Basement-cover relationships and regional structure in the Grandjean Fjord – Bessel Fjord region (75°–76°N), North-East Greenland

Johan D. Friderichsen, Niels Henriksen and Robin A. Strachan

Geological mapping and isotopic investigations demonstrate that the Grandjean Fjord – Bessel Fjord region can be divided into three rock groups: (1) a Lower Proterozoic basement gneiss complex; (2) a Middle Proterozoic supracrustal cover (Smallefjord sequence); and (3) Upper Proterozoic metasediments (Eleonore Bay Supergroup). The basement gneiss complex largely comprises *c.* 2.0–1.7 Ga calc-alkaline granitoid orthogneisses with intercalated migmatitic supracrustal rocks. The complex is deformed by at least two sets of approximately coaxial folds which may be either Proterozoic or Caledonian in age. The Smallefjord sequence is comprised mostly of migmatitic schists and gneisses which underwent high-grade metamorphism during the late Middle Proterozoic. The dominant deformation structures within the Smallefjord sequence are associated with the development of ductile shear zones along the boundaries of all the major tectonostratigraphic units and are thought to be Caledonian in age.

J. D. F. & N. H., Geological Survey of Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.
R. A. S., Geology & Cartography Division, School of Construction & Earth Sciences, Oxford Brookes University, Headington, Oxford OX3 0BP, U.K.

The part of the East Greenland Caledonian fold belt between Grandjean Fjord and Bessel Fjord (75°–76°N; Fig. 1) comprises the northern part of the 'Grandjean Fjord metamorphic complex' of Haller (1970, 1971). This incorporates a metamorphic complex of infracrustal and supracrustal rocks, which occurs on both sides of the graben-like enclave of Upper Proterozoic Eleonore Bay Supergroup (EBG) rocks centred on Ardencaple Fjord and Bredefjord (Fig. 1). Infracrustal rocks occur in an arcuate belt running from the inner part of Grandjean Fjord northwards along the margin of the Inland Ice to inner Bessel Fjord, then curving to follow the north side of Bessel Fjord. On the published maps of Koch & Haller (1971), infracrustal rocks were distinguished as synorogenic granite, migmatitic gneiss with amphibolite and mica schist bands, and mica schist/biotite gneiss. Metamorphosed supracrustal rocks were thought to occur mainly between the infracrustal rocks and the outcrop of the Eleonore Bay Supergroup (EBG), and were distinguished as garnet mica schists, biotite paragneisses and various siliceous schists and gneisses. In accordance with the then prevailing concept of a pervasive Caledonian orogeny (Haller, 1953, 1955, 1970, 1971), virtually all crystalline rock units were considered to be Caledonian in age, with the supracrustal rocks viewed as metamorphic derivatives of the EBG.

Geological mapping and associated isotopic investigations have confirmed that the region can be divided into three distinct rock groups, although it is now clear that they record a complex polyorogenic history. These rock groups comprise: (1) a Lower Proterozoic basement gneiss complex of gneisses and granites; (2) a Middle Proterozoic cover of semi-pelites and psammites (Smallefjord sequence of Henriksen *et al.*, 1989); and (3) Upper Proterozoic metasediments (EBG). These rock groups are everywhere separated by ductile shear zones and brittle faults.

In this contribution we summarise the lithological characteristics and regional structure of the basement gneiss complex and the Smallefjord sequence, and also review the nature of their structural relationship to the EBG. The latter topic is also dealt with by Higgins & Soper (1994). In combination with recently acquired iso-

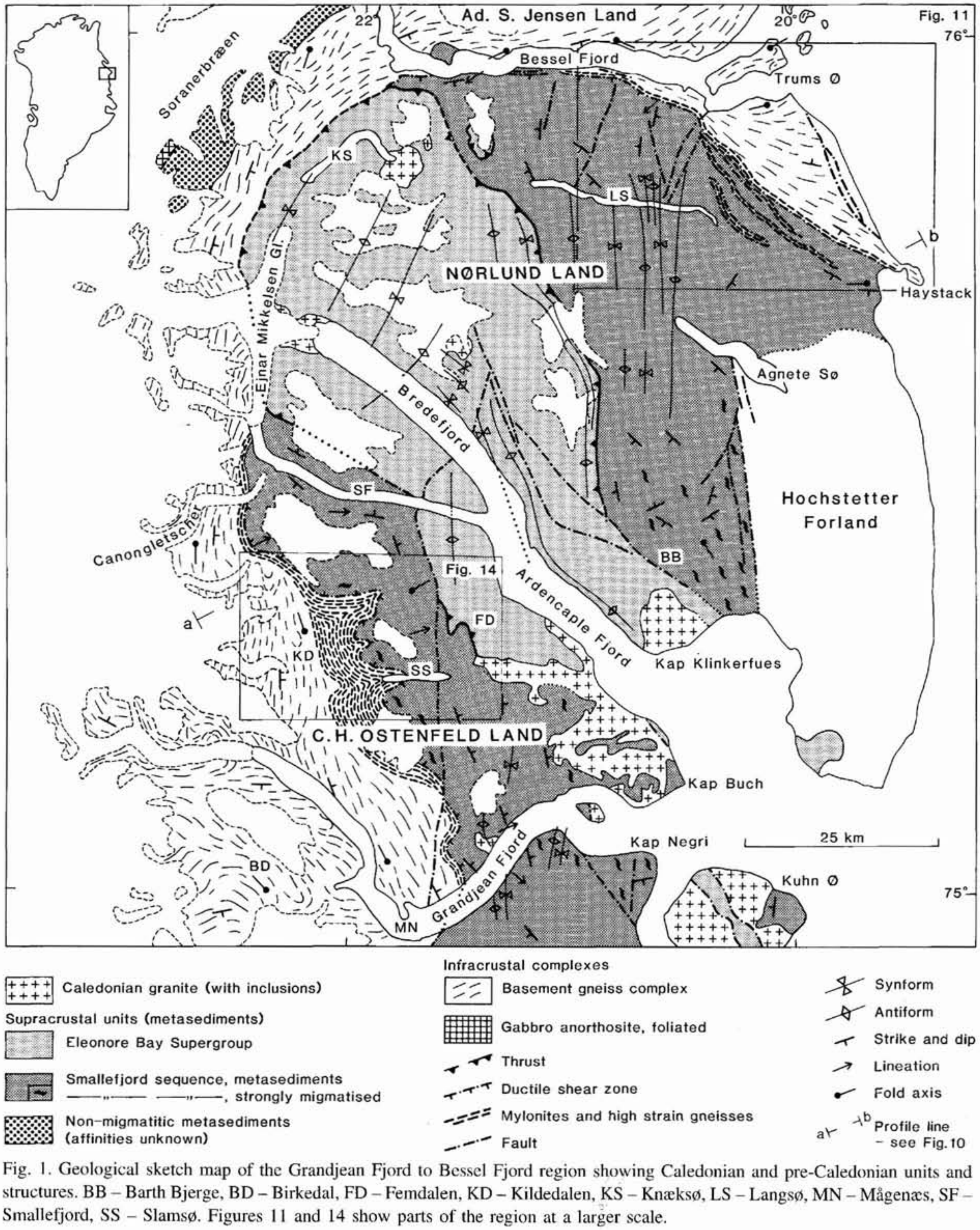


Fig. 1. Geological sketch map of the Grandjean Fjord to Bessel Fjord region showing Caledonian and pre-Caledonian units and structures. BB – Barth Bjerge, BD – Birkedal, FD – Femdalen, KD – Kildedalen, KS – Knæksø, LS – Langsø, MN – Mågenæs, SF – Smallefjord, SS – Slamsø. Figures 11 and 14 show parts of the region at a larger scale.

topic data, which place constraints on the ages of these units, this allows critical evaluation of possible regional correlations with other parts of the Caledonian belt in East Greenland.

Fig. 2. Grey banded hornblende-biotite gneiss cut by subconcordant sheets of light grey orthogneiss. Birkedal, south-west of inner Grandjean Fjord. Hammer for scale.

Basement gneiss complex

Excellent exposures of the basement gneiss complex occur along steep 1000–1500 m high valley sides and fjord sections in the west and north of the region. The basement gneiss complex occurs structurally below the Smallefjord sequence and the EBG. The main rock types are various types of tonalitic to granodioritic orthogneiss with sheets of leucocratic granitic gneiss. Concordant strips of migmatitic paragneiss are commonly interbanded with the orthogneisses. Non-migmatised metasediments interbanded with orthogneisses west of Bessel Fjord and south of Grandjean Fjord may represent a former cover sequence to the gneiss complex.

Orthogneiss

In the Grandjean Fjord – Ejnar Mikkelsen Gletscher area the orthogneisses mainly comprise grey, banded hornblende-biotite tonalitic-quartz dioritic gneisses (Fig. 2) which are cut by subconcordant centimetre to metre wide sheets of pinkish granitic-granodioritic gneiss. A major concordant sheet of quartz-monzonitic augen gneiss with 3–5 cm long microcline augen occurs at Mågenæs on the north side of Grandjean Fjord. Contacts with adjacent grey gneisses are gradational, and the augen gneiss also incorporates younger sheets of biotite-bearing granitic gneiss. A 1.5 km wide N-S trending concordant sheet of granodioritic to monzo-granitic gneiss has been traced for 7–8 km west of Kildedalen. The central part of the sheet is a foliated biotite-hornblende granodiorite, which towards the outer margin becomes gneissic; contacts with adjacent grey gneisses are transitional over 100 m. The northern part of the granodiorite sheet is a heterogeneous augen granite with amphibolite inclusions, which is cut by numerous sheets of pink granite gneiss. South of Canongletscher a 50 m wide concordant band of weakly foliated quartz diorite was emplaced into grey gneisses at a late stage in regional deformation.

