurs in syn-melting fabrics implying that melting and uplift were synchronous. Rare euhedral, fresh, blue magmatic cordierite has been recorded in some diatexitic leucosomes, but when found in leucogranites it more typically occurs as large (up to 10 cm in diameter) quartz-cordierite symplectic porphyroblasts in relatively restite-free areas. Rounded quartz intergrowths in almandine garnet are a common feature of garnet growth in the presence of a melt when garnet forms as a peritectic phase during water-undersaturated melting. Melting reactions are, as yet, poorly constrained, but the abundance of cordierite in leucosomes and melanosomes suggests that melting occurred at relatively low pressure (<0.4–0.5 GPa). One likely melt-producing reaction is:

bt + sil + qz = grt (crd at low P) ± kfs + melt

(Thompson 1983; Peterson & Newton 1989; Carrington & Watt 1995). If melts were produced by this reaction then maximum temperatures can be constrained to >750°C at pressures of 0.4–0.5 GPa, and portions of the resulting water-undersaturated granitic melts

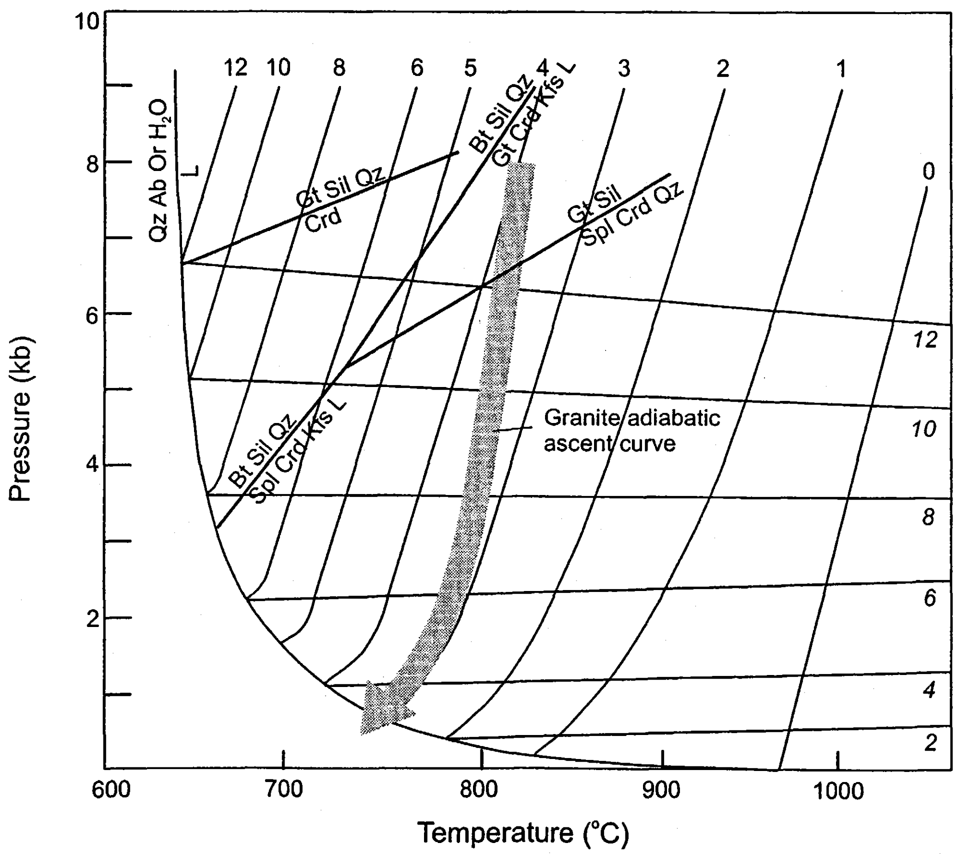

Figure 3. *P-T diagram showing the main melt producing and decompression reactions in granulite facies migmatites. The large grey arrow shows the calculated P-T ascent curve for a granitic melt containing 2 wt% H2O, formed at 820°C and ascending adiabatically. Dry melts formed in granulite facies terranes can ascend great distances in the crust, since crystallisation will not occur until the wet granite solidus is reached. In contrast, as soon as melts formed on the wet granite solidus (Qz+Ab+Or+H_2O = L) start to ascend they intersect the solidus and crystallise.*

could ascend without immediate crystallisation (Fig. 3). The formation of water-undersaturated melts is associated with metamorphism under granulite facies conditions, suggesting that in some areas metamorphic grade exceeded the upper amphibolite grade suggested by Thyrsted (1978). In contrast to the high grade gneissic migmatites of the Dammen region, the "migmatites" of Forsblad Fjord, which occur beneath the contact with the EBG and form much of the northern shore of the central part of the fjord, are lower grade, and comprise mainly psammitic and biotite-sillimanite gneisses veined by leucogranite material, rather than true migmatitic gneisses undergoing anatexis *in situ*. Melanosomes are only rarely developed, and leucocratic veins are deformed, boudinaged and folded along with the country rocks. Both paragneisses and veins are folded by small isoclinal folds with steep axial planes parallel to foliation and hinges which plunge gently south-west. At the western end of Forsblad Fjord, close to the "Fjord Region Detachment" which Andresen & Hartz (in press) interpret as a major top-down-to-the-east extensional detachment, kyanite occurs as the main aluminosilicate mineral; further east sillimanite dominates. Relatively low temperature conditions (compared to the Dammen area) are also reflected by the behaviour of many of the xenoliths within the anatectic granites and granitic migmatites exposed at Caledoniaø. Rafts and schollen within these granitic migmatites are comprised of abundant biotite schlieren, psammitic xenoliths with rounded margins and veined metapelitic blocks. Little or no melting or disaggregation is evident within even the most heavily veined xenoliths. A northwards decrease in the amount of melting and granite volumes in the area is consistent with other regional studies, suggesting that the GSMZ is exposed south of Forsblad Fjord as a tilted mid-crustal block, exposing progressively deeper rocks southwards towards Scoresby Sund (where granulitic rocks have been recorded, e.g. Chadwick 1975).

2.3 U-Pb dating

Zircons from one sample of gneissic migmatite have been analysed using SHRIMP at the Isotope Science Research Centre, Perth, Western Australia. The analyses were performed *in situ* in thin section to constrain whether the analysed zircons formed during melting or represent pre-existing detrital zircons.

Analytical technique

Sensitivity for Pb isotopes was *c.* 13 cps/ppm/nA for zircon; primary beam current 3.5 nA; mass resolution (1% valley) *c.* 5000. Correction of measured isotope ratios for common Pb was based on the measured ^{204}Pb. Beam overlap due to the small size of the zircons in the analysed sample, coupled with the increased surface contamination due to section relief, led to relatively large ^{204}Pb corrections being applied (Table 1). The common Pb component, being largely surface contaminant, was modelled on the composition of Broken Hill ore Pb. Pb/U isotopic ratios in the case of zircon, were corrected for instrumental inter-element discrimination using the observed co-variation between Pb+/U+ and UO+/U+ (Compston *et al.* 1984, 1992, 1995) determined from interspersed analyses of the Perth standard zircon CZ3 (564 Ma; ^{206}Pb/^{238}U = 0.0914). The uncertainty per data set associated with this correction was 2.0%.

