Gneiss complex of the Skærfjorden region (76°–78°N), North-East Greenland

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The crystalline rocks of the Skærfjorden region are dominated by grey migmatitic orthogneisses with smaller bodies of ultramafic, mafic and metasedimentary lithologies. Archaean rocks (~ 3.0 Ga) have been documented, but crustal additions were predominantly Early Proterozoic (2.0–1.75 Ga) in age, reflecting subduction zone magmatism. Following Early Proterozoic orogenesis and migmatisation, granitic sheets (~ 1.7 Ga) and dolerite dykes were intruded. These intrusive rocks were subsequently deformed and metamorphosed in the Caledonian orogeny (~ 400 Ma). The Skærfjorden region is located in the Caledonian hinterland, where orogen parallel stretching and extension followed an early nappe stage.

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North-East Greenland includes some of the least known bedrock around the Greenland Inland Ice. The study area (Fig. 1) lies between 76° and 78°N, and includes exposures around Skærfjorden, Germania Land, Daniel Bruun Land, Okselandet, Søndermarken, Nordmarken and Jökelbugten. The geology is dominated by a heterogeneous assortment of crystalline gneisses that have been affected by both Precambrian and Phanerozoic orogenic events. The study area lies east of the Storstrømmen shear zone, a major structural element of North-East Greenland (Holdsworth & Strachan, 1991), and within the Caledonian fold and thrust belt. The geology of Dronning Louise Land and Hertugen af Orléans Land to the west, and the Dove Bugt region to the south of the study area, while referenced here, are discussed more fully elsewhere (Chadwick *et al.*, 1990; Chadwick & Friend, 1991; Holdsworth & Strachan, 1991; Henriksen, 1991; Strachan *et al.*, 1991, 1992).

The study area is geologically notable for several reasons. The only Archaean outcrop in North-East Greenland is found in the Danmarkshavn area (Steiger *et al.*, 1976). Pods of eclogite *s.s.* are widespread throughout Nordmarken, Søndermarken, and Germania Land (Gilotti, 1993, 1994), occurring in an area of comparable size to the eclogite-bearing Western Gneiss Region in Norway. Exposures in this part of North-East Greenland provide a transect, over 150 km long, through the Caledonian fold and thrust belt, from the foreland in western Dronning Louise Land through the highly reworked hinterland in our study area. The Caledonian geology of North-East Greenland may present a mirror image of that seen in west-central Norway.

Lithology

The distribution of lithologies is shown on the simplified map in Figure 1. The bedrock is dominated by a heterogeneous complex of grey orthogneisses, often migmatitic, which contain lenses of mafic, ultramafic and metasedimentary rocks. Later intrusive rocks include sheets of often porphyritic metagranitoids and metadolerite dykes. The field and isotopic data establish intrusive events of batholithic dimensions in the Early Proterozoic, followed by deformation and metamorphism producing polyphase gneiss complexes. Pre-existing rocks cut by the gneiss protoliths are discussed first, then the polyphase gneisses themselves, followed by the younger intrusive rocks. Brief descriptions of all the major lithologies, emphasising the field relationships, are found in Friderichsen *et al.* (1991). Here we focus on subsequent petrographic and geochemical work.

A relative chronology of sedimentation, intrusion, deformation and metamorphism has been established by Chadwick *et al.* (1990), Friderichsen *et al.* (1991) and

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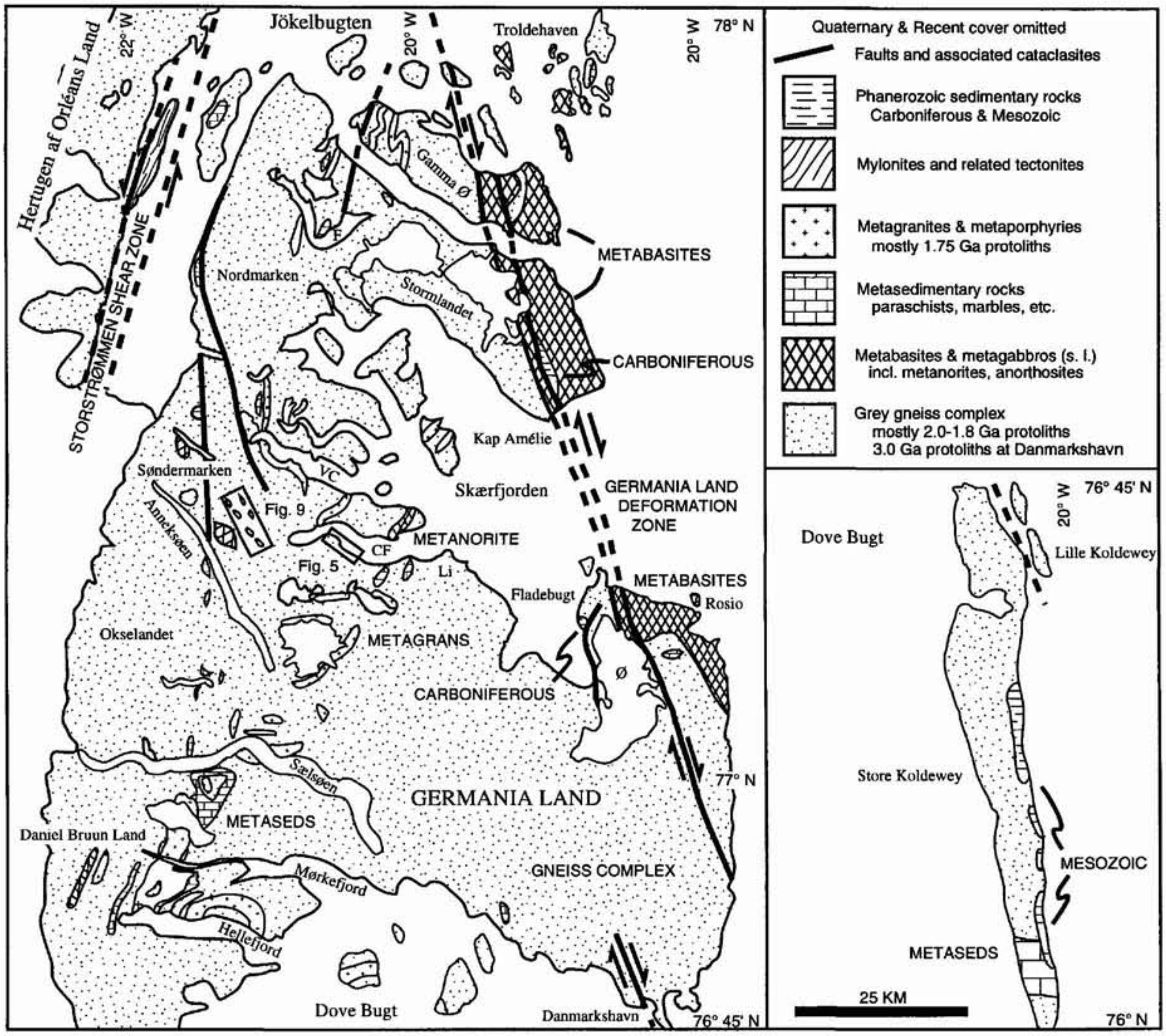