The main rock types in the Ejnar Mikkelsen Gletscher – Bessel Fjord area are grey, migmatitic hornblende-biotite gneisses similar to those described above. North of Bessel Fjord, these incorporate numerous amphibolite and ultramafic pods and lenses. The gneisses are banded on a centimetre to hundred metre scale (Fig. 3). Concordant sheets of granitic gneiss occur as mappable units

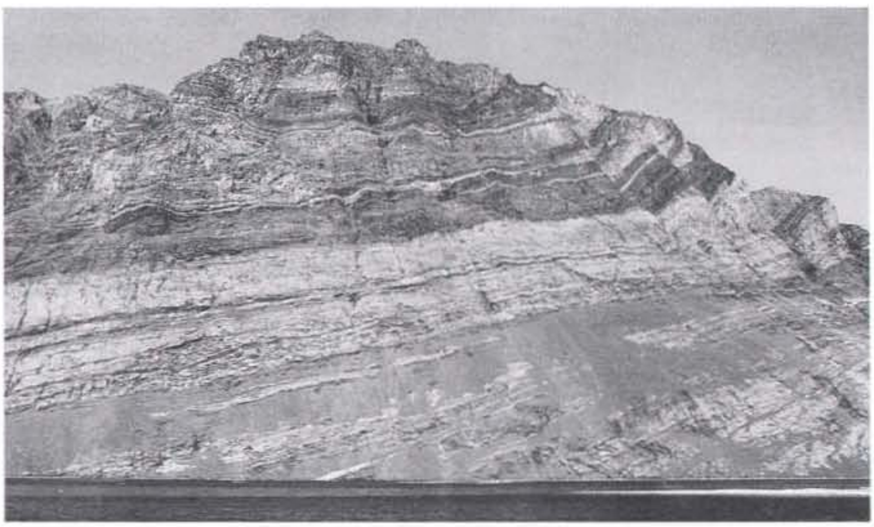


Fig. 3. Banded gneiss succession north of Trums Ø, outer Bessel Fjord. Cliff 600 m high.

Fig. 4. Quartz dioritic hornblende-biotite gneiss with relict plutonic texture cut by foliated neosome veins. This rock has yielded a Sm-Nd model age of 2.33 Ga. North of inner Bessel Fjord.

up to 100 m wide and traceable for up to 20 km; these contain inclusions of grey gneiss and amphibolite and are thus apparently younger than their host gneisses. A later series of rocks comprise various heterogeneously deformed plutonic rocks which locally preserve their original homogeneous character and plutonic textures, albeit in highly recrystallised form (Fig. 4); an example is a medium-grained quartz monzonitic gneiss found north of innermost Bessel Fjord and also on the plateau area to the west.

Deformed gabbro anorthosite and anorthositic rock types occur on a small semi-peninsula at the rim of the Inland Ice (Fig. 1). Here they are in probable fault contact with non-migmatised supracrustal rocks to the east. The sequence is strongly deformed and recrystallised (Fig. 5), but the characteristic textural pattern between leucocratic and mafic components is generally preserved, as are remnants of large, probably primary plagioclase crystals. Similar rock types have been found as a few rare inclusions in grey gneisses near Mågenæs, on the north side of Grandjean Fjord, and have also been recorded in the Dove Bugt area to the north (Chadwick & Friend, 1991).

Paragneisses

Migmatised supracrustal rocks are commonly interbanded with the orthogneisses of the gneiss complex. They include rusty brown weathering micaceous schists and gneisses and dark greenish-black amphibolites. The mica schists and gneisses comprise quartz-plagioclase-biotite with minor garnet, sillimanite and muscovite. They form extensive mappable horizons which may vary in width from less than a metre to over a hundred metres, and can be traced for several kilometres. Amphibolites comprise hornblende-plagioclase with minor garnet, and are less extensively developed. The two lithologies are often associated, implying an origin as parts of an interbanded supracrustal sequence of sediments and basic (volcanic) rocks. Carbonate bands and quartzites are also locally present, for example in the outermost part of the Bessel Fjord area.

Supracrustal cover rocks

A 2–3 km wide belt of unmigmatised supracrustal rocks can be traced for 30–35 km along the rim of Soranerbræen, west of Bessel Fjord (Fig. 1). The dominant lithology is a rusty brown mica schist with an amphibolite facies mineral assemblage of quartz-plagioclase-biotite-garnet-muscovite with rare sillimanite. Subordinate bands, up to 10–20 m wide, of dark amphibolite and large lenses of ultramafic rocks occur in places. The supracrustal rocks have a concordant contact with adjacent gneisses; gneissic bands up to some hundreds of metres in width occur locally in the supracrustals and may represent fold cores or thrust slices. On the basis of their unmigmatised character the supracrustal rocks are interpreted to represent a former cover sequence to the gneisses. A similar conclusion was reached in the Birkedal area south of Grandjean Fjord for two other occurrences of metasediments. These comprise in one case a biotite-garnet pelitic gneiss which is several hundred metres wide and interfolded with adjacent gneisses (Fig. 6). The second occurrence is a hornblende-garnet gneiss which has a geochemistry characteristic of a SiO_2-rich and Al, Mg, Ca and Na-poor greywacke sediment (see below).

Geochemistry of the basement gneiss complex

Kalsbeek (1994) described the geochemistry of the Lower Proterozoic basement gneisses in North-East Greenland including units from the Grandjean Fjord – Bessel Fjord region. The older grey tonalitic-granodioritic gneisses are thought to have been derived from volcanic arc granitoids, whereas younger granitic sheets represent collision-type granites and post-orogenic ('A-type') granites. Sm-Nd isotopic data indicates that the granitoid sheets are in places contaminated with Archaean crustal material. Chemical analyses of later Caledonian granites (Fig. 7; Hansen *et al.*, 1994) show that these are different from the basement gneisses and gran-

Fig. 5. Deformed gabbro anorthosite. South-east margin of Soranerbræen, west of Bessel Fjord. This rock has yielded a Sm-Nd model age of 2146 Ma (Stecher & Henriksen, 1994).

ites, and generally comparable with the syn-collision granites of Pearce *et al.* (1984). The basement gneisses and associated granitoid units can mainly be classified as 'volcanic arc granites'; some are 'within-plate granites'.

Representative examples and average chemical analyses for the basement rocks of the Grandjean Fjord – Bessel Fjord region are given in Table 1 and sample locations are shown on the index map. The full chemical data is available from the Survey on request. Seven analysed samples of the older grey orthogneisses are granitic, granodioritic or tonalitic in composition. One with a monzodioritic composition has only 56.01% SiO_2 and is more mafic than the average gneisses.

The gneisses all have low Al index ($Al_2O_3/(Na_2O + K_2O + CaO)$) with an average of 0.90 and a relatively low K_2O/Na_2O ratio with an average of 0.59. The eleven analysed samples of younger granitic gneiss are also granitic, granodioritic or tonalitic in composition. Nearly all these granitic rocks have a low Al index with an average of 0.97 and a low K_2O/Na_2O ratio. Plotted on a quartz–alkali feldspar–plagioclase diagram (QAP, Fig. 7A) there is clearly an overlap between the two different