Table 1. 204Pb corrected SHRIMP data for Sample 441341.

Analysis	U (ppm)	Th (ppm)	Th/U	^{204}Pb (counts)	$^{204}Pb/^{206}Pb$	$^{206}Pb^{*}/^{238}U$	$^{207}Pb^{*}/^{235}U$	$^{207}Pb^{*}/^{206}Pb^{*}$	Age (Ma)
441341-1	258	187	0.72558	20	0.00007 ±0.00002	0.29000 ±0.00310	4.06982 ±0.05384	0.10179 +/-0.00067	1657 +/-12
441341-2	389	72	0.18480	2561	0.01002 ±0.00020	0.24029 ±0.00268	3.17815 ±0.13541	0.09593 +/-0.00381	1546 +/-75
441341-3	367	65	0.17807	267	0.00152 ±0.00010	0.25950 ±0.00282	3.59847 ±0.07539	0.10057 +/-0.00167	1635 +/-31
441341-4	476	175	0.36715	97	0.00024 ±0.00003	0.30289 ±0.00312	4.44550 ±0.05506	0.10645 +/-0.00061	1739 +/-10
441341-5	614	128	0.20823	134	0.00028 ±0.00003	0.26828 ±0.00274	3.68800 ±0.04560	0.09970 +/-0.00058	1619 +/-11
441341-6	278	169	0.60658	36	0.00015 ±0.00003	0.25768 ±0.00275	3.33285 ±0.04685	0.09381 +/-0.00075	1504 +/-15
441341-7	285	232	0.81322	633	0.00409 ±0.00017	0.21092 ±0.00234	2.93777 ±0.09403	0.10102 +/-0.00290	1643 +/-53
441341-8	409	64	0.15727	135	0.00064 ±0.00006	0.17325 ±0.00182	3.11540 ±0.04590	0.13042 +/-0.00118	2104 +/-16
441341-9	338	152	0.45096	115	0.00054 ±0.00006	0.23928 ±0.00253	3.09868 ±0.04987	0.09392 +/-0.00102	1507 +/-21
441341-10	108	61	0.56163	102	0.00116 ±0.00013	0.27239 ±0.00326	4.10427 ±0.10303	0.10928 +/-0.00225	1787 +/-38
441341-11	630	300	0.47605	217	0.00043 ±0.00003	0.28480 ±0.00290	4.04452 ±0.05012	0.10300 +/-0.00061	1679 +/-11

Sample and zircon characteristics

The sample analysed (441341) was collected from a series of cordierite-rich stromatic gneissic migmatites on the northern shore of Furesø (UTM: 26X 0534405 7991997). It is a typical banded stromatic migmatite of semi-pelitic composition with isoclinally folded granitic leucosomes up to 1 cm wide and narrow biotite- and spinel-rich melanosomes (2–3 mm). Zircons are concentrated in the melanosome and mesosome areas of the sample, and most typically occur as inclusions within biotite. Larger grains are also found in more leucocratic portions of the mesosome. Zircons are small (typically less than 50 μm in diameter), rounded and show no evidence for new rim growth related to dissolution or regrowth during partial melting.

Results and interpretation

Analytical results are shown in Table 1. Due to problems with correction for common Pb (based on measured ^{204}Pb concentrations) due to beam spot overlap and surface contamination, the SHRIMP data shows a considerable spread (Fig. 4). Two data sets can be recognised on the basis of the size of the ^{204}Pb correction (Table 1). A group of samples with reasonably concordant ages and small errors (with small amounts of contaminant ^{204}Pb and correspondingly small corrections for common Pb) and a series of points (shaded symbols) with large common Pb corrections which lie off the concordia. We believe that the near-concordant zircon analyses (which range in age from 1739±10 Ma to 1504±15 Ma) represent an entrained mid-Proterozoic zircon population. Further work on zircon separates will be required to determine whether the spread of this data is real (e.g. there are several sources for the metasedimentary gneisses in the Furesø area) or whether partial resetting (perhaps by Caledonian migmatisation) has occurred.