Fig. 1. Simplified bedrock geology map of the study area between 76°–78°N. VC, V. Clausen Fjord; Li, Kap Li; CF, C. F. Mourier Fjord; F, Flyversø; Ø, Østtungerne.

Chadwick & Friend (1991), and is summarised in Figure 2. Intrusive episodes have been dated from the Archaean (~ 3.0 Ga), Early Proterozoic (2.0–1.7 Ga) and Caledonian (~ 0.4 Ga); however, only Early Proterozoic magmatism is volumetrically significant. Sedimentary rocks probably date from the Archaean (?) to Early Proterozoic, Middle Proterozoic (?), Late Proterozoic to Early Palaeozoic, Carboniferous and Mesozoic. Orogenic episodes in the Early Proterozoic and Middle Palaeozoic (Caledonian) are well established, but Archaean and Grenville disturbances cannot be ruled out.

Archaean

There is some isotopic evidence for crustal additions in the Archaean in the study area. One polyphase gneiss sample near the Danmarkshavn weather station has yielded an Archaean (~ 3.0 Ga), U-Pb age (upper intercept) on zircon separates (Steiger *et al.*, 1976), recently confirmed by new SHRIMP analyses (Nutman & Kalsbeek, 1994). This age has been interpreted as the crystallisation of the igneous protolith. No other sample between latitudes 75° and 78°N has yielded an Archaean age, though isotopic work in this region is sparse.

The Archaean gneisses around Danmarkshavn are very similar to gneisses throughout the rest of the study area. Mafic bodies and sedimentary rocks are found as xenoliths within the granitoid protoliths to the gneisses. Subsequent deformation and metamorphism has produced a polyphase gneiss complex dominated by grey, quartzofeldspathic orthogneisses. Isolated pods and boudinaged blocks of eclogite and websterite are commonly found within the grey gneisses (Gilotti, 1994). The isotopically dated sample from Danmarkshavn is a granodioritic gneiss bearing hornblende, biotite and garnet, interbanded with amphibolites and cut by small leucocratic veins. A mafic dyke swarm cuts gneissosity and associated tight to isoclinal folds in this area (Fig. 3), and was in turn deformed and metamorphosed in the amphibolite facies, probably during the Caledonian orogeny (Steiger *et al.*, 1976). The relative chronology of cross-cutting relationships, both intrusive and deformational, is the same at Danmarkshavn as the rest of the study area. The only notable difference is the greater abundance of mafic dykes around Danmarkshavn, compared with most other areas.

Early Proterozoic to Archaean

Isotopic data suggest substantial crustal additions to the basement crystalline complexes in the Early Proterozoic. A granitic orthogneiss from southern Dronning Louise Land yielded a U-Pb upper intercept of 1910 Ma, based on single zircon analyses (Tucker *et al.*, 1993). Kalsbeek *et al.* (1993) report U-Pb, concordant ages for single zircons from an Okselandet gneiss (determined on the SHRIMP) of 1975 Ma. These ages are interpreted to date the crystallisation of the igneous protoliths of the rocks. Concordant zircons of Early Proterozoic age are also present in the Late Proterozoic to Early Palaeozoic Zebra Series arenites of northern Dronning Louise Land (Strachan *et al.*, 1992). Tucker *et al.* (1993) argue for a local provenance for the Proterozoic detritus, based on total-gas Ar ages of ~ 1.7–1.6 Ga for detrital white micas. Sm-Nd and Rb-Sr model ages from samples throughout North-East Greenland scatter about a *c.* 2 Ga isochron (Kalsbeek *et al.*, 1993).

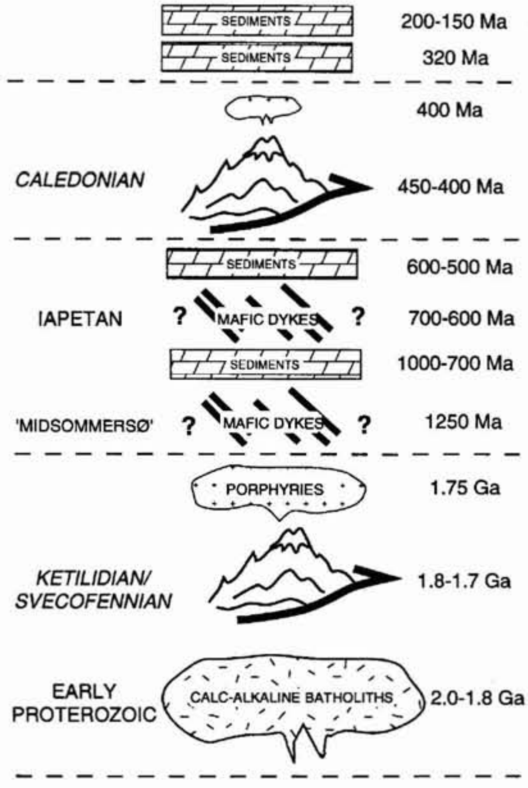


Fig. 2. Sedimentary, magmatic and tectonic events for North-East Greenland between 75°–78°N.