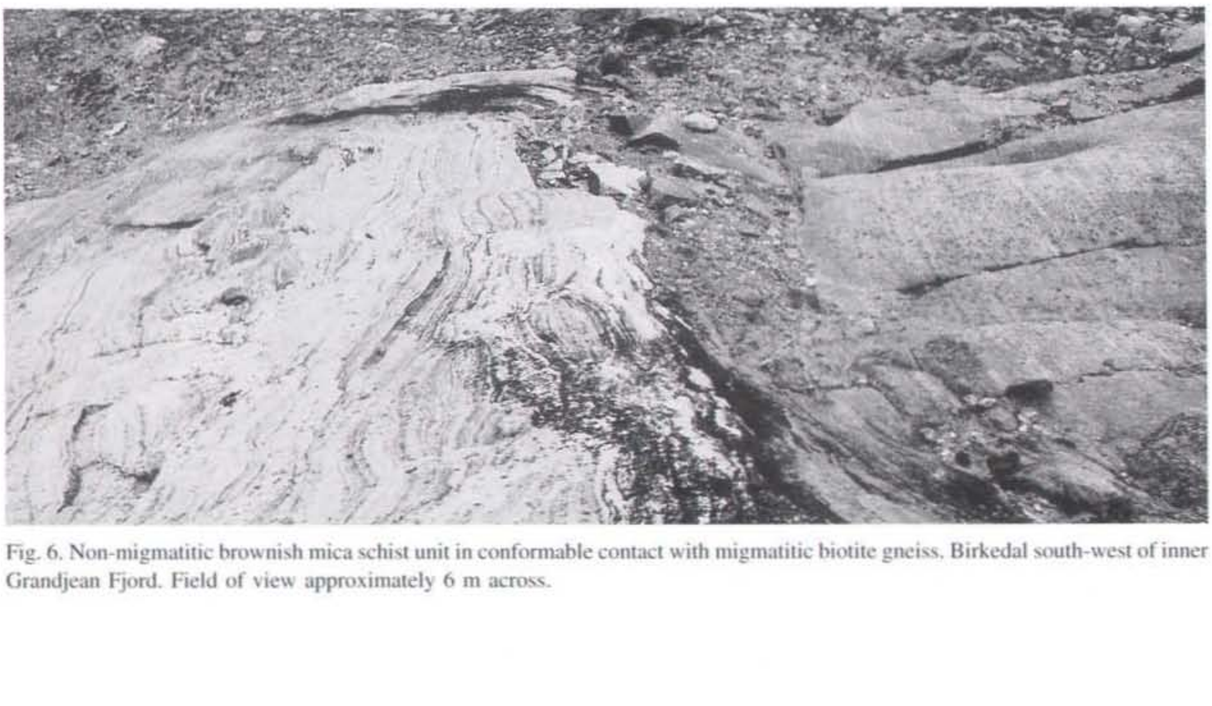
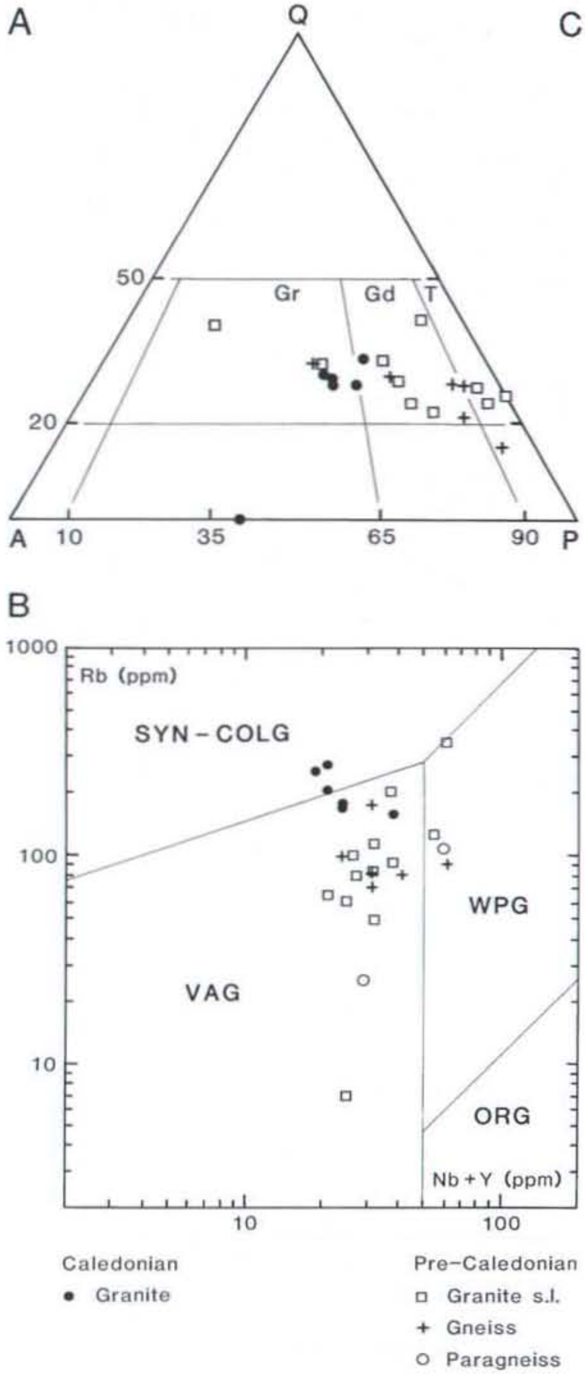


Fig. 6. Non-migmatitic brownish mica schist unit in conformable contact with migmatitic biotite gneiss. Birkedal south-west of inner Grandjean Fjord. Field of view approximately 6 m across.



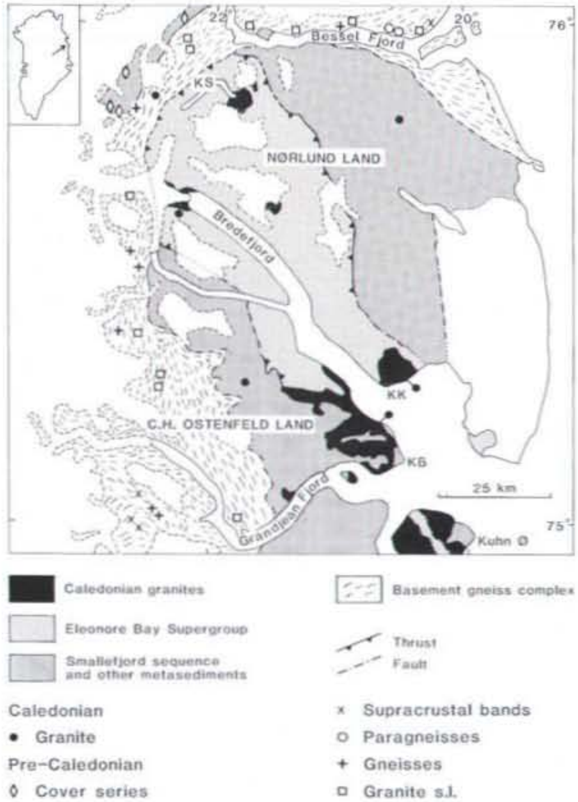


Fig. 7. Chemical composition of Early Proterozoic basement granites and gneisses, and Caledonian granites.
A: Quartz-K-feldspar-plagioclase (QAP) diagram according to Streckeisen (1976). The pre-Caledonian basement rocks are granitic to tonalitic, whereas most Caledonian intrusives are granitic.
B: Diagram discriminating between granitoid rocks of different tectonic settings according to Pearce *et al.* (1984). VAG – volcanic arc granites, SYN-COLG – syn-collision granites, ORG – ocean ridge granites, WPG – within plate granites.
C: Index map showing locations of analysed samples.

groups of basement rock types, which is also the case on the Rb versus Nb + Y diagram (Fig. 7B) used by Pearce *et al.* (1984) to discriminate between various geotectonic settings of the granites. For comparison, Caledonian granites from the Grandjean Fjord – Bessel Fjord region have also been plotted in Figures 7A and 7B. The conclusion from the geochemical data is that both the older grey orthogneisses and associated younger foliated granitic sheets are comparable in composition and cannot be separated geochemically; they are all calc-alkaline granitoids.

Selected supracrustal units within the basement gneiss complex have been chemically analysed. Two mica schist bands correspond to Fe-Mg rich shales in composition.

Table 1. Chemical analyses of granitoid rock from the basement complex

GGU no.	Plutonic grey gneisses 327818 (example)	Plutonic grey gneisses Average of 7	Granites *s.l.* 327838 (example)	Granites *s.l.* Average of 11
SiO_2	62.67	63.50	68.56	68.56
TiO_2	0.79	0.63	0.50	0.40
Al_2O_3	15.13	15.32	15.10	14.85
Fe_2O_3	1.55	1.63	0.86	1.02
FeO	5.11	3.66	2.13	2.53
MnO	0.13	0.08	0.04	0.06
MgO	2.27	2.43	1.06	1.37
CaO	4.20	4.19	2.89	3.10
Na_2O	3.73	3.69	3.85	3.76
K_2O	2.60	3.23	3.50	3.34
P_2O_5	0.25	0.26	0.21	0.24
Vol	0.62	0.73	0.59	0.67
	99.04	99.35	99.28	99.90
Rb	91		64	
Pb	12		13	
Sr	347		577	
Y	42		10	
Th	11		1	
Zr	338		127	
Nb	19		11	
Zn	82		43	
Cu	14		13	
Ni	19		5	
Ga	20		18	
U	2		2	
La	65		28	
Ce	110		45	
Nd	41		18	
Sm	8		3	
Eu	2		1	
Yb	4		1	
Sc	17		5	
Th	10		1	
Cs	3		0	
Hf	10		6	

Major elements were analysed at GGU by XRF on glass disks; Na_2O by AAS. Trace elements: Rb-Ga were analysed at the Institute of Geology, University of Copenhagen with calibration against USGS rock standards. Other trace elements (U-Hf) were analysed by Activation Laboratories Ltd., Ontario, Canada by instrumental neutron activation. Examples selected close to averages.

Two non-migmatitic metasedimentary bands from the Birkedal area are most probably derived from a quartz-rich greywacke and a phyllitic unit respectively; the latter is now a mica schist.

Four analyses of samples of the supracrustal sequence along the rim of Soranerbræen, west of Bessel Fjord (Table 2), all show a composition which is close to the composition of an average greywacke (Wedepohl, 1969).

Table 2. Chemical analyses of four mica schists from the zone of metasediments west of Bessel Fjord

GGU no.	Mica schists 327941 (example)	Average of 4
SiO_2	65.62	65.79
TiO_2	0.69	0.64
Al_2O_3	14.52	14.92
Fe_2O_3	0.46	0.99
FeO	4.97	4.90
MnO	0.05	0.06
MgO	3.26	3.17
CaO	2.42	2.18
Na_2O	3.04	2.27
K_2O	2.80	3.03
P_2O_5	0.14	0.15
Vol	1.22	1.41
	99.19	99.51

The two columns show, respectively, average of the four analyses and, as an example, the analysis closest to the average. Analysed at GGU, see Table 1 text.

Age of the basement gneiss complex

Rb-Sr and Sm-Nd model ages of basement rocks in the Caledonian fold belt of North-East Greenland show that most of these rocks are related to a Lower Proterozoic age of crust formation (Kalsbeek *et al.*, 1993). Kalsbeek *et al.* also report three U-Pb within-zircon (SHRIMP) analyses which yielded ages between 1974 and 1739 Ma, confirming the Rb-Sr and Sm-Nd data. Archaean rocks are not common, the most notable example being the area near Danmarkshavn (*c.* 76°45'N) studied by Steiger *et al.* (1979); recent SHRIMP analyses on new sample collections from Danmarkshavn have confirmed the Archaean age (A. P. Nutman, personal communication 1994). The Sm-Nd analyses presented by Kalsbeek *et al.* also demonstrate that the Proterozoic gneisses contain substantial proportions of older, probably Archaean, crustal material.