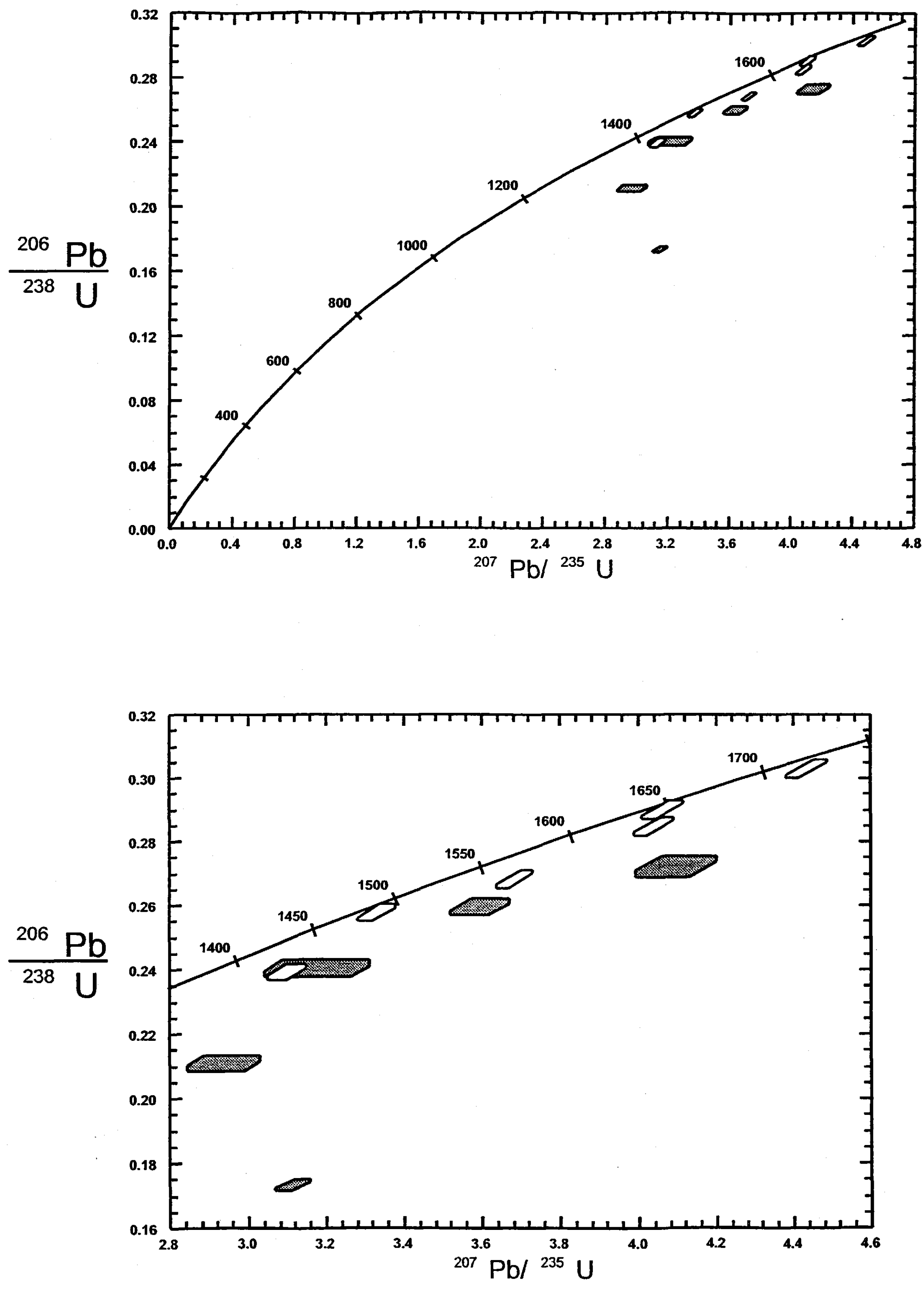

Figure 4. *SHRIMP data for sample 441341, a gneissic migmatite from the north side of Fureshø. Data shows a considerable spread resulting from common Pb correction errors as a result of high background ^{204}Pb. (Open symbols – low ^{204}Pb contents; Shaded symbols – high ^{204}Pb contents).*

3. Granitic rocks

3.1 Relationships with host rocks

A transition from ductile anatectic granites to veined and agmatitic quartzite and upwards into sheeted granite bodies (interleaved with migmatitic paragneisses) is excellently exposed at the eastern end of Forsblad Fjord. Here a series of granitic veins cut EBG quartzites and appear to feed large sheet-like Caledonian granites. In Dammen, the same upwards progression from migmatitic metapelites and anatectic granites to sheeted granites and paragneisses occurs. Granite sheets increase in number and thickness upwards towards the summits of the Stauning Alper, which are often comprised of massive sheets of granite up to 500–600 m thick. The sheeted granite zones are characterised by two-mica leucogranite sheets concordant to the foliation, which typically contain small clumps of biotite (perhaps pseudomorphing cordierite) and more scattered muscovite. At Randenæs, and on the southern side of Forsblad Fjord east of Caledonia¯, the sheeted granite-metasediment zone contains cross-cutting, subvertical granite and pegmatite dykes and agmatitic psammites, while in the Dammen area the sheets are mainly concordant with the foliation in the more migmatitic host rocks.

Several Caledonian granite bodies were studied for comparison with migmatite leucosome compositions. On the west shore of Alpefjord and Dammen a subhorizontal contact occurs between migmatitic paragneisses and anatectic granites (below) and a thick (200–300 m) weakly foliated and lineated K-feldspar megacrystic granite. This granite has been intruded along the contact between GSMZ migmatites and the lower part of the EBG in Alpefjord (Fig. 2). Further north this granite shows a very sharp upper contact with overlying EBG quartzites. At the contact the granite develops a coarse leucocratic pegmatitic facies up to 15 cm thick, which is cut by small normal faults showing extension down-to-the-east. Small fine-grained granitic and aplitic veins intrude along these faults, indicating that the final crystallisation of the granites occurred before eastwards extension was complete. In pelitic layers within the EBG quartzites right on the contact small spots of cordierite are common. Further north, in EBG quartzites approximately 5 km west of Kap Mæchel, small flames of granite can be seen intruding along the quartzite foliation and rafts and blocks of quartzite appear to float in the granite. These stoping textures are unlikely to represent the ascent mechanism of the granites, since the majority of the larger plutons contain little or no entrained restitic material or enclaves, and more likely reflect processes occurring at the depth of emplacement.

3.2 Structures, fabrics and timing of melting and emplacement

The majority of the leucocratic Caledonian granite sheets can be considered post-kinematic – they preserve no evidence of any metamorphic fabrics and cross-cut host rock foliations in strongly deformed basal EBG quartzites. On the west side of Dammen, and in several fallen boulder samples around the south end of Dammen, it appears that unfoliated Caledonian granites cross-cut the foliation developed in the migmatitic paragneisses, implying that granite emplacement was post-tectonic (and, hence, post-extensional). Some Caledonian age granites are deformed, however. The large K-feldspar megacrystic granite noted on the western side of Dammen and Alpefjord at the contact between the EBG and GSMZ has developed a weakly foliated and lineated fabric with K-feldspar megacrysts plunging gently eastwards. This granite is clearly Caledonian in age as it intrudes strongly deformed EBG quartzites. If the fabric is syn-emplacement (e.g. igneous in origin) then the granite may have been intruded into an extensional shear with top to the east displacement between the GSMZ migmatites to the south and the EBG to the north (presumably with a dextral component to the movement as well). If the fabric was developed after intrusion then the deformation event which forms the main EBG foliation must post-date granite emplacement in some areas and pre-date it in others. In summary, the strong structural control on many of the migmatite leucosomes, in addition to the complex deformation patterns exhibited by many of the gneissic migmatites and anatectic granites, suggests that the majority of the melting in the GSMZ occurred at an early stage of the extensional deformation which is recorded throughout the Dammen and Alpefjord area. In contrast, relationships between the Caledonian leucogranites and host migmatitic and metasedimentary lithologies suggests that the majority of granites were emplaced after the main phase of deformation. Some early Caledonian leucogranites do show evidence for extension and were presumably emplaced early in the orogenic history, and evidence exists that some extension was still occurring during the last stages of crystallisation.

3.3 Tectonic setting

Syntectonic water-undersaturated melting in an extensional regime provides an excellent setting for the extraction, coalescence and upwards ascent of granitic melt (e.g. Clemens 1992; Scaillet *et al.* 1995; Carr 1992) and it is possible that some of the granitic material in the Caledonian granites may come from partial melting of the sedimentary succession. Several important aspects of their generation and emplacement remain unclear at this stage, however. Were the migmatites associated with the Caledonian granites formed by crustal thickening (e.g. Barrovian metamorphism) or are they related to crustal thinning and heating during the extensional regime seen throughout the region? Large scale horizontal structures (notably flat-lying foliations and recumbent folds) are common features of terrains undergoing extensional collapse after crustal thickening (Sandiford 1989). Extension may be initiated by a reduction in horizontal compression or by detachment of the thickened lower boundary layer during convergence. Metamorphic belts showing extensional collapse commonly contain large late to post-tectonic granite and leucogranite bodies formed by decompression melting as mid-crustal levels are unroofed (Swapp & Hollister 1991; Carr 1992, Scaillet *et al.* 1995). The GSMZ migmatites, which we interpret as the footwall to a large extensional contact which brought high grade rocks up from depth, show early, water-saturated melting (stromatic migmatites), later, cordierite-bearing leucosomes which may be related to water-undersaturated decompression melting (e.g. Carson *et al.* 1997) and decompression textures consistent with rapid uplift. In the southern GSMZ the contrasting migmatite morphologies (water-saturated and water-undersaturated) have been interpreted as two separate events, but may be better considered as two stages of melting in one metamorphic cycle. If this is the case, and decompression melting has given rise to large volumes of granitic melt, then the majority of the post-tectonic Caledonian granites may have formed at greater depths than the surrounding migmatites.