Metasedimentary rocks. Metasedimentary rocks are found as isolated pods and lenses within the grey gneisses, and occasionally as mappable sheets or trains of boudin, as in Daniel Bruun Land (Fig. 1). There are three main associations of metasediments: marbles and calc-silicate rocks; semi-pelitic to pelitic schists; and quartzites. These supracrustal rocks could have been incorporated into the granitoid complexes during intrusion or infolded during one or more of the subsequent orogenic events. The metasediments may therefore represent different ages or different depositional environments, although many of the metasediments appear to predate the main Early Proterozoic intrusive events, given the cross-cutting field relationships.

Marble and calc-silicate rocks are relatively common in the western part of the map area, extending in a poorly defined belt from northern Nordmarken south to Daniel Bruun Land (Fig. 1); however, they are rare to the east. Lithologies vary from pure marble to calc-silicate rocks to calcareous schists and gneisses, occasionally associated with semipelitic schists. Calc-silicate assemblages contain calcite, diopside, tremolitic amphibole, sphene and zircon.

Semipelitic to pelitic schists and gneisses are few, and form isolated bodies, not semi-continuous horizons. West of Kap Li, finely laminated garnet-biotite-kyanite paragneisses are interlayered with melanocratic, biotite-rich garnet-kyanite gneisses and schists, as well as more mundane quartzofeldspathic gneisses and amphibolites. North-east of Annekssøen, garnet-biotite-kyanite quartzofeldspathic gneisses are associated with garnet-rich rocks, purplish biotite-rich gneisses, rusty weathering gneisses, and amphibolite pods. Garnet-biotite-sillimanite schists, with and without muscovite, are also found just south of V. Clausen Fjord. Two-mica schists and garnet-biotite schists are exposed in north-east Germania Land and around Danmarkshavn (Table 1).

Fig 3. Metadolerite dyke about 1 m thick cutting tightly folded gneisses near Danmarkshavn.

About 200 m of metasandstones and related rocks were discovered on an island in south-eastern Jökelbugten near Troldehaven. The lithologies are massive to thickly banded, and composed of variable proportions of plagioclase, quartz, alkali feldspar, hornblende, biotite, and other minerals. Most of the rocks are dominated by plagioclase, and some would be classified petrographically as anorthosites. However the abundance of quartz, the paucity of hornblende, biotite and clinopyroxene, and the near absence of mafites in the section all support sedimentary protoliths.

Ultrabasic, basic and anorthositic lenses. Ultrabasic rocks are not very common in the study area. Only one peridotite was discovered, a large dunite body composed of olivine and minor clinopyroxene, orthopyroxene and spinel (chromite?). Wyllie (1957) reported three hornblendites (with accessory pyroxene and olivine) from Sælsøen; a similar rock composed of hornblende, lesser orthopyroxene and minor, dark green spinel was found in Søndermarken. Pyroxenites, mainly garnet websterites and websterites, are scattered around southern Nordmarken and Danmarkshavn; detailed discussion of the pyroxenites and related rocks can be found in Gilotti (1994). Friderichsen *et al.* (1991) hypothesised that the pyroxenites and related rocks were once parts of layered basic intrusions.

One variety of basic body is preserved (in low strain

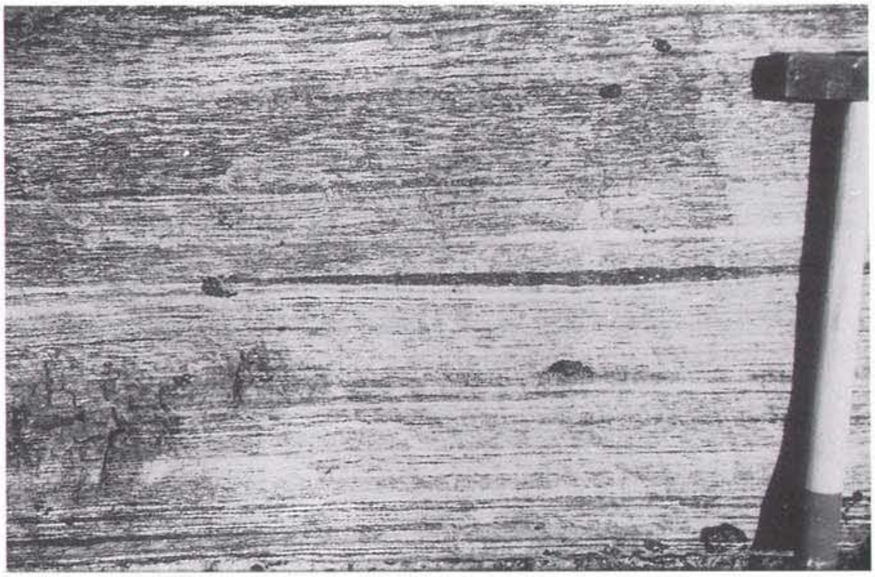


Fig. 4. Photograph of highly lineated and metamorphosed anorthosite and anorthositic gabbro, with one small mafic schlieren. West Søndermarken.

areas) as xenoliths in agmatite. Many of these blocks contain eclogitic (*s.l.*) garnet-clinopyroxene assemblages, often partially retrogressed to hornblende and plagioclase (Table 1). Eclogites (*s.s.*) and garnet-clinopyroxene rocks are described comprehensively by Gilotti (1993, 1994). Very thick sheets of massive amphibolite, perhaps with relict eclogitic assemblages, are exposed at Trækpasset on southern Store Koldewey (Bronner, 1948).

North of Anneksøen, anorthosites, leucogabbros and gabbros, metamorphosed and deformed, are cut by metadolerite dykes (Table 1). One finely banded meta-anorthosite (Fig. 4) is composed of plagioclase, hornblende, scapolite (replacing plagioclase), opaque oxides and apatite. Thin bands of metamorphosed gabbroic anorthosite are also found on both Store and Lille Koldewey, associated with amphibolites and hornblendites. Pods and lenses of metamorphosed gabbro-anorthosite, some with relict igneous textures, are also found in western Dove Bugt (Chadwick *et al.*, 1990), where they are cut by grey gneiss sheets and mafic dykes. A large body of gabbro-anorthosite is located south of Bessel Fjord (75°50'N, 23°45'W; Henriksen *et al.*, 1989), and has yielded an Sm-Nd model age of 2146 Ma (Stecher & Henriksen, 1994).