In the Dronning Louise Land region, U-Pb dates for detrital zircon grains within the late Proterozoic – early Palaeozoic foreland cover sequence (Zebra Series) define an age range of detritus between 3001 and 1700 Ma (Tucker *et al.*, 1993). A U-Pb zircon age of 1909 Ma was obtained for an orthogneiss within the Caledonian fold belt of eastern Dronning Louise Land.

Of the samples from North-East Greenland studied by Kalsbeek *et al.* (1993), eight were from orthogneisses forming part of the basement gneiss complex between Grandjean Fjord and Bessel Fjord discussed in this paper. Seven of the samples yielded Sm-Nd model ages in the range 2.11–2.33 Ga, and a single sample from Bessel Fjord an age of 3.04 Ga.

Smallefjord sequence

The basement gneiss complex is overlain by metasediments of the Smallefjord sequence (Fig. 1). The most extensive exposures are in C. H. Ostenfeld Land and in north-east Nørlund Land; outcrops are notably good in Smallefjord (Fig. 1).

Metasedimentary lithologies

The Smallefjord sequence mainly comprises medium to coarse-grained semi-pelitic schists and gneisses. These are commonly interlayered with bands of psammite which vary in width from less than a metre up to several hundred metres. Metamorphic parageneses are amphibolite facies assemblages of quartz-plagioclase-biotite-muscovite, often with garnet, sillimanite, or kyanite in semi-pelitic lithologies. Pods and lenses of calc-silicate material are common and inferred to represent metamorphosed concretions; they contain an amphibolite facies mineral assemblage of hornblende-garnet-quartz-plagioclase-pyroxene. Bands of orthoquartzite, up to 50 m wide, are present locally in the vicinity of Slamsø and Langsø (Fig. 1). Horizons of pale-green, diopside-bearing impure marble occur near the structural base of the sequence; the most persistent of these, north-east of Langsø, is 100 m wide and has been traced for 25 km. Sedimentary structures are completely absent, and it is not possible to establish a stratigraphical succession. Both the lower and upper boundaries are tectonic and the sequence is so highly deformed that it is only possible to infer a minimum thickness of one kilometre. An early imbricate basement/cover relation is revealed by an intimate interbanding of basement gneisses and Smallefjord sequence metasediments in the boundary zone between the two units.

The Smallefjord sequence is pervasively migmatised and both semi-pelitic and psammite lithologies are characterised by discontinuous concordant layers and augen of quartzo-feldspathic material, up to 20–30 cm wide. These are composed of approximately equal proportions of quartz, plagioclase and K-feldspar, and are commonly veined by thin biotite selvedges thought to have been produced by *in situ* segregation during peak regional amphibolite facies metamorphism. Where the volume of neosome is large (30–50%), extreme mobility results in the development of anomalously complex structures (Fig. 8). In the area between Langsø and Barth Bjerge (Fig. 1), where the degree of migmatisation is greatest, the metasediments contain numerous laterally persistent sheets of concordant, leucocratic granitoid material up to 150 m wide. The sheets comprise quartz-feldspar-biotite-muscovite, and show a variably developed foliation defined by alignment of these minerals, and biotite-muscovite schlieren thought to represent remnants of the host paragneisses. The complexly interdigitating and generally diffuse nature of the contacts between these granitoid sheets and the host paragneisses is consistent with an origin by *in situ* partial melting of the metasediments.

Metabasic rocks

Subconcordant sheets and pods of foliated amphibolite are locally common. They contain an amphibolite facies metamorphic assemblage of hornblende-plagioclase-quartz often with garnet, and like the host gneissic schists are commonly veined by migmatitic neosome. These metabasic rocks are interpreted as basic intrusions which have undergone most, if not all, of the tectonic history recorded by the host metasediments. Similar foliated metabasic intrusions occur north-east of Agnete Sø (Fig. 1), but here they are generally discordant. North of Slamsø (Fig. 1) the metasediments are intruded by discordant sheets of metadolerite up to 50 m wide. These intrusions are undeformed and contain a metamorphic assemblage of granoblastic clinopyroxene-garnet-plagioclase. Field relations thus imply the existence of at least two different suites of metabasic intrusions.

Granitic gneisses and augen granites

Strongly deformed intrusive sheets of granitic gneiss and augen granite, up to 30 m wide, occur north-east of Agnete Sø, and around Langsø and Slamsø (Fig. 1). Contacts with host gneisses are sharp and slightly discordant. They have been subjected to thorough metamorphic recrystallisation and are characterised by lenticular feldspar (mostly microcline) porphyroclasts, 1–2 cm long, enveloped by micaceous foliae and quartz ribbons. Granitic gneisses at Langsø also contain minor amounts of hornblende and garnet.

Age of the Smallefjord sequence

Original stratigraphic relationships between the basement gneiss complex, the Smallefjord sequence and the EBG have been obscured by ductile deformation. It is therefore necessary to rely on geochronological studies to provide constraints on the age of the Smallefjord sequence. Single zircon U-Pb ages have been obtained from

Fig. 8. Anomalous small scale folds in migmatitic Smallefjord sequence cut by late Caledonian veins. Barth Bjerge.

two samples of semi-pelitic paragneiss from the Smallefjord sequence (GGU 249933 and 249939; Strachan *et al.*, in press). Analyses can be divided broadly into three groups:

(1) >1000 Ma zircons, which display a polymodal age distribution, with 'peaks' at *c.* 1800, 1560, 1370, 1220 and 1040 Ma. In addition, two late Archaean zircons were detected. These zircons are interpreted as detrital in origin and derived from granitic rocks (or gneisses) of different ages.

(2) Zircons which yield a mean $^{206}Pb/^{238}Pb$ age of 953 ± 13 Ma. These grains grew during a high-grade tectonothermal event, in some cases as mantles on >1000 Ma grains. Limited petrographic evidence indicates that these grains grew *in situ*.

(3) Zircons which yield a weighted mean $^{206}Pb/^{238}b$ age of 445 ± 10 Ma. This is interpreted to record Caledonian metamorphism during the late Ordovician.

The interpretation that the second group of zircons grew *in situ* during a high-grade tectonothermal event implies that the Smallefjord sequence was deposited between *c.* 1040 Ma and the time of the first metamorphism at 953 ± 13 Ma.

Caledonian granitic intrusions and vein complexes

Complexes of anastomosing veins cutting variably deformed granite, pegmatite and aplite veins are ubiquitous within the Smallefjord sequence and the structurally highest levels of the basement gneiss complex (Fig. 9). Similar anastomosing veins which intrude parts of the EBG are evidently Caledonian in age. The intrusions comprise variable proportions of quartz, plagioclase and K-feldspar with minor biotite and muscovite. Individual sheets or veins have sharp contacts with host lithologies, and may vary in width from a few centimetres to 4–5 m. There is every transition from subconcordant foliated sheets, which may be folded and boudinaged and display a thorough solid-state deformation fabric, to undeformed, ramifying networks of veins and sheets which preserve magmatic features such as oscillatory zoning in feldspars. The density of veining is extremely variable, with the highest proportion of veins in the south and south-west of the area. Major vein complexes are located along the

Fig. 9. Anastomosing vein complex in the highest levels of the basement complex and the overlying Smallefjord sequence. North end of Kildedalen. Cliff height approximately 700 metres. Lake at 392 metres a.s.l.

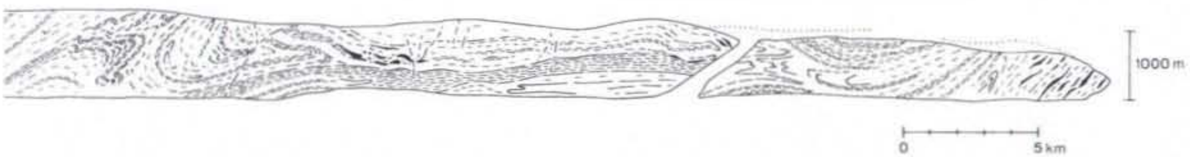


Fig. 10. Sketch of structures in banded basement gneisses along the cliff section on the south side of inner Grandjean Fjord, showing major recumbent isoclines refolded by younger north–south trending upright folds. The latter are interpretated as being Caledonian.

basement-Smallefjord sequence boundary in Kildedalen, along the Smallefjord sequence-EBG boundary in Femdalen, and within the Smallefjord sequence at Kap Buch and Kap Negri (Fig. 1). These complexes locally comprise up to 80% granitic material, as subconcordant multiphase sheets enclosing lenticular, discontinuous screens of host lithologies.

Regional deformation and metamorphism

The basement gneiss complex and Smallefjord sequence together record a complex and polyphase deformational history, which may be simplified into two regionally important groups of structures. The first group is represented by large-scale, complex polyphase folds which are clearly recognised only in the basement gneiss complex. The second group of structures is associated with regional deformation of the Smallefjord sequence, and the approximately coeval formation of ductile shear zones along the boundaries of all the major tectono-stratigraphic units in the region. These structures are post-dated by upright folding broadly associated with the development of a regional south-east plunging synform defined by foliation dips in the basement and Smallefjord sequence, and late, steep brittle faults.