Further uncertainty exists as to when the melting and granite emplacement occurred – do the gneissic migmatites represent a "Grenvillian" melting event which was subsequently reworked by Caledonian anatexis or are they simply the earliest structures formed during Caledonian syn-deformational migmatisation? Why do the migmatites and anatectic granites found at lower structural levels have strong, predominantly flat-lying fabrics, whereas the Caledonian granites (whose sheeted nature and location at a possible major tectonic boundary suggests that their emplacement may be controlled by extensional and dilatational jogs) are, on the whole, undeformed? One hypothesis is that the Caledonian granites, sheeted granitic dykes and migmatites result from the intrusion of magmas into different levels of the crustal pile. The agmatitic quartzites of the EBG have deformed in a brittle way, with evidence for stoping at emplacement levels during the latest parts of the orogeny. Lower in the crustal pile, where more ductile deformation regimes occur and ambient temperatures are hotter, granites have more concordant geometries and often merge with migmatitic rocks. Crustal temperatures may have been enhanced by large volumes of granitic magmas, but country rock temperatures must have been high enough (by heating during either crustal thickening or extension) to generate melts. Subsequent extension may have juxtaposed the different structural layers. If this hypothesis is correct then the source for the granites may lie at a deeper level and is not currently exposed, consistent with the absence in the area of any large restitic portions of lower crust.

4. Concluding remarks

The relationships between the migmatites of Nathorst Land and the Caledonian Stauning Alper granites are still, as yet, unclear. Detailed SHRIMP analysis of zircons from the migmatitic paragneisses should help in our understanding of the origin of these granites, by providing both protolith and melting ages from the surrounding migmatites. It is hoped that we will be able to trace protolith zircon populations upwards as they ascend as entrained restitic material in leucogranite veins and concordant sheets. Other aims are to distinguish, if a distinction exists, between paragneisses of lower EBG origin and older metasedimentary units within the GSMZ, in order to distinguish granite source regions and to evaluate the apparently important role that the contact between these two units has played in determining the emplacement level of the Stauning Alper Caledonian granites. If the source rocks for the Caledonian granites can be recognised, and the timing of the melting events within the metasedimentary units which host these granites (along with the crystallisation ages of the Caledonian plutons) established we will have a much better understanding of the Caledonian and pre-Caledonian evolution of the Stauning Alper and Nathorst Land regions, and a much fuller appreciation of how granites are formed, how they migrate from their melting sites and ascend in the crust, and what controls their emplacement and final geometry.

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Magnetic susceptibilities of rocks in Gletscherland, Nathorst Land and Charcot Land, East Greenland

Vera Schlindwein

Abstract: Magnetic susceptibilities of typical rocks in Gletscherland, Nathorst Land, and Charcot Land were measured in order to supplement the aeromagnetic survey of East Greenland flown by the Alfred Wegener Institute for Polar and Marine Research (AWI), Bremerhaven, in 1993–1996. Pronounced magnetic anomalies distinguish the study area from the otherwise weakly magnetic Caledonian mountain range. The crystalline rocks of the study area have low magnetic susceptibilities with a few exceptions. A magnetite-bearing granitic gneiss was found to account for the anomalies over Gletscherland. In Nathorst Land, highly magnetic layers within metasedimentary sequences were detected, and are probably responsible for the magnetic signature. The non-magnetic basement rocks of Charcot Land are surrounded by magnetically susceptible supracrustal rocks with a low-grade metamorphic overprint.

VS: *Alfred Wegener Institute for Polar and Marine Research, Columbusstrasse, D-27568 Bremerhaven, Germany*

Following the aeromagnetic survey of East Greenland between 70°N and 84°N carried out by the Alfred Wegener Institute for Polar and Marine Research (AWI), Bremerhaven, in 1993–1996, the 1997–1998 geological mapping project by the Geological Survey of Denmark and Greenland (GEUS) of the region between 72°N and 75°N provided the ideal logistic and scientific basis for detailed ground studies of magnetically anomalous areas. Of special interest were the high amplitude magnetic anomalies of Gletscherland, the extended area of flat anomalies in Nathorst Land and the anomalies associated with the Charcot Land window (Fig. 1). In order to detect possible sources of magnetic anomalies, the magnetic properties of the surface rocks needed to be measured. In this study, the measurements were confined to determining the magnetic susceptibility.

1. Data acquisition and processing

The field work consisted of collecting *in situ* susceptibility data together with geological observations of the studied rock types, their extent and relationships to other rocks. Altogether 102 localities were visited from seven different field camps (Fig. 2). The magnetic susceptibilities were measured with an Exploranium KT-9 kappameter. For a statistically significant database, between 10 and 150 susceptibility readings were taken per locality, depending upon the homogeneity of the exposed rocks or the size of the outcrop. In total, 3330 susceptibility values were recorded. In a few cases, bands of potentially magnetite-bearing rocks were over-represented in the measurements at a locality. The relative proportion of these rocks in the examined outcrop was estimated and the data were weighted accordingly for the calculation of site mean values. The susceptibility data were classified in several groups according to lithology and geological provinces. The classification is based on field observations and on the geological map by Koch & Haller (1971). Site