Heterogeneous gneiss complex. The study area is overwhelmingly dominated by polyphase and polymetamorphic gneiss complexes, consisting of variable proportions of quartzofeldspathic lithologies and mafic amphibolite, mixed together on a variety of scales. An example of an approximately 2 km section through the gneiss complex is shown in Figure 5, which we use to illustrate the lithological diversity. The section is located on the monoclinal eastern limb of the largest upright antiform, exposed on the southern cliff face of C. F. Mourier Fjord that is figured in Haller (1956, 1970). Haller (1970, 1983) interpreted the migmatisation and agmatisation of this cliff section to be Caledonian in age, based on work in the Caledonian infrastructure to the south; however, our field work supports an Early Proterozoic genesis with lesser modification in the Caledonian.

The section is dominated by dark weathering, deformed agmatites and migmatites (mixed unit), whose mafic content is approximately 15–20%. Subequant blocks and lenses of mafite and dark weathering grani-

Table 1. Selected whole rock analyses for the major lithologies in the Skærfjorden area

	1	2	3	4	5	6	7	8	9	10
GGU No.	407508	363064	407514	363049	407559	327851	363184	364514	364645	363138
SiO_2	59.5	54.7	51.5	50.9	50.1	67.4	66.4	50.1	49.4	69.2
TiO_2	0.7	0.1	0.5	1.5	0.1	0.4	0.9	0.3	1.0	0.4
Al_2O_3	21.0	3.8	6.4	13.2	23.8	16.7	14.0	18.0	14.0	14.2
Fe_2O_3	2.0	1.1	3.0	4.1	1.8	–	1.2	1.6	3.3	2.6
FeO	5.0	7.3	7.3	9.6	3.3	2.8	3.4	6.1	9.2	0.0
MnO	0.1	0.2	0.2	0.2	0.1	0.0	0.1	0.1	0.2	0.0
MgO	4.0	24.4	16.1	6.5	6.3	1.2	0.1	9.8	7.5	0.9
CaO	1.8	4.7	12.0	9.7	9.9	3.9	3.0	9.4	11.4	2.2
Na_2O	2.1	0.4	1.1	2.7	3.2	4.7	3.0	2.5	2.1	4.0
K_2O	2.4	1.0	0.5	0.6	0.6	1.5	5.0	0.3	0.3	4.1
P_2O_5	0.0	0.0	0.1	0.1	0.0	0.1	0.3	0.0	0.1	0.2
loi	1.1	1.6	1.0	1.0	0.7	0.6	0.6	1.6	1.6	0.3
	99.7	99.3	99.7	100.1	99.9	99.3	98.0	99.8	100.1	98.1
Y	44	24	24	78	–	7	–	11	27	–
Nb	–	15	45	–	–	16	–	10	25	–
Zr	113	27	161	82	–	150	–	11	153	–
Cr	412	3986	88	1122	53	11	–	549	212	–
Ni	131	750	73	515	109	6	–	219	121	–
Cu	31	6	91	13	47	3	2	47	171	3
Zn	99	99	135	157	50	49	71	33	64	0
V	151	43	242	57	6	35	21	83	328	4
Rb	153	51	51	64	30	65	82	22	38	60
Sr	92	12	134	98	1379	518	651	422	118	744
Ba	–	–	50	–	158	291	–	382	209	–

1: garnet-biotite paragneiss; 2: orthopyroxenite; 3: garnet websterite; 4: eclogite; 5: anorthosite; 6: grey quartzofeldspathic gneiss; 7: porphyritic metagranitoid; 8: metanorite; 9: metabasaltic dyke; 10: late undeformed granite.

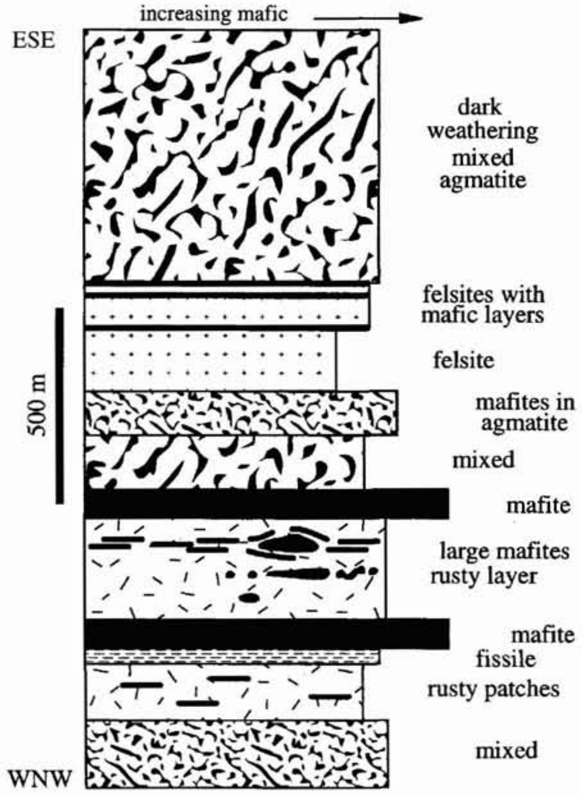


Fig. 5. Simplified lithologic log of 600 m high cliff section along the south shore of C. F. Mourier Fjord. 'Top' of section towards ESE. Compare with photograph in Haller (1956).

toids range from metres to tens of metres (occasionally larger); persistent mafic layers are not typical of the agmatitic unit. The matrix is composed of granodioritic to tonalitic metagranitoids, cut by a large number of deformed granitic veins (aplites to pegmatites). One grey gneiss is composed of quartz, plagioclase, lesser microcline and minor amounts of hornblende, biotite, garnet, opaque oxides and apatite. The matrix is best characterised as a veined orthogneiss, rather than a true migmatite, as intrusive relationships can be unraveled.