Polyphase folding of basement gneisses

Spectacular cliff sections provide evidence for at least two phases of approximately coaxial folding in the crystalline basement gneisses. Although complex in detail, foliation and fold axial traces within the basement trend generally northwards from Grandjean Fjord, to swing eastwards in the Bessel Fjord area. In the west of the region, areas of flat-lying or gently-undulating foliation alternate with areas within which foliation is generally steeply inclined to the east. The flat-lying zones are dominated by recumbent isoclines with wavelengths of up to 5 km (Figs 10, 12). Fold axes plunge gently to the north or south, subparallel to a variably developed mineral lineation. Anomalously complex fold geometries have been observed in inaccessible cliff sections and may

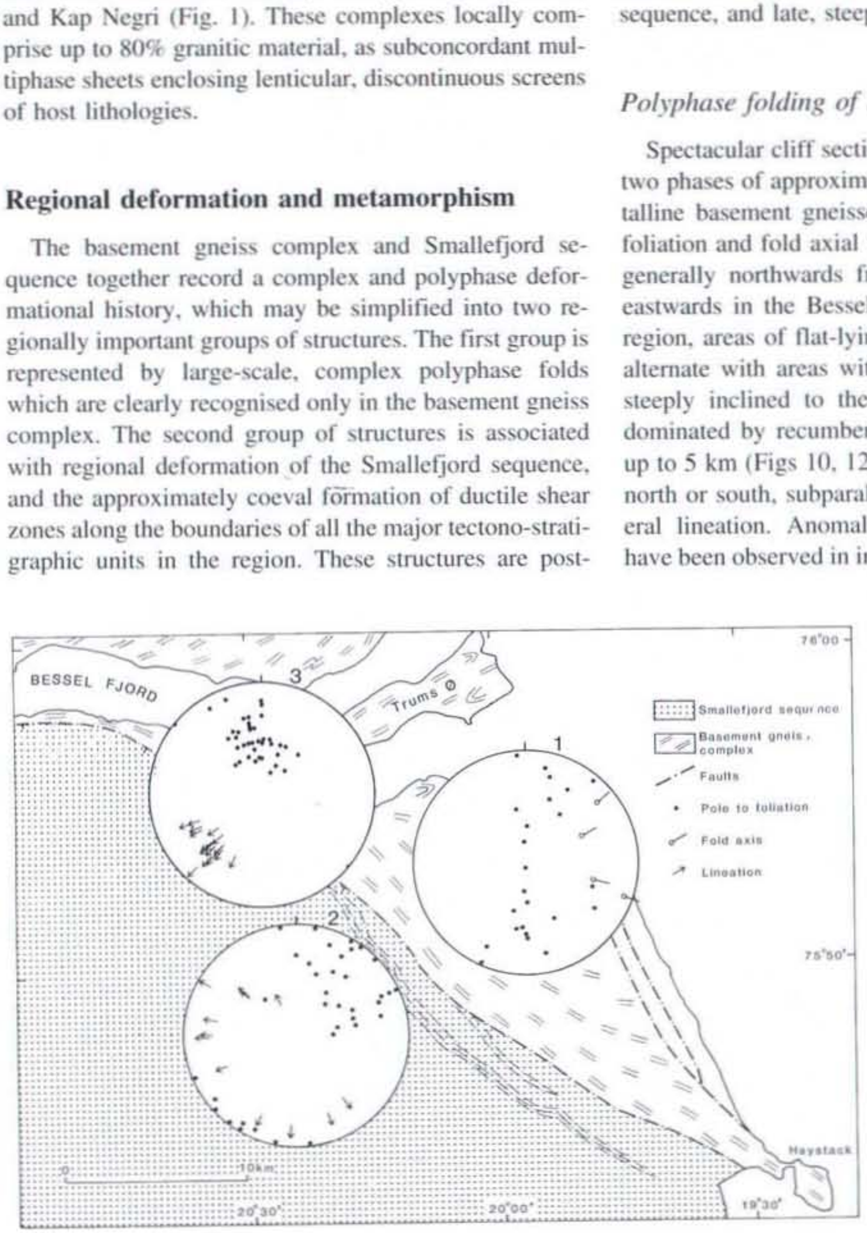


Fig. 11. Equal area stereonet plots, lower hemisphere, of small scale structural elements in (1) basement gneisses, (2) Smallefjord sequence, and (3) ductile shear zone between (1) and (2). The fault separating the Smallefjord sequence and the basement gneiss complex is the steep eastern part of the Bessel Fjord shear zone. Note the subparallel shear zones south of the fault (thin streaks). North-east Nørlund Land, for location see Fig. 1.

Fig. 12. Major isoclinal fold in basement orthogneisses, refolded by north–south trending open folds with steep axial surfaces. North of innermost Grandjean Fjord at glacier front. Cliff height approximately 1200 m.

result from the development of discontinuities on fold limbs, in combination with either progressive refolding of isoclines or the formation of highly curvilinear sheath folds. Areas of steeply-dipping foliation correspond to zones of refolding about axial surfaces which are moderately to steeply inclined to the east (Figs 10, 12). These later folds also trend N–S and the refolding of earlier isoclines generates numerous type 3 interference patterns (*sensu* Ramsay, 1967). Axial traces of both fold sets trend E–W in the Bessel Fjord area, with axes plunging gently west. There are no clear lines of evidence which allow unambiguous dating of these structures. In the Dove Bugt area to the north, similar structures have been assigned a lower Palaeozoic (Caledonian) age (Chadwick & Friend, 1994), but a Proterozoic age cannot be discounted.

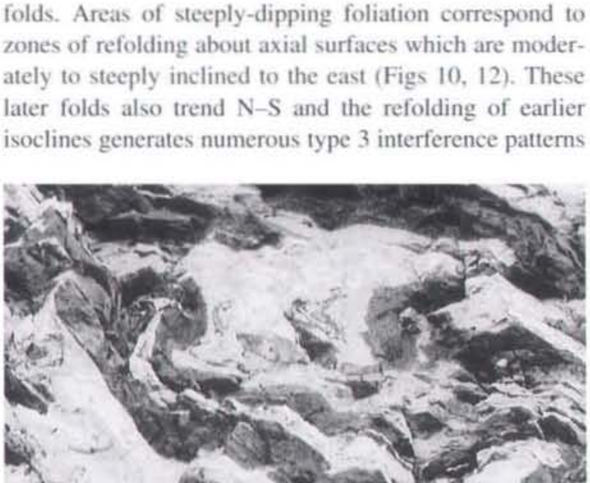


Fig. 13. Mobilised and disharmonically folded marble incorporating amphibolite rafts in the Bessel Fjord shear zone. East of Langsø, south of outer Bessel Fjord. Hammer for scale.

Regional folding of the Smallefjord sequence

The dominant structures within the Smallefjord sequence are tight-to-isoclinal, commonly reclined, minor folds of gneissic banding and migmatite fabrics. Fold axes are generally parallel to an approximately NE–SW to E–W trending mineral extension lineation defined by aligned micas, sillimanite, amphiboles and quartz-feldspar aggregates. Although these folds post-date peak regional metamorphism and migmatisation, the axial planar recrystallisation of biotite and hornblende and the common presence of radiating laths of sillimanite implies that amphibolite facies conditions persisted both during and after folding. The regional foliation within the Smallefjord sequence is thus composite in origin. No major folds related to this phase of deformation have been identified.

U-Pb zircon dating of deformed granitoid rocks which intrude the Smallefjord sequence (Hansen *et al.*, 1994) indicates a Caledonian age for regional folding and coeval fabric development. A granitic gneiss collected north of Langsø yielded an age of *c.* 400 Ma, probably the age

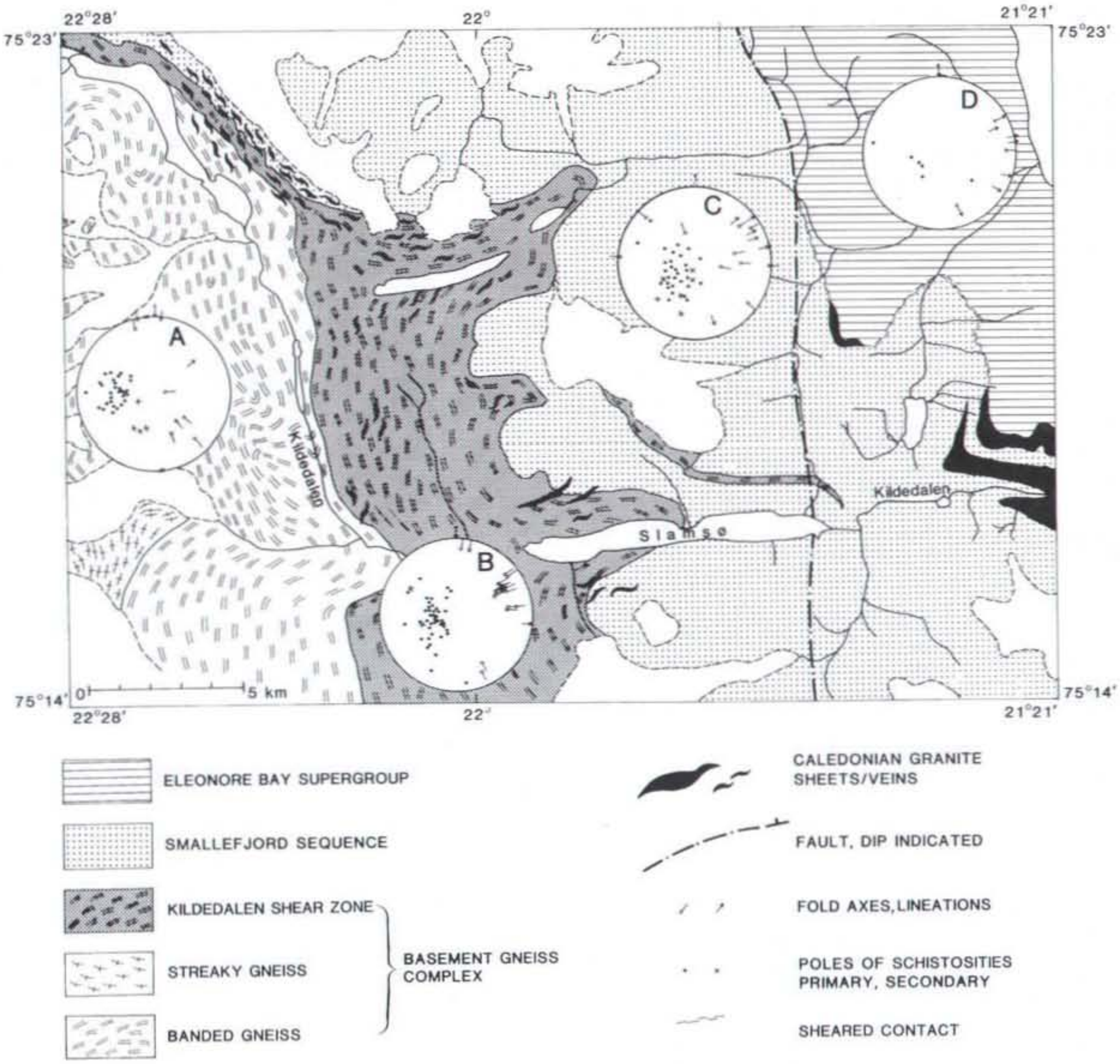


Fig. 14. Map and stereogram plots (lower hemisphere) from the area around inner Kildedalen showing Kildedalen shear zone between the Lower Proterozoic basement gneisses and the Middle Proterozoic Smallefjord sequence. Stereograms A to D represent the four main rock groups. For location see Fig. 1.