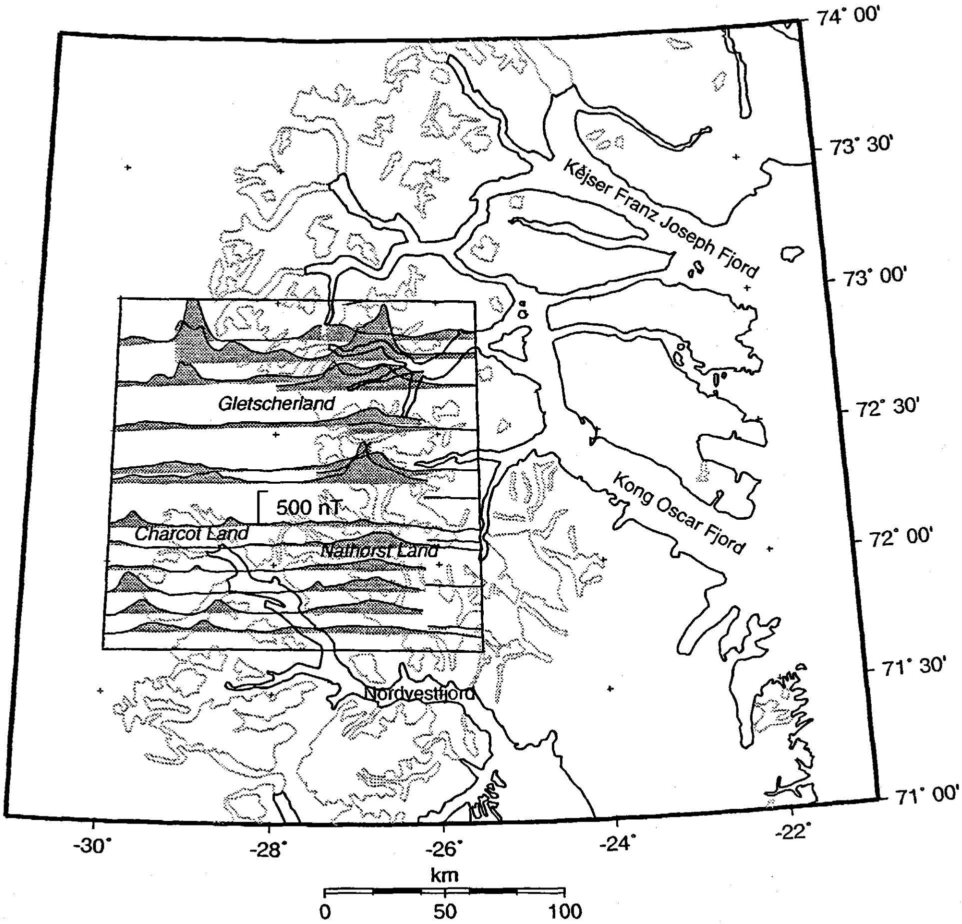

Figure 1. *Location of the study area. Aeromagnetic anomalies are displayed as wiggles, positive anomalies are shaded. Scale valid at 72° N. For legend see Figure 2.*

means were calculated for all localities taking weighting factors into account. The results are shown in the logarithmic bar plots of Figures 3–5.

2. Magnetic minerals

Ferrimagnetic minerals yield the largest contribution to the magnetic susceptibility of a rock. Magnetite (Fe_3O_4) and its solid solution with ulvospinel (Fe_2TiO_4) are considered to be the dominant ferrimagnetic phases for magnetic studies of crustal rocks (Blakely & Connard 1989). The volume fraction 'f' of magnetite in a rock sample can be estimated from its magnetic susceptibility κ by the approximate relationship (see Shive *et al.* 1992, for references):

$$f \approx \frac{5}{4\pi}\kappa$$

Whereas diamagnetic minerals like quartz or plagioclase do not produce a significant susceptibility, paramagnetic minerals such as biotite, amphibole, pyroxene or olivine typically have susceptibilities between 0.75 and $3 \cdot 10^{-3}$ SI units (Henkel 1991).

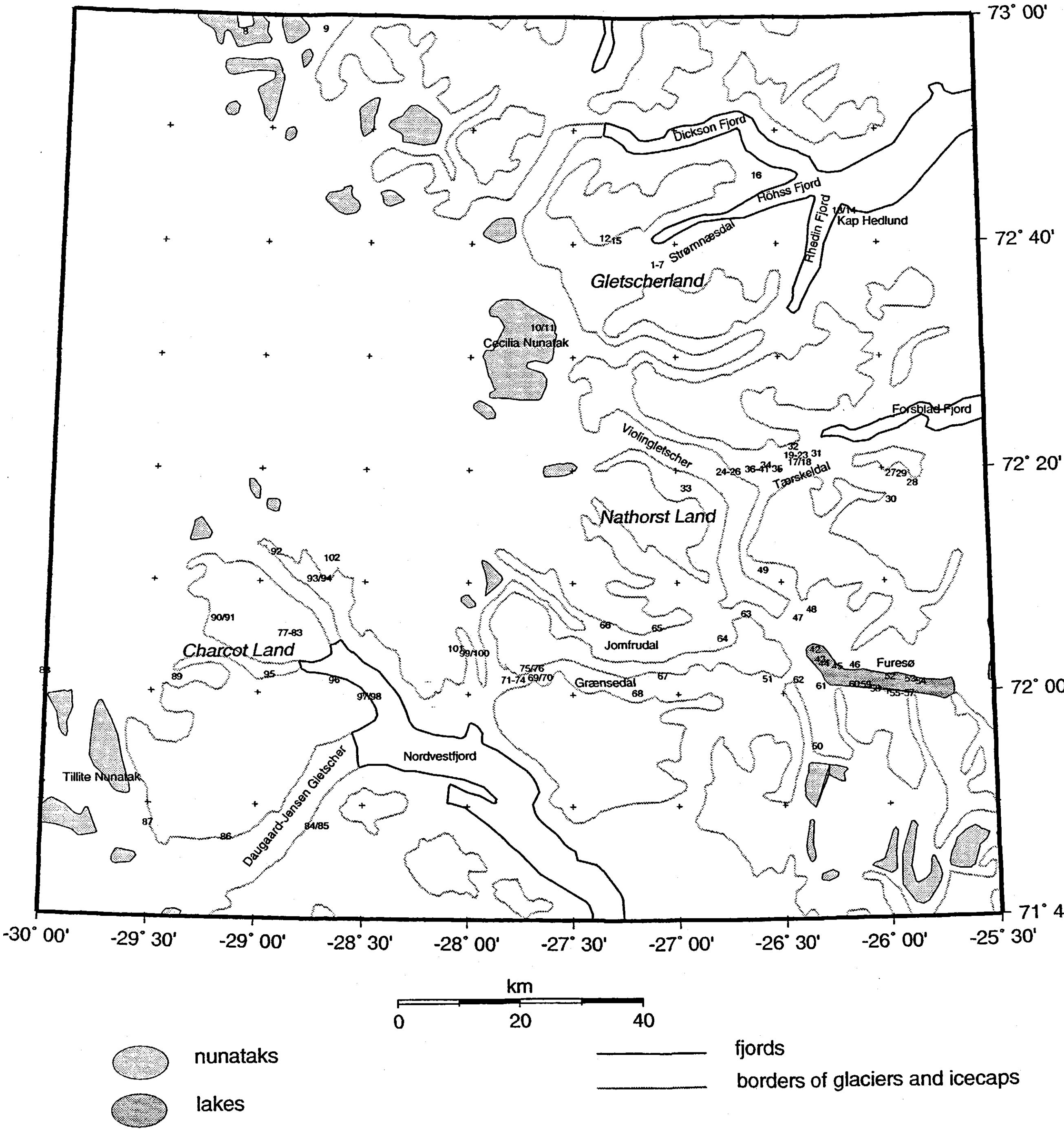

Figure 2. *Localities of susceptibility measurements. The positions of the localities are indicated by their numbers. For clarity, closely spaced localities are grouped (e.g. 36 –41 in Tærskeldal).*

3. Susceptibilities and geological observations

Basement rocks

In Figure 3 the site mean susceptibilities of basement lithologies are displayed. Following Higgins *et al.* (1981) the terminology "basement" is used here to describe infracrustal gneiss complexes, especially the Gletscherland complex (Fig. 2).