A variant of this mixed unit contains large mafic-ultramafic bodies, up to several hundred metres in length (Fig. 5). This horizon on the C. F. Mourier Fjord section corresponds to the upper (south-western) carbonate layer in Figure 1, although carbonate is apparently not present in the the C. F. Mourier Fjord section. One mafic rock from this unit is composed of equal proportions of diopsidic clinopyroxene, garnet and hornblendic amphibole, with minor amounts of plagioclase, sphene and opaque oxides. The largest mafites are surrounded by rusty layers tens of metres thick; however, these rusty weathering gneisses are not unusual in either mineralogy or mineral proportions. Rusty patches and layers are found throughout the study area but only a few are lithologically controlled (e.g. mica-rich gneisses or mafites).

A few layers or bands in the C. F. Mourier Fjord section are monolithologic (or approximately so). Mafic bands, usually less than 100 m in thickness, could have many origins: basaltic flows; dykes or sills; or flattened megaxenoliths. Trondhjemites to aplites, typically garnet bearing, are often associated with these mafic horizons; one sample is composed of quartz, microcline, and plagioclase with minor garnet, apatite and opaque oxide. Several varieties of metamorphosed granitoid, from diorite to granite, form massive, relatively homogeneous bands and layers within this section. Felsic bands composed of metamorphosed monzonites and granites are often much thicker than other metagranitoids.

One common unit in the study area, not exposed on the C. F. Mourier Fjord section, is a yellow to cream weathering, felsic gneiss. This creamy gneiss forms a large body at the tip of V. Clausen Fjord (Fig. 1), and is scattered throughout Nordmarken, mostly as thin sheets. This unit grades from more typical agmatitic grey gneiss with small mafic xenoliths into creamy migmatitic felsite with a ghost-like gneissosity and very few mafites. A typical creamy metagranitoid is composed of quartz and microcline, with minor plagioclase, biotite, garnet, zircon, apatite, sphene and opaque oxides.

Eight amphibolite sheets, layers and lenses from the Skærfjorden region have been studied in detail. The amphibolites are composed of variable proportions of hornblende, plagioclase, clinopyroxene (slightly green to colourless) and colourless to pink garnet. Minor phases include biotite, quartz, zircon, sphene, apatite and opaque oxides. Clinopyroxene and garnet are almost ubiquitous in 'amphibolites' from this region. Some clinopyroxene may be igneous in origin. However, textures and microstructures suggest that in some rocks, both clinopyroxene and garnet are metamorphic, and that this high to very high grade (granulite to eclogite facies) metamorphic paragenesis has been partially replaced by the moderate grade (amphibolite facies) paragenesis of hornblende and plagioclase. High grade metamorphism in mafic rocks is discussed by Gilotti (1994).

Twenty-five quartzofeldspathic gneisses from the Skærfjorden region have been studied in detail (Kalsbeek, in press). The gneisses are composed of variable proportions of plagioclase, alkali feldspar (microcline to orthoclase), quartz, hornblende (dark green to bluish green), and green, brown or black biotite. Colourless to pinkish garnet is a common constituent. Pale green to colourless clinopyroxene has been noted from a few samples of quartzofeldspathic gneiss; the granular, recrystallised texture of these gneisses suggests that clinopyroxene is metamorphic. Kyanite has also been noted in several samples. Minor phases include epidote, muscovite (both probably retrograde), apatite, zircon, sphene, rutile, monazite (?) and opaque oxides.

Major element analyses have been completed for 64 quartzofeldspathic gneisses; some of these rocks were sampled as far south as latitude 75°N. Cation norms with orthoclase + hypersthene recalculated to biotite + quartz, a fair approximation of the modal composition of granitoids, are shown in a QAP diagram in Figure 6a. Most of the analysed rocks occupy the granite, granodiorite and tonalite fields (Streckeisen, 1976); a few samples correspond to diorite, quartz diorite and monzonite (Table 1).

On an AFM diagram (Fig. 6b), most of the analysed samples fall in the calc-alkaline field, as defined by Irvine & Baragar (1971). Tonalitic to granodioritic calc-alkaline granitoids are typical of subduction zone magmatism preceding collision (Group 1 of Harris *et al.*, 1986); smaller calc-alkaline intrusions can also form during collision and mountain building (Group 3). The large volumes of calc-alkaline granitoids were most likely generated during Early Proterozoic (2000–1750 Ma) subduction of oceanic crust in North-East Greenland.

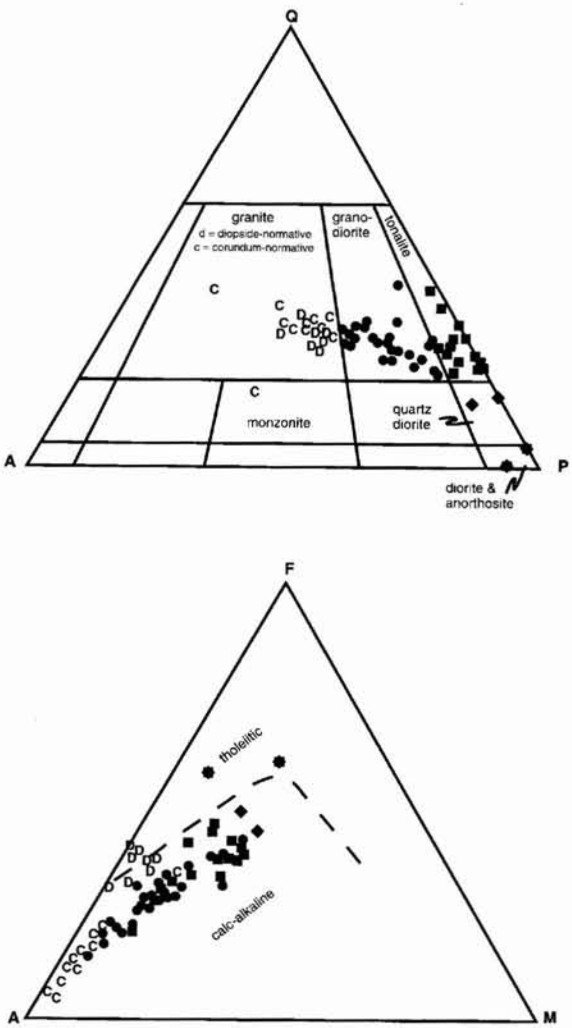


Fig. 6. a. Quartz-alkali feldspar-plagioclase (QAP) ternary diagram showing normative mineralogy of 64 quartzofeldspathic gneisses from North-East Greenland. Lithologic subdivisions from Streckeisen (1976). b. Alkalies-iron-magnesium (AFM) ternary diagram showing compositions of the 64 quartzofeldspathic gneisses. Dashed line separates tholeiitic from calc-alkaline differentiation trends.