of intrusion. The margins of this granitic gneiss body are discordant to the compositional banding and migmatitic fabrics in host metasediments, and the intrusion carries a penetrative solid-state deformation fabric which is subparallel to the regional foliation. A heterogeneously deformed leucogranite collected north of Slamsø yielded an age of 409^{+4}_{-3} Ma (Hansen *et al.*, 1994), also interpreted as an intrusion age. This is one of a series of subconcordant sheets which carry both a variably developed solid-state planar deformation fabric parallel to the regional foliation, and a pervasive ENE-trending lineation.

Ductile shear zones along the basement – Smallefjord sequence boundary

(1) *Inner Bessel Fjord – Haystack.* In this region, the basement-Smallefjord sequence contact is marked by the Bessel Fjord shear zone (BFSZ). This shear zone has an arcuate trace, trending eastwards along the south shore of Bessel Fjord, then curving to run south-east towards Haystack (Fig. 11). Along the south shore of Bessel Fjord, the BFSZ comprises an up to 150 m wide zone of heterogeneous ductile shear within which basement

gneisses, Smallefjord sequence semi-pelitic gneisses, and granites and pegmatites are deformed into belts of mylonitic gneisses and schists which dip gently to moderately to the south. All gradations are apparent between augen of relatively low strain which preserve original gneissic fabrics, through zones of moderate superimposed strains characterised by regular and planar gneissic banding, to continuous belts up to 50 metres wide of mylonitic lithologies. Numerous sheets of undeformed granite and pegmatite of presumed Caledonian age intrude the basement gneisses and Smallefjord sequence, north and south of Bessel Fjord respectively. Within the shear zone, discordant relationships between granites and country rocks are only apparent in areas of low strain; they are progressively modified into concordance as strain increases, and no granites or pegmatites were observed to truncate the mylonite fabric.

South-west of Trums Ø, the BFSZ is displaced by a steep, NNE-trending dextral fault (Fig. 11). East of this fault the shear zone dips steeply to moderately to the south-west, and comprises a further two mappable high strain zones in addition to that located along the main basement-cover contact. The structurally lowest of these zones is traceable for *c.* 25 km, and located along a prominent impure marble unit within the Smallefjord sequence (Fig. 13). It comprises a complex zone of disharmonically deformed mylonitic marble which incorporates numerous detached blocks of mylonitic amphibolite and semi-pelitic gneiss. At a structurally higher level to the south-west another belt of mylonitised semi-pelitic gneiss is traceable for 12 km (Fig. 11). A thin strip of

Fig. 15. Low angle discordant contact between basement orthogneisses (lower light coloured unit) and the Kildedalen shear zone comprising strongly sheared basement gneisses. Smallefjord sequence at top. Cliff height *c.* 400 m. Northernmost Kildedalen.

Fig. 16. Major reclined Caledonian antiform folding the Kildedalen shear zone. East side of Kildedalen, west-north-west of Slamsø. Photograph from Lauge Koch aerial photograph collection, Geological Museum, Copenhagen (W. Diehl, 1955).

mylonitic basement gneiss occurs between these two high strain zones (Fig. 11), although it is uncertain whether it occupies the core of an isoclinal fold or rests on a plane of dislocation.

Rock units within the BFSZ contain a mineral extension lineation defined by alignment of micas, amphiboles and quartz-feldspar aggregates. Along the south shore of Bessel Fjord this lineation plunges obliquely down-dip to the south-west (Fig. 11). A top-to-the-south-west (extensional) sense of displacement parallel to the lineation may be deduced from rotated porphyroclasts (sigma and delta types), C-S fabrics and mesoscopic shear zones. In the eastern part of the shear zone the linear fabric generally plunges steeply down-dip to the south-west, although is locally extremely variable in orientation (Fig. 11).

Petrographic study of mylonites from the BFSZ indicates that deformation occurred within the upper amphibolite facies. In thin-section, ribbons of dynamically recrystallised quartz, amphibole and mica wrap garnets and ductile deformed feldspar porphyroclasts. In mylonitic gneisses of the Smallefjord sequence, laths of fresh sillimanite lie parallel to the fabric and are in apparent textural equilibrium with recrystallised biotite and muscovite. Randomly oriented fibrolite mats overgrow the mylonite fabric, indicating a further period of mineral growth under mid- to upper amphibolite facies conditions after mylonitisation.

(2) *Grandjean Fjord – Ejnar Mikkelsen Gletscher.* The contact between the basement gneisses and the Smallefjord sequence in this region is defined by the Kildedalen shear zone (KSZ). West of Slamsø (Fig. 14) the KSZ is characterised by a prominent easterly-dipping belt, 3.5

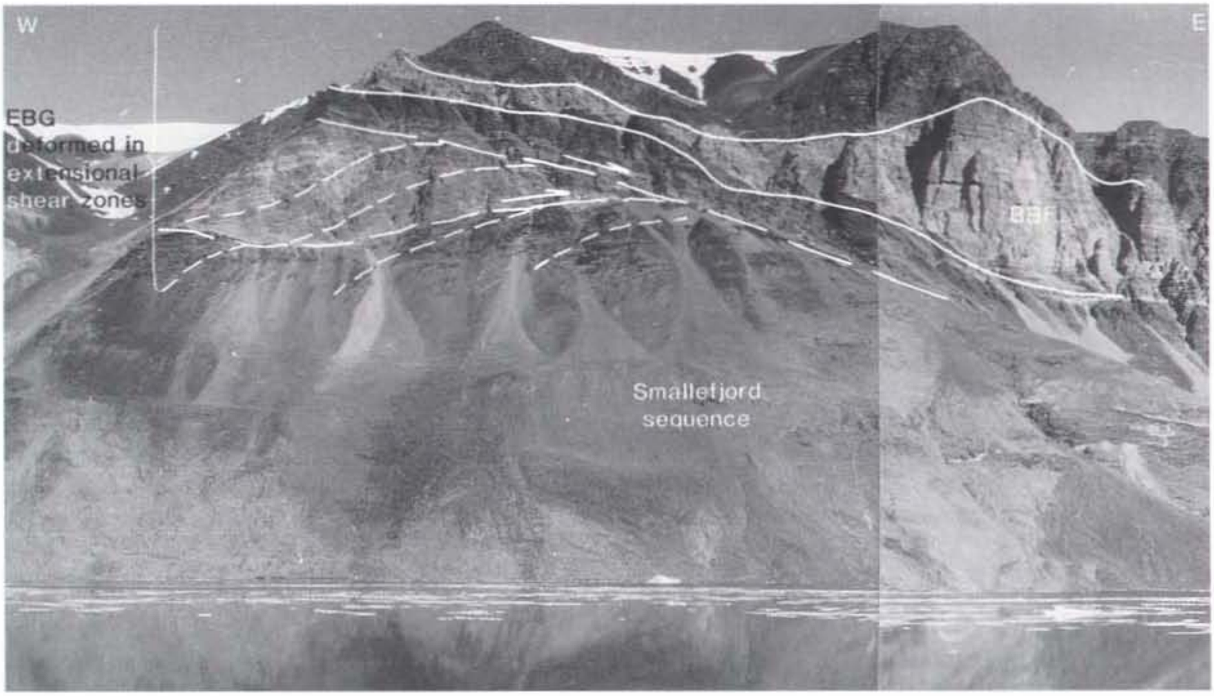


Fig. 17. Boundary between EBG and underlying Smallefjord sequence rocks. Low dipping extensional shear zones are indicated. BBF – Berzelius Bjerg Formation of the EBG. North shore of outer Smallefjord, cliff height 1535 m.

km wide, of flaggy, regularly banded basement gneiss; the width of reworked basement rocks decreases northwards to 1.2 km in the area between north Kildedalen and Smallefjord. Lithologic banding is typically on a scale of 1–5 cm; low-angle discordances between different orthogneiss types are occasionally discernable, but most contacts are concordant. Caledonian granite and pegmatite veins are commonly highly discordant to their country rocks west and east of the KSZ, but within the shear zone are generally either tightly folded or highly attenuated and boudinaged. The regularity of fabric characteristic of the KSZ contrasts sharply with the coarsely-interlayered 'low strain' gneisses west of the shear zone which have much more variable structural trends and irregular discordant contacts between different orthogneiss types. In north Kildedalen, the base of the KSZ is a prominent east-dipping fault (Fig. 15). High strains appear to have been particularly concentrated in the uppermost levels of the basement since only the lowermost 100–150 m of the Smallefjord sequence is strongly deformed.