The basement gneisses include a variety of well banded, often veined, grey hornblende, biotite and granitic gneisses. The variety of the gneisses is reflected by the site mean susceptibilities. About a third of the site mean susceptibilities concentrate at low values of $0.3 \cdot 10^{-3}$ SI units, which may mainly reflect the susceptibility of the paramagnetic minerals included in the gneiss. In addition, a range of site means between 1 and $20 \cdot 10^{-3}$ SI units is observed, which probably witness to a corresponding range of magnetite concentrations of 0.4‰, to 8‰. At localities 3, 5 and 65 magnetite was seen in hand specimen.

Dark amphibolitic bands and lenses are plentiful within the basement complex. They are concordant and deformed together with the basement gneisses. The measurements listed in this group stem from bands of at least metre size, whereas measurements from thin bands within the gneisses were incorporated into the class of basement gneisses. Magnetically, the amphibolites are characterised by fairly uniform site means of about $1 \cdot 10^{-3}$ SI units, reflecting the typical susceptibility of its mafic, paramagnetic mineralogy as observed by Henkel (1991).

A chain of ultramafic bodies ranging in size between 2 x 5 m and about 50 x 500 m is embedded in the gneisses of Tærskeldal (localities 19, 21, 25, 35). They are in part heavily altered and show a variety of mineral assemblages including olivine, clinopyroxene, amphibole, hornblende and bronzite. The range of site mean susceptibilities between 10 and $70 \cdot 10^{-3}$ SI units testifies to a varying content of ferrimagnetic minerals. The ultramafic body encountered at locality 85 east of Daugaard-Jensen Gletscher fits into this picture.

Localities 15,16 and 33 were identified on the aeromagnetic map as centres of major positive anomalies. At all three localities a light grey to pinkish, medium-grained homogeneous magnetite-bearing granitic gneiss was found, consisting mainly of quartz, feldspar and biotite. Garnet is absent. Compared to the basement gneisses, the granitic gneiss is weakly deformed and foliated, with leucocratic veins and pockets cross-cutting the gneissosity. The presence of oxides can be guessed from the appearance of the weathered surfaces. At locality 16, dark schlieren of pure magnetite were seen, making up roughly 50% of some boulders. Apart from these bands, the rock type is fairly homogeneously magnetic with high average susceptibilities of about $40 \cdot 10^{-3}$ SI units at all localities. The outcrops are each of roughly km size. At locality 33 south-west of Violingletscher, the contact to the surrounding gneisses is exposed showing clearly that the granitic gneiss crosscuts older structures of the basement gneisses.

Supracrustal rocks

A variety of supracrustal rocks were examined in the field. The resulting site mean susceptibilities are shown in Figure 4.

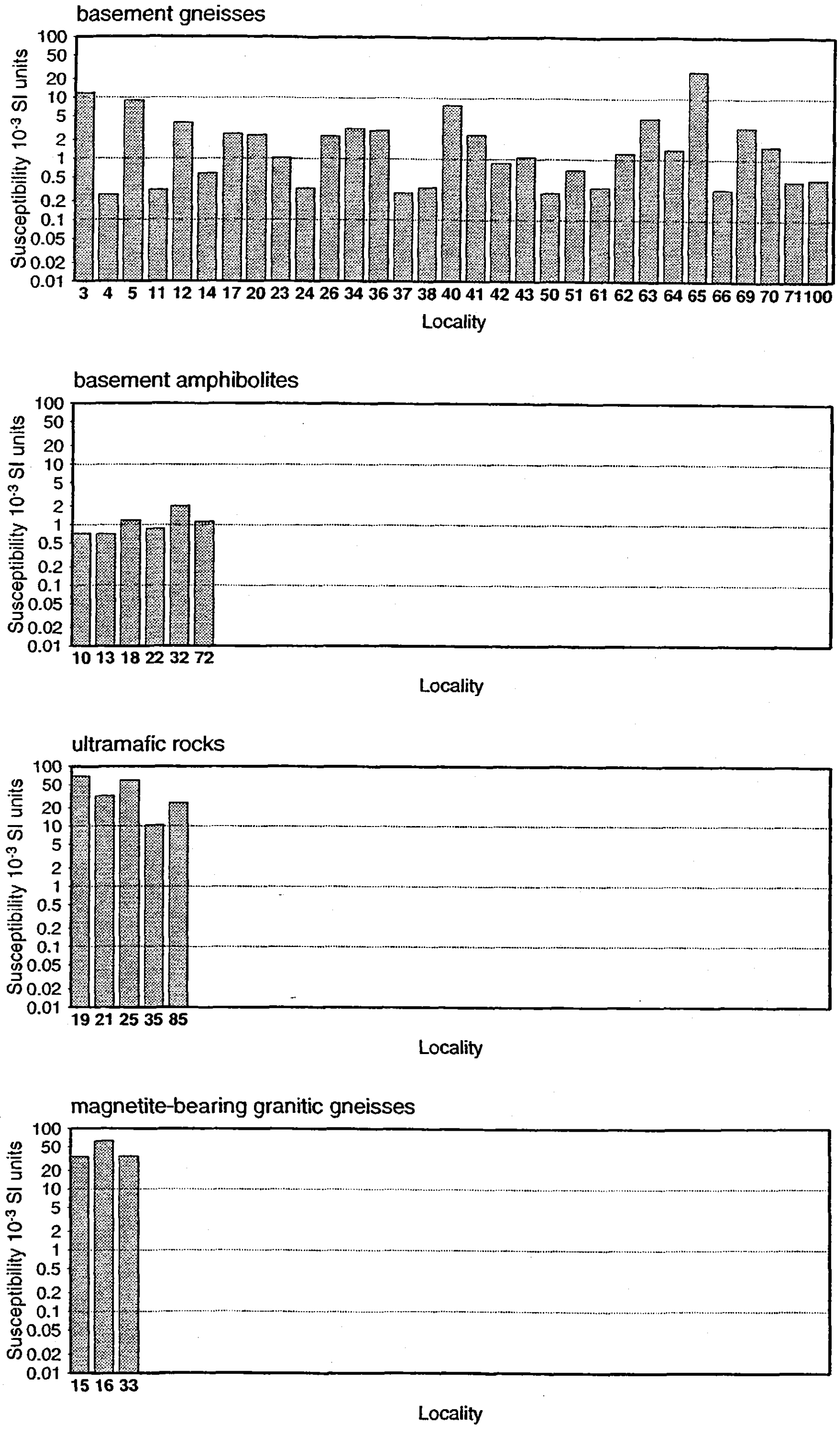

Figure 3. *Site mean susceptibilities for different lithologies of the infracrustal gneiss complexes. The positions of the localities are shown in Figure 2. The lithologies are described in the text.*

Included in the basement complex are enclaves of metasedimentary rock units, notably marble-amphibolite associations and rusty red weathering metasediments. Their character is similar to the Krummedal supracrustal sequence, but their relationships are not firmly established (Henriksen 1985). The rock type is weakly magnetic showing typically susceptibilities of about $0.4 \cdot 10^{-3}$ SI units. However, two exceptions occur, showing one order of magnitude higher susceptibilities. At locality 7 in Strømnæsdal, a thin mafic band making up less than 10% of the outcrop of metasedimentary rocks yielded a susceptibility of about $23 \cdot 10^{-3}$ SI units, giving rise to the increased site mean value. Locality 73 in Græensedal consists of a very weathered mica-garnet-schist which is adjacent to a prominent magnetic amphibolitic band (localities 74 and 76).