Eastern Skærfjorden area. The rocks to the east of the Germania Land deformation zone (GLDZ) are dominated by mafic amphibolites, metagabbros and metanorites, in unknown contact relations with polyphase gneisses (Fig. 1). There are also dark weathering, quartzofeldspathic gneisses east of the GLDZ that are not mafic in composition. Despite the differences, we do not interpret the GLDZ as a 'terrane' boundary (see Hull & Gilotti, 1994). The gneiss complex to the east of the GLDZ contains many of the same intrusive and cross-cutting relationships as elements to the west of the GLDZ. Rather than a separate 'terrane', the eastern segment is a locus of mafic magmatism of Early Proterozoic age. Ages of 2000–1950 Ma have been determined on the SHRIMP for zircons from a tonalite from easternmost Gamma Ø (Nutman & Kalsbeek, 1994).

The mafic magmatism is centred around eastern Stormlandet and Gamma Ø, and extends south into Germania Land and north into the islands of Troldehaven (Fig. 1). The mafic complex is dominated by amphibolites (hornblende-plagioclase ± garnet rocks) of mafic to sometimes intermediate composition, but in many places deformation is low and protolith characteristics are evident. Protoliths include anorthositic gabbros, leucogabbros, gabbro, dolerite and norites (Table 1). Cross-cutting relationships among these mafites were observed in a couple of localities. Near Østtungerne, xenoliths or autoliths of finer grained, dark microgabbro are found in leucogabbro. On Rosio, very coarse grained (locally pegmatitic) norite with relict orthopyroxene and plagioclase laths exhibits grain size and compositional layering of primary origin. Both the norite and adjacent red metagranites are cut by metabasalt dykes.

There are a variety of quartzofeldspathic gneisses adjacent to this mafic complex. The quartzofeldspathic rocks are dominated by hornblende-bearing grey gneisses with centi- to decimetre thick bands of biotite-rich garnet gneiss and thick layers of medium grained metagranitoids. Eclogitic pods (garnet-clinopyroxene-hornblende-plagioclase rocks) were found within these gneisses in

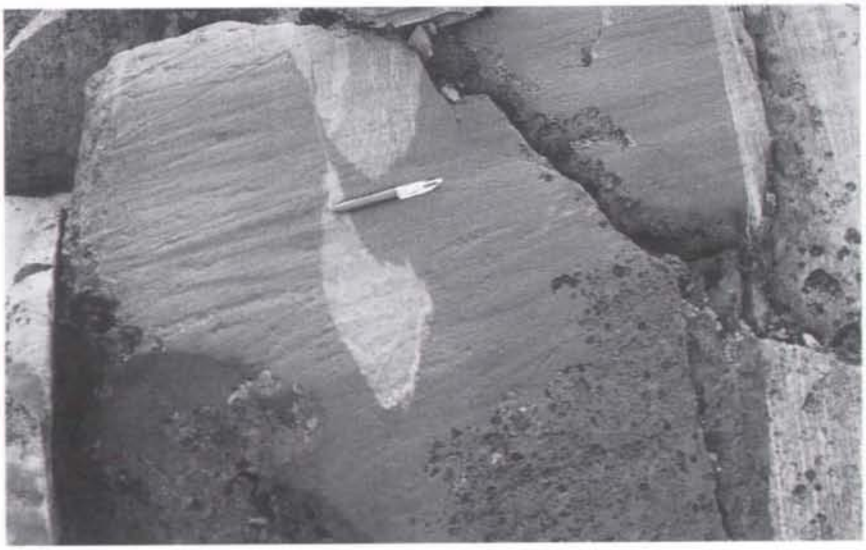


Fig. 7. Cross-cutting metadolerite dyke at Kap Li containing xenoliths of folded gneiss. Pen for scale.

Troldehaven and in north-easternmost Germania Land (Gilotti, 1994). Red weathering megacrystic metagranitoids, similar to the potassium feldspar metaporphyries elsewhere, are found at several localities. Both mafites and dark weathering gneisses are cut by large, red to white weathering, undeformed pegmatite dykes.

Late metagranitoid sheets. Important chronological and structural markers in the survey area are sheets and layers of red, pink and grey weathering, relatively homogeneous, often porphyritic metagranitoid. The red-pink metaporphyries cut the polyphase gneisses; xenoliths of gneiss are found along their intrusive margins, and gneissosity is truncated. The simple tectonic fabrics and lack of serious migmatisation of the metagranitoid sheets also supports their relatively late position in the intrusive chronology. Similar rock sequences are described by Chadwick *et al.* (1990) and Chadwick & Friend (1991) in western Dove Bugt. A granitic gneiss from Okselandet and a cross-cutting metagranitoid from Mørkefjord were dated by the U-Pb method using zircon separates (analysed on the SHRIMP) at 1765 and 1740 Ma, respectively (Kalsbeek *et al.*, 1993).

This suite of metagranitoids is dominated by K-feldspar (orthoclase to microcline), plagioclase and quartz in varied ratios; biotite, hornblende, garnet, zircon, apatite, sphene, monazite and opaque oxides are secondary or accessory phases. K-feldspar is occasionally rimmed by sodic plagioclase, producing a rapikivi texture. However, the plagioclase overgrowth may reflect metamorphism rather than cooling in a granitic magma. Biotite, hornblendic amphibole and garnet are often found together in these rocks; their microstructures suggest a metamorphic rather than igneous origin.

The geochemistry and normative mineralogy of these metagranitoids is variable (Fig. 6 and Table 1). Some are rich in potassium (5–7% K_2O), and have $K_2O/Na_2O > 1$, typical of granites derived by partial melting of pre-existing crustal rocks. These late- to post-orogenic metagranitoids were most likely produced by partial melting of over-thickened crust (Group 2 magmas of Harris *et al.*, 1986), formed during an Early Proterozoic orogenesis (see Fig. 6b).