Reworking of basement was associated with the development of numerous tight-to-isoclinal mesoscopic to macroscopic folds (Fig. 16) which are characterised by highly flattened and attenuated limbs and thickened hinge zones. Fold axes mostly plunge parallel to an ESE–WSW trending mineral extension lineation, although locally they have highly curvilinear geometries. These structures are absent in the basement gneisses west of the KSZ, but are coplanar and colinear with regional (Caledonian) structures in the Smallefjord sequence. Kinematic indicators are rare within the KSZ. Top to the NE (extensional) displacement parallel to the mineral lineation is indicated by the sense of shear and folding exhibited by

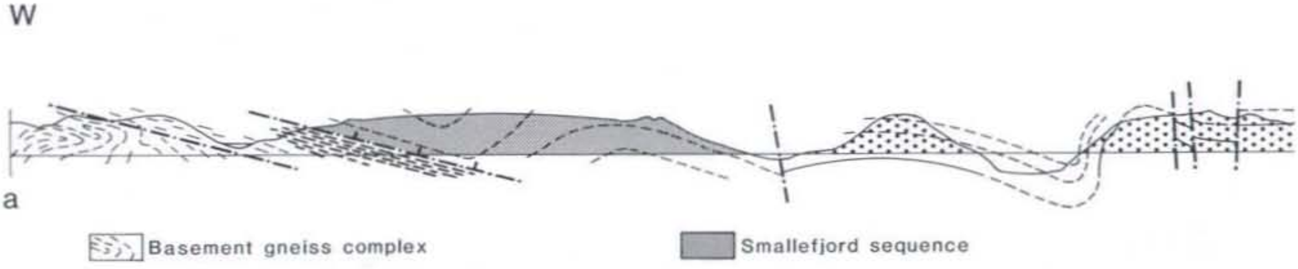


Fig. 18. Cross-section between Haystack in the east and Canongletscher in the west showing structural relationships between

deformed granite veins and locally by the direction of ductile rotation of banding displayed by gneisses in the immediate footwall to the shear zone (Fig. 15).

Thin-section analysis demonstrates that deformation occurred within the amphibolite facies. In reworked basement rocks, bands of dynamically recrystallised hornblende and biotite alternate with annealed granoblastic aggregates of quartz and feldspar. Mylonitic gneisses of the Smallefjord sequence carry a penetrative quartz-mica ribbon fabric overgrown by fibrolite mats, showing that mid- to upper amphibolite facies metamorphic conditions persisted after deformation.

In the poorly exposed area between Ejnar Mikkelsen Gletscher and Bessel Fjord, the Smallefjord sequence is apparently absent and the basement is in brittle fault contact with the EBG (Fig. 1). A well exposed valley section west of Knæksø demonstrates that a belt of strongly to moderately deformed basement rocks up to 1 km wide resembling those of the KSZ occurs immediately west of the fault. Given the field and petrographic evidence which indicates that the Kildedalen and Bessel Fjord shear zones have the same structural position, formed at similar grades of metamorphism, and have the same age relationships to Caledonian structures and granitic vein complexes, it is suggested that they formed approximately contemporaneously and were active during a period of extension in the Caledonian orogeny.

Ductile shear zones along the margins of the Eleonore Bay Supergroup

The EBG is partly bounded by steep, brittle faults (Fig. 1). Elsewhere its contacts with the underlying Smallefjord sequence are gently to moderately-inclined ductile shear zones, which are often disrupted or obscured by intense granite sheeting (cf. also Soper & Higgins, 1993; Higgins & Soper, 1994). These shear zones are belts, several hundred metres wide, within which mylonitic gneisses and schists derived from the Smallefjord sequence pass apparently transitionally into strongly foliated and lineated metasedimentary rocks of the EBG. Mylonitic granitic sheets inferred to have been emplaced either prior to or during shearing are cut by less deformed discordant sheets. Strain and metamorphic grade decrease rapidly within the EBG away from the marginal shear zones (Soper & Higgins, 1993).

Traverses across the fault/shear zone which defines the south-west boundary of the EBG demonstrate that the linear fabric present within the shear zone and lower parts of the EBG is colinear with the regional (Caledonian) lineation in the Smallefjord sequence (Fig. 14D). A top-to-the-north-east (extensional) sense of displacement across the shear zone is indicated by extensional shear bands and macroscopic shear zones (Fig. 17). This is consistent with field evidence east of Ejnar Mikkelsen Gletscher where Soper & Higgins (1993) indicate that minor folds in the shear zone verge down-dip to the north-east.

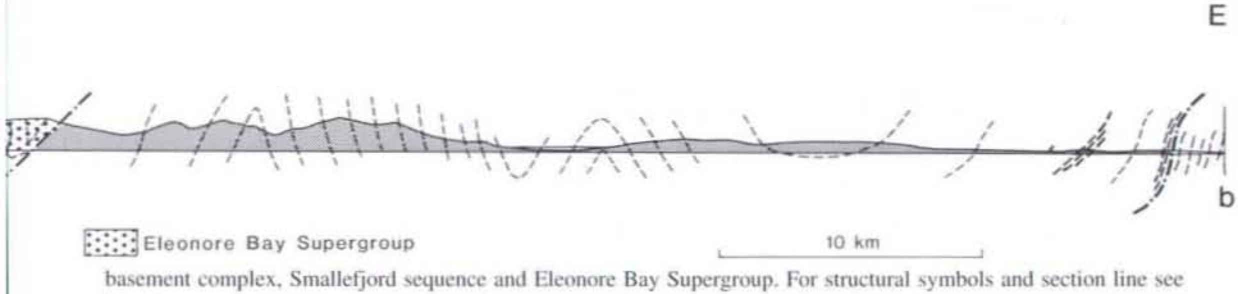
The shear zone which defines the north-east boundary of the EBG was not examined in detail. Soper & Higgins (1993) record both extensional and compressional kinematic indicators, and accordingly infer a complex movement history.

Late folds and brittle faults

Foliation within the basement gneisses and the Smallefjord sequence define a regional south-plunging shallow synform, the core of which is occupied by the EBG (Fig. 18). Structures which may have formed during this period of deformation comprise a series of N–S trending major folds in the area south of Langsø (Fig. 1). Late brittle faults trend approximately N–S and are marked by zones up to 200 m wide of crushed and variably cataclased country rock. The major thrust fault which defines the north-west margin of the EBG, and the fault which trends south from the east end of Smallefjord to Grandjean Fjord (Fig. 1), both downthrow to the east and are plausibly related to the development of the Late Palaeozoic Hochstetter Forland basin.

Regional correlations

The basement gneisses between Grandjean Fjord and Bessel Fjord represent the eastern part of the Laurentian shield, which was involved in the Caledonian deformation. In recent papers, Kalsbeek *et al.* (1993) and Kals-



basement complex, Smallefjord sequence and Eleonore Bay Supergroup. For structural symbols and section line see Fig. 1.

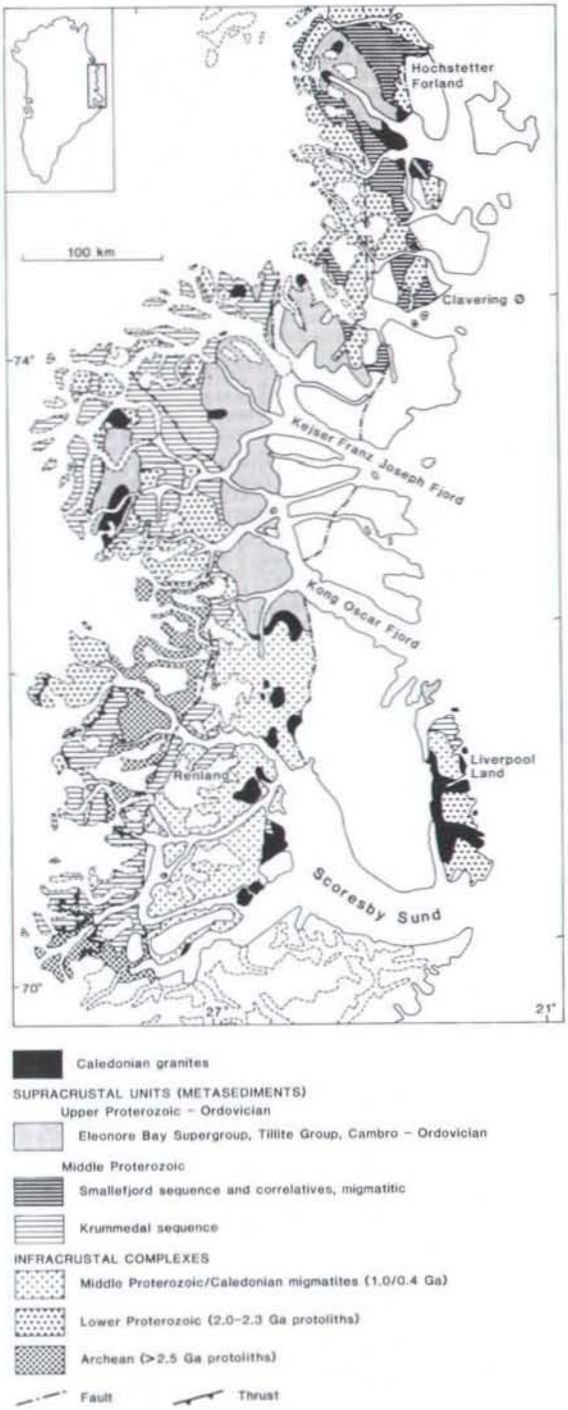


Fig. 19. Map of part of the East Greenland Caledonides showing distribution of Middle Proterozoic metasediments, infracrustal basement complexes, and the Upper Proterozoic to Ordovician sediments. The basement has been subdivided according to the interpretation af isotopic age data into three units: Archaean, Lower Proterozoic and Middle Proterozoic.

beek (1994) described the geochemistry of the basement gneiss complexes of North-East Greenland, including those discussed in this paper, and made regional correlations and interpretations.