The association of amphibolites with marbles in the supracrustal sequences is very common in the region. However, in the area around Jomfrudal and Græensedal strikingly magnetic varieties of the amphibolitic rocks were found. They form part of often flat-lying metasedimentary sequences, up to a few 100 m thick, intercalated frequently in the basement gneisses. The rock type is characterised as a garnetiferous amphibolite, showing varying degrees of alteration. The site mean susceptibilities are divided in two classes and demonstrate that this rock type is not necessarily magnetite-bearing. The lower values between 1 and $4 \cdot 10^{-3}$ SI units are typical values for amphibolites comparable to those of the basement amphibolites (Fig. 3). However, an increased content of magnetite is necessary to produce the values of $17 \cdot 10^{-3}$ SI units observed at the other localities. The susceptibilities at each of these localities vary considerably (Fig. 3), testifying to a very inhomogeneous distribution of magnetite, which is not only found in the amphibolites but also encountered in thin metasedimentary layers (mica-chlorite-schist, locality 76).

The migmatite zone bordering the west side of the Gletscherland complex has been studied along the shores of Furesø. The susceptibilities are fairly homogeneous and only vary between 0.1 and $0.4 \cdot 10^{-3}$ SI units. The outlier at locality 57 with $0.01 \cdot 10^{-3}$ SI units is produced by a band of clean, recrystallized quartzites included in the sequence. Decreasing susceptibility with increasing proportion of leucosome was observed in some cases, but could not be confirmed in all cases.

During two helicopter reconnaissance flights, Eleonore Bay Supergroup (EBSG) and related metasedimentary rocks were studied. Localities 8 and 9 are situated in the western nunatak zone. At locality 9, a quartzitic rock, occurring in the lower part of the Petermann Bjerg Group (of the EBSG) was examined. Localities 28 and 29 lie in the EBSG in Schaffhauserdal close to the boundary with the migmatite complex described above. At all localities essentially non-magnetic rock types were found, as illustrated by the low site mean susceptibilities.

Charcot Land

In the Charcot Land tectonic window (Fig. 2), susceptibility measurements of the infracrustal basement rocks as well as the overlying Charcot Land supracrustal sequence were made (Fig. 5); the latter consists of metasedimentary rocks as well as basic extrusives and intrusives (Higgins 1982),

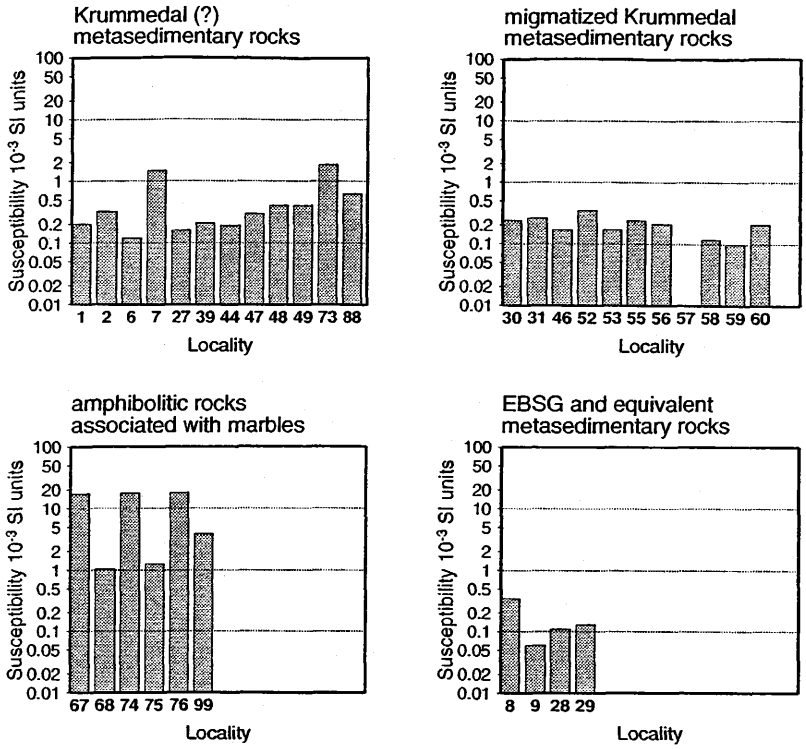

Figure 4. *Site mean susceptibilities for different supracrustal lithologies. The positions of the localities are shown in Figure 2. The lithologies are described in the text. EBSG: Eleonore Bay Supergroup.*

The site means of basement gneiss localities are displayed along with the values obtained from the muscovite-granite intrusion in Charcot Land (localities 79, 91, 95). The gneisses are veined, homogeneous, grey gneisses containing concordant bands of amphibolites. In the roof zone of the granite intrusion, the gneisses are cut by numerous pegmatite dykes which make up large proportions of the rocks close to the batholith. The susceptibilities of about $0.3 \cdot 10^{-3}$ SI units for both rock types reflect their mainly felsic nature combined with the absence of ferrimagnetic minerals.

Amphibolites were also encountered within the Charcot Land supracrustal sequence, often in association with marbles. However, measurements were only taken at two localities, which does not allow any general conclusions regarding their magnetic properties. Locality 83 shows a typical amphibolite susceptibility, whereas clearly increased values ($7 \cdot 10^{-3}$ SI units) were observed for the outcrop of amphibolites at locality 98, which is adjacent to the small lens of highly magnetic garnet-mica-schist of locality 97.

The metasedimentary rocks studied comprise pelitic to psammitic units, marbles (locality 82) and a garnet-mica-schist (locality 97). The pelitic to psammitic rocks show susceptibilities of $0.5 \cdot 10^{-3}$ SI units at all localities. The marbles are even less magnetic. The garnet-mica-schist of locality 97 has unusual magnetic properties. It shows the largest site mean susceptibility of all localities ($138 \cdot 10^{-3}$ SI units). Apart from large garnet crystals (> 5 cm) in a matrix of mica, the rock must comprise on average 5.5% magnetite. This highly magnetic garnet-mica-schist was confined to an outcrop of about 10 x 50 m surrounded by amphibolitic rocks (locality 98).