Middle to Late Proterozoic

Basic dykes. Mafic dykes, now deformed and metamorphosed, are ubiquitous in the study area. Dykes are usually recognised by their straight planar contacts, sheet- or band-like morphologies, and cross-cutting relationships with older rocks and structures. Some of the mafic boudin, blocks, lenses and layers found throughout the map area were probably originally dykes and sills, but they have been so deformed that all their igneous characteristics have been lost.

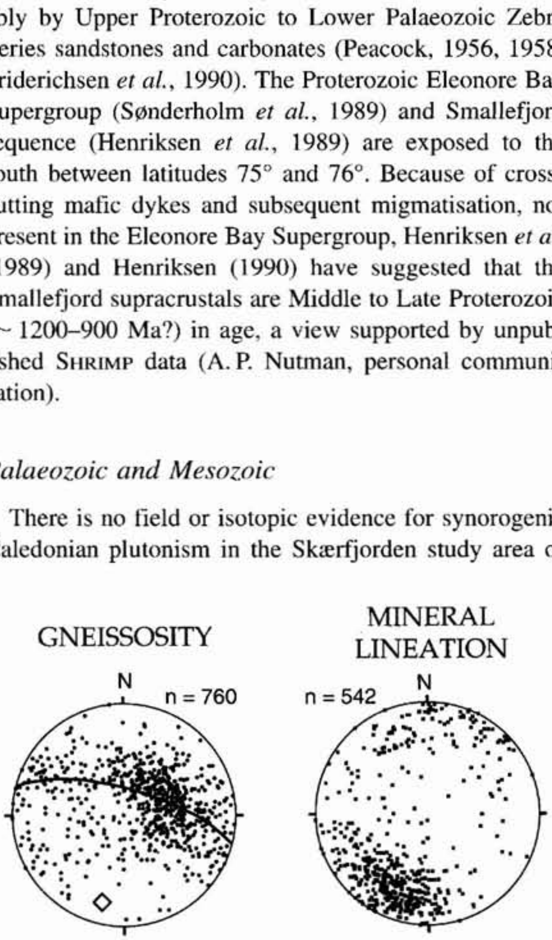
The clearly cross-cutting dykes are important chronological markers separating the two main deformations in the study area (Early Proterozoic and Caledonian). Mafic dykes truncate gneissosity and associated structures, such as isoclinal folds, and occasionally contain xenoliths of gneiss (Fig. 7). Similar mafic dykes, with the same petrographic and geochemical characteristics, also intrude the late porphyritic metagranitoids. The dykes (and metagranitoids) are in turn deformed and metamorphosed to at least amphibolite facies.

The basic dykes of North-East Greenland may belong to one or more of five major periods of mafic dyke intrusion in Greenland, North America and Scandinavia in the Middle to Late Proterozoic. The dykes of the Skærfjorden area are typical continental tholeiites (Table 1) and appear to be consanguineous, representing only one magmatic event (J. M. H., unpublished data). Furthermore, the major and trace element compositions of these dykes are unexceptional, and do not permit distinction of more than one generation of continental tholeiitic magmatism.

Sedimentary strata. Middle to Late Proterozoic sedimentary rocks have not been identified in the Skærfjorden study area. In western Dronning Louise Land, the Proterozoic Trekant Series of sandstones, siltstones and conglomerates (cut by mafic dykes), is overlain unconformably by Upper Proterozoic to Lower Palaeozoic Zebra Series sandstones and carbonates (Peacock, 1956, 1958; Friderichsen *et al.*, 1990). The Proterozoic Eleonore Bay Supergroup (Sønderholm *et al.*, 1989) and Smallefjord sequence (Henriksen *et al.*, 1989) are exposed to the south between latitudes 75° and 76°. Because of cross-cutting mafic dykes and subsequent migmatisation, not present in the Eleonore Bay Supergroup, Henriksen *et al.* (1989) and Henriksen (1990) have suggested that the Smallefjord supracrustals are Middle to Late Proterozoic (~ 1200–900 Ma?) in age, a view supported by unpublished SHRIMP data (A. P. Nutman, personal communication).

Palaeozoic and Mesozoic

There is no field or isotopic evidence for synorogenic Caledonian plutonism in the Skærfjorden study area of North-East Greenland, although a few late- to post-Caledonian plutons have been identified (Table 1). An essentially undeformed, very coarse grained granite south-west of V. Clausen Fjord is composed of microcline and lesser quartz, with minor amounts of plagioclase, biotite, zircon, apatite and monazite (?). Undeformed granitic pegmatites of probable Caledonian age are scattered throughout the study area, with a particularly dense swarm on the east side of Fladebugt. The Eleonore Bay Supergroup to the south is cut by a number of small granitic plutons, which have been dated at 405–390 Ma using U-Pb analyses of zircon separates (Hansen *et al.*, 1994).



Evalue	Evector	
10.00	070	58°
3.70	295	23°
1.79	196	20°

Evalue	Evector	
10.00	205	21°
2.84	310	33°
0.71	089	49°

Fig. 8. Geometries of gneissosity and mineral lineations, along with calculated eigenvectors and eigenvalues (normalised to a maximum value of 10). All stereonets are lower hemisphere, equal area.

Carboniferous sedimentary rocks (conglomerates and sandstones) extend for approximately 10 km along the Chatham Elv fault north of Kap Amélie in Stormlandet (Hull & Gilotti, 1994). Macro- and microfossils indicate an Upper Westphalian (Pennsylvanian) age (S. Piasecki, personal communication). Mesozoic strata are preserved in the hangingwalls of a major system of down to the west normal faults, and are composed of conglomerates, quartzites, arkoses and lesser siltstones (Friderichsen *et al.*, 1991). Plant fossils indicate a Jurassic age (B. E. Koch, personal communiation). Middle to Upper Jurassic marine strata are found on Store Koldewey, overlain by Lower Cretaceous sedimentary rocks (Stemmerik & Piasecki, 1990).