The following discussion centres on possible correlation of the Smallefjord sequence with various rock units exposed within the Caledonian belt in East Greenland. Henriksen *et al.*, (1989) proposed a tentative correlation of the Smallefjord sequence with the Middle Proterozoic Krummedal sequence exposed in the Scoresby Sund region (70°–72°N; Fig. 19). It is therefore appropriate to review briefly the geology of the Krummedal sequence.

The Krummedal supracrustal sequence was erected as an informal stratigraphic unit in the Scoresby Sund region, 70°–72°N (Henriksen & Higgins, 1969). A recent review of the Krummedal supracrustal sequence and equivalents in central East Greenland (72°–74°N) was published by Higgins (1988). It comprises a 2500–8000 m thick sequence of pelites, semi-pelites, and quartzites which have been variously metamorphosed within the amphibolite facies. Lateral and vertical lithological variations are considerable, and correlation between the various local successions recognised has not been possible as a result of structural complexity and the scarcity of sedimentary structures. Marbles are present locally near the structural base of the sequence. The contact between the Krummedal supracrustal sequence and the underlying Archaean basement in the Scoresby Sund region (Flyverfjord infracrustal complex; Henriksen *et al.*, 1980) and in central East Greenland is mostly concordant, with the two units complexly interfolded. Rare discordances between basement gneiss and rusty quartzites and schists may, however, result from the very local preservation of an original unconformity (Higgins *et al.*, 1981). Lenses and horizons of amphibolite are conspicuous in lower levels of the succession.

Isotopic age determinations indicate a Middle Proterozoic age for the Krummedal supracrustal sequence. In the Scoresby Sund region, a Rb-Sr whole rock isochron age of 1122 ± 93 Ma obtained from mica schist is interpreted as dating regional metamorphism. This is supported by a U-Pb monazite age of 1010 ± 10 Ma (Hansen *et al.*, 1978). Augen granite sheets which intrude migmatised equivalents of the Krummedal supracrustal sequence have yielded a U-Pb zircon age of 1053 ± 40 Ma and a Rb-Sr whole rock isochron age of 987 ± 23 Ma (Steiger *et al.*, 1979).

Rb-Sr data obtained from supracrustal rocks from the fjord zone of central East Greenland (72°–74°N) plot on a *c.* 1250 Ma reference line (Rex & Gledhill, 1981). This age estimate is broadly consistent with Rb-Sr whole rock isochron ages obtained from foliated 'older granites' which intrude the supracrustal sequence; two such granites have given ages of 1000 ± 70 Ma and 1080 ± 200 Ma, whereas other similar granites have given ages around 750–650 Ma (Rex & Gledhill, 1981). The validity and significance of these younger ages is uncertain.

The marked similarities in structural setting, lithology and age of metamorphism of the Smallefjord sequence, the widespread cover sequences of the central fjord zone and the Krummedal supracrustal sequence are indications that these units are broadly correlatible. Differences in estimates of ages of metamorphism for these sequences are thought to be at least in part due to variations in the precision of the isotopic techniques employed, as well as the inaccuracies now known to be inherent in the Rb-Sr method. A tripartite tectonostratigraphy which comprises: (1) late Archaean to Lower Proterozoic basement; (2) Middle Proterozoic supracrustal cover; and (3) Upper Proterozoic to early Palaeozoic sediments; may now be applied with confidence to much of the East Greenland Caledonides in the region 70°–76°N.

References

Chadwick, B. & Friend, C. R. L. 1991: The high-grade gneisses in the south-west of Dove Bugt: an old gneiss complex in a deep part of the Caledonides of North-East Greenland. *Rapp. Grønlands geol. Unders.* **152,** 103–111.

Chadwick, B. & Friend, C. R. L. 1994: Reaction of Precambrian high-grade gneisses to Caledonian ductile deformation and younger faulting in Dove Bugt, North-East Greenland. *Rapp. Grønlands geol. Unders.* **162** (this volume).

Haller, J. 1953: Geologie und Petrographie von West-Andrées Land und Ost-Frænkels Land (NE-Grönland). *Meddr Grønland* **113**(5), 196 pp.

Haller, J. 1955: Der 'Zentrale Metamorphe Komplex' von NE-Grönland. Teil I. Die geologische Karte von Suess Land, Gletscherland und Goodenoughs Land. *Meddr Grønland* **73,**1 (3), 174 pp.

Haller, J. 1970: Tectonic map of East Greenland (1:500,000). An account of tectonism, plutonism, and volcanism in East Greenland. *Meddr Grønland* **171**(5), 286 pp.

Haller, J. 1971: *Geology of the East Greenland Caledonides,* 415 pp. London, New York, Sydney & Toronto: Interscience Publishers.

Hansen, B. T., Higgins, A. K. & Bär, M.-T. 1978: Rb-Sr and U-Pb age patterns in polymetamorphic sediments from the southern part of the East Greenland Caledonides. *Bull. geol. Soc. Denmark* **27**, 55–62.

Hansen, B. T., Henriksen, N. & Kalsbeek, F. 1994: Age and origin of Caledonian granites in the Grandjean Fjord – Bessel Fjord region (75°–75°N), North-East Greenland. *Rapp. Grønlands geol. Unders.* **162** (this volume).

Henriksen, N. & Higgins, A. K. 1969: Preliminary results of mapping in the crystalline complex around Nordvestfjord, Scoresby Sund, East Greenland. *Rapp. Grønlands geol. Unders.* **21,** 5–20.

Henriksen, N., Friderichsen, J. D., Strachan, R. A., Soper, N. J. & Higgins, A. K. 1989: Caledonian and pre-Caledonian geology of the region between Grandjean Fjord and Bessel Fjord (75°–76°N), North-East Greenland. *Rapp. Grønlands geol. Unders.* **145,** 90–97.

Higgins A. K. 1988: The Krummedal supracrustal sequence in East Greenland. *In* Winchester, J. A. (ed.) *Later Proterozoic stratigraphy of the North Atlantic regions,* 86–96. Blackie.

Higgins, A. K. & Soper, N. J. 1994: Structure of the Eleonore Bay Supergroup at Ardencaple Fjord, North-East Greenland. *Rapp. Grønlands geol. Unders.* **162** (this volume).

Higgins, A. K., Friderichsen, J. D. & Thyrsted, T. 1981: Precambrian metamorphic complexes in the East Greenland Caledonides (72°–74°N) – their relationships to the Eleonore Bay Group, and Caledonian orogenesis. *Rapp. Grønlands geol. Unders.* **104,** 5–46.

Kalsbeek, F. 1994: Geochemistry of Early Proterozoic basement gneisses from the Caledonian fold belt of North-East Greenland: recurrent orogenic activity along the western margin of North Atlantic Ocean. Submitted to *Precambrian Research.*

Kalsbeek, F., Nutman, A. P. & Taylor, P. N. 1993: Palaeoproterozoic basement province in the Caledonian fold belt of North-East Greenland. *Precambrian Res.* **63**, 163–178.

Koch, L. & Haller, J. 1971: Geological map of East Greenland 72°–76°N. Lat. (1:250,000). *Meddr Grønland* **183,** 26 pp.

Pearce, J. A., Harris, N. B. W. & Tindle, A. G. 1984: Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *J. Petrol.* **25,** 956–983.

Ramsay, J. G. 1967: *Folding and fracturing of rocks,* 586 pp. New York: McGraw-Hill.

Rex, D. C. & Gledhill, A. R. 1981: Isotopic studies in the East Greenland Caledonides (72°–74°N) – Precambrian and Caledonian ages. *Rapp. Grønlands geol. Unders.* **104,** 47–72.

Soper, N. J. & Higgins, A. K. 1993: Basement-cover relationships in the East Greenland Caledonides: evidence from the Eleonore Bay Supergroup at Ardencaple Fjord. *Trans. Roy. Soc. Edinb.: Earth Sci.* **84**, 103–115.

Stecher, O. & Henriksen, N. 1994: Sm-Nd model age an early Proterozoic gabbro-anorthosite from the Caledonian fold belt in North-East Greenland. *Rapp. Grønlands geol. Unders.* **162** (this volume).

Steiger, R. H., Hansen, B. T., Schuler, C. H., Bär, M. T. & Henriksen, N. 1979: Polyorogenic nature of the southern Caledonian fold belt in East Greenland: an isotopic age study. *J. Geol.* **87**, 475–495.

Strachan, R. A., Nutman, A. P. & Friderichsen, J. D. in press: SHRIMP U-Pb zircon geochronology of the Smallefjord (metasedimentary) sequence: implications for crustal history and structure of the Greenland Caledonides. *J. geol. Soc. Lond.*

Streckeisen, A. L. 1976: To each plutonic rock its proper name. *Earth Sci. Rev.* **12,** 1–33.

Tucker, R. D., Dallmeyer, R. D. & Strachan, R. A. 1993: Age and tectonothermal record of Laurentian basement, Caledonides of NE Greenland. *J. geol. Soc. Lond.* **150,** 371–379.

Wedepohl, K. H. 1969: *Handbook of geochemistry* **1,** 442 pp. Berlin: Springer-Verlag.