The basic intrusives and extrusives show increasing metamorphic grades towards the north. At locality 84, greenschists, representing the low-grade equivalent of lavas and tuffs (Higgins 1982), are exposed close to the thrust forming the eastern boundary of the Charcot Land window. The magnetisation increases rapidly away from the thrust towards the less sheared parts of the *c.* 50 m thick band of greenschists. Two outcrops of hornblende gabbro (Higgins 1982) yielded very different susceptibilities. Whereas the hornblende gabbro at locality 86 is clearly foliated and weakly magnetic, the gabbro at locality 87 exhibits no foliation, although the mineral assemblage testifies to a metamorphic overprint. A site mean value of about $27 \cdot 10^{-3}$ SI units is attributed to this locality. An amphibole-garnet-hornblende rock at locality 94 could represent an amphibolite facies version of the basic extrusives and intrusives. However, it could equally well belong to the class of amphibolites, although, in contrast to localities 83 and 98, it was not here associated with marbles. A susceptibility of $29 \cdot 10^{-3}$ SI units was measured.

4. Correlation with magnetic anomalies and discussion

The site mean susceptibilities together with estimates of the regional importance of the examined rock types were used for comparison with the aeromagnetic anomaly map. Locally, this qualitative analysis was supported quantitatively by 2-D forward modelling of selected magnetic anomalies. Most of the magnetic provinces in the studied area could reasonably be explained in terms of surface geology.

Gletscherland

The 2-D forward modelling showed that the pronounced magnetic anomalies between Dickson Fjord and Röhss Fjord, and south of Violingletscher (Fig. 1), can be produced by the magnetite-bearing granitic gneisses. Source dimensions smaller than 1 km x 300 m are necessary to account for the observed anomalies, using the measured susceptibilities. The outcrops were estimated to be at least of this size. Local occurrences of magnetically susceptible basement rocks (localities 3, 5) and the ultramafic bodies of Tærskeldal might contribute to the magnetic field.

The high amplitude magnetic anomalies seem to be a typical feature of the Gletscherland infracrustal complex. The degree of Caledonian reworking of this complex is controversially discussed. Haller (1971) attributed the majority of the structures to Caledonian tectonics, whereas Henriksen & Higgins (1976) and Higgins *et al.* (1981) considered the deformation of the complex to be essentially Late Archaean to Early Proterozoic in age, with only minor Caledonian overprinting.

In contrast to the Caledonian orogen as a whole, magnetite is present in large quantities in the granitic gneisses of Gletscherland. The uniform distribution of magnetite in these rocks at all studied localities suggests that magnetite is more likely to be a primary ingredi-

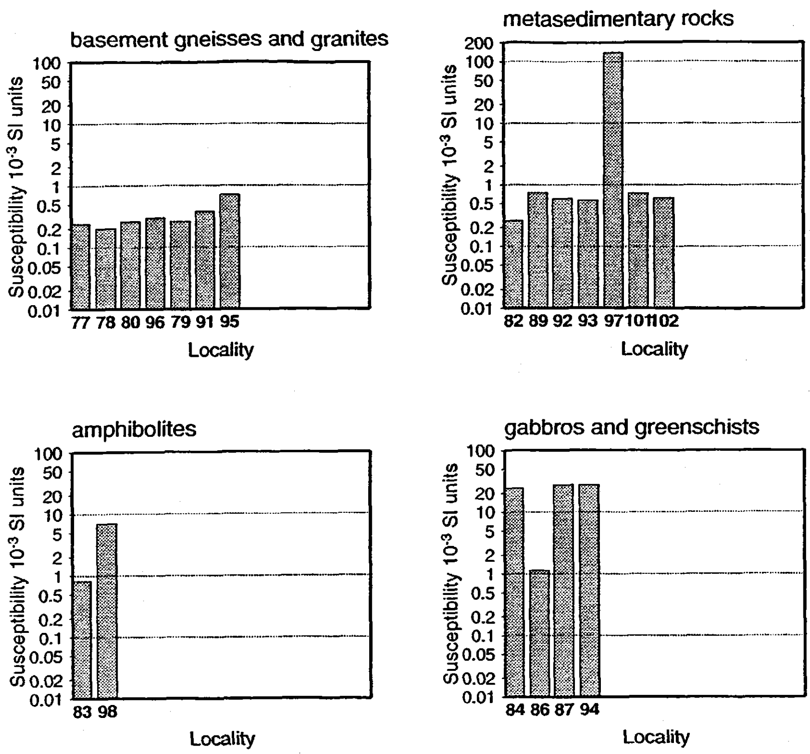

Figure 5. *Site mean susceptibilities for different lithologies of the Charcot Land window. The positions of the localities are shown in Figure 2. The lithologies are described in the text.*

ent than produced locally, for example during metamorphism at favourable P-T and compositional conditions. Age determination on this granitic gneiss yielded no conclusive results (Rex & Gledhill 1981). However, the rock cross-cuts older structures at Violingletscher and at Kap Robert (Rex & Gledhill 1981), and is itself foliated due to a Caledonian or Late Proterozoic (?) metamorphic event.

Thus, the magnetite must have survived at least Caledonian metamorphism, producing the foliation (if not acquired earlier) but retaining the magnetite. Either the special lithology of this rock could preserve magnetite during metamorphism, implying that the occurrence of this rock type is a property of the Gletscherland complex, or metamorphic conditions in Gletscherland must have been such that magnetite was not consumed (e.g. low-grade). A combination of both factors might be most likely.

Nathorst Land

Nathorst Land can be distinguished magnetically from the Gletscherland complex by the absence of high amplitude magnetic anomalies, although geologically the definition of the south end of the Gletscherland complex is difficult (Higgins *et al.* 1981; Escher & Pulvertaft 1995; Henriksen & Higgins 1976). The flat anomalies of Nathorst Land could result from magnetite-rich layers included in the marble-amphibolite metasedimentary sequences, which occur frequently in the area. Forward modelling shows that a *c.* 150 m thick, extended layer with a susceptibility corresponding to locality 76 can produce the anomaly pattern. The magnetically susceptible rocks from this area show a partial retrograde alteration. The distribution of ferrimagnetic minerals is very heterogeneous suggesting that they might have been produced locally at favourable conditions during retrogression (M. Sergeyev, personnal communication 1996). Again, this process can be attributed to a combination of favourable lithology and special metamorphic conditions characterising the region.

Charcot Land

A close link between surface geology and aeromagnetic anomalies was found in Charcot Land. The Charcot Land infracrustal rocks and the intrusion of muscovite-granite appear as magnetic lows. Nor are the metasedimentary rocks of the Charcot Land supracrustal series associated with magnetic anomalies. The volume of the strongly magnetic garnet-mica-schist at locality 96 seems to be too small to have any magnetic effect at the 3700 m high survey altitude. The ring of moderately positive anomalies around the central magnetic low coincides with exposures of weakly metamorphosed basic extrusives and intrusives as described above.

The southern, eastern and western boundary of the Charcot Land window can be inferred from the aeromagnetic data. It coincides with the geological boundary, where it is exposed, for example on Tillit Nunatak. Hence, the aeromagnetic data can be used to determine a rough boundary in the ice-covered area to the west. The northern boundary is both geologically and magnetically ambiguous due to the higher metamorphic grade of the Charcot Land supracrustal rocks making a distinction from the surrounding Caledonian complexes difficult.

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