Structure and metamorphism

Early deformation and metamorphism were accompanied by widespread partial melting, producing veins and migmatites, some of which were subsequently deformed during progressive tectonism. The resulting gneisses are typically quite complex, regardless of scale of observation, and heterogeneous; one outcrop may preserve original intrusive relationships, while the adjacent exposure shows refolded isoclines. As most outcrops lack markers such as the late metagranitoids and metadolerite dykes, the effects of subsequent (Caledonian) deformation cannot be generally evaluated. There are, however, many areas or domains where older cross-cutting relationships are well preserved (mafic dykes at a high angle to gneissosity, for example), such that Proterozoic fabrics and structures can be examined directly.

Migmatisation and gneiss forming event: Early Proterozoic

Proterozoic deformation has produced a penetrative fabric, consisting of gneissosity (tectonic banding) parallel to schistosity, and an associated lineation (mineral or shape). The development of gneissosity was accompanied by folding and boudinage. Gneissosity is uniformly

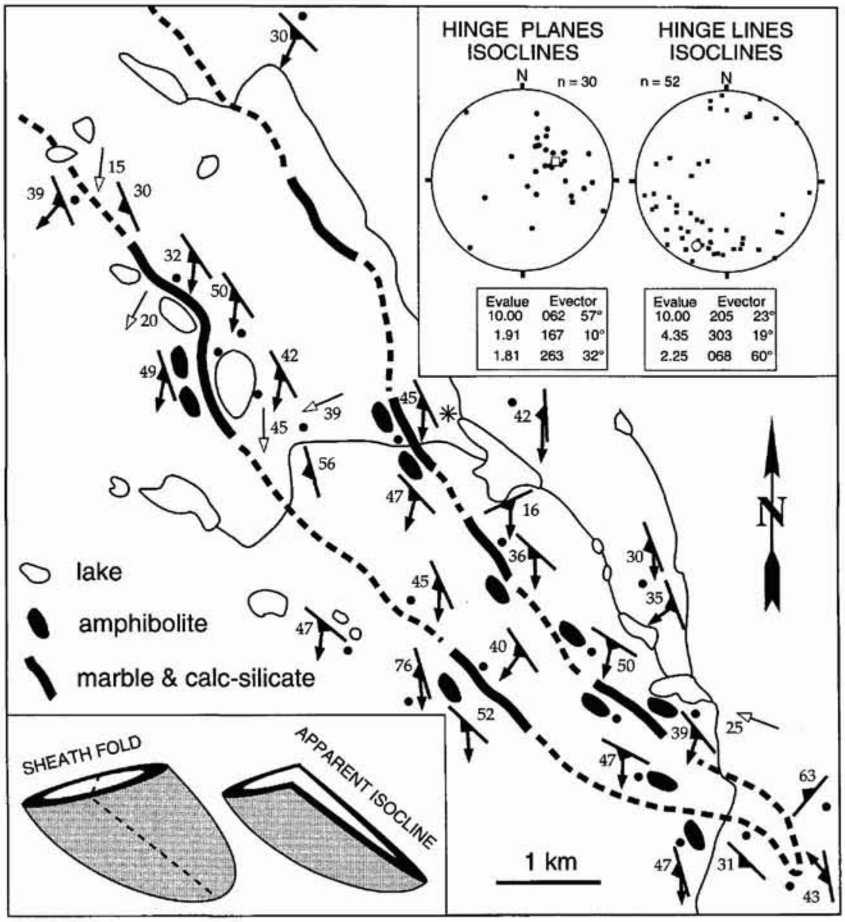


Fig. 9. Map showing double band of calc-silicates (black stripes) outlining a large isoclinal fold in Søndermarken. The lower inset illustrates the effect of exposure on the apparent fold topology. The upper inset illustrates the geometries of minor intrafolial isoclines.

oriented over large areas (500–1000 km^2), with northerly strikes and steep dips in Germania Land and Okselandet, and moderate to shallow westerly dips in Søndermarken and Nordmarken (Fig. 8; see also Fig. 2 in Friderichsen *et al.*, 1991). Gneissosity is fanned about a shallow SSW plunging axis (20° towards 190°) that parallels the eigenvector for mineral and shape lineations (21° towards 205°). It is difficult to evaluate the significance of these fabric geometries; penetrative Caledonian deformation would rotate most Proterozoic fabrics.

Widespread, outcrop scale isoclines and parallelism of lithologic units points to large isoclinal folds as an important structural element. One candidate for a large isocline is a double band of marble and calc-silicate rock in Søndermarken (Fig. 9). These recumbent to shallowly inclined folds may be sheath-like in topology (inset in Fig. 9). Another reclined to recumbent isocline in northern Nordmarken is disharmonic, with a rounded hinge in more mafic layers but detached in a more felsic layer. All of these larger isoclines have a shallow SSW plunge.

Small isoclinal folds of gneissosity with Class II (similar) morphologies are common throughout the study area. These intrafolial isoclines appear 'rootless' within the tectonic banding, because of highly attenuated limbs. Hinge lines of intrafolial folds plunge shallowly SSW (Fig. 9), parallel to mineral lineations and later upright folds. Many of these minor folds are refolded, and interference patterns are common. Folds with strongly recurved hinge lines, including sheath-like folds, are also found within the study area. Deviation from cylindricity may account for some of the scatter of hinge line orientations seen in Figure 9.

The age or ages of these structures is unclear. The classical interpretation would invoke multiple deformation phases for both the noncylindrical and interference folds, implying multiple tectonic events, but an equally valid alternative involves progressive deformation in a general noncoaxial strain field. Without closely spaced temporal markers and detailed geometric and kinematic data, these hypotheses cannot be evaluated properly. We are confident, however, that many of the isoclinal folds and related structures are Early Proterozoic in age; e.g., isoclinal folds are cut by mafic dykes subsequently deformed and metamorphosed in the Caledonian.

Boudinage is another important structural process at the outcrop scale (Fig. 10). Both competent layer boudinage (of mafic-ultramafic and tonalitic bodies) and foliation boudinage (of small packets of gneiss) are common, producing a number of boudin-related structural associations. In the necks between boudin, box-like scar folds with opposing asymmetries can develop into closed eye folds that mimic sheath folds; pegmatites and quartz veins are also common in boudin necks (Fig. 10a). In the narrow (centimetre-metre) carapace around boudin, very high strains are common, producing intrafolial isoclines in pin stripe to mylonitic gneisses (Fig. 10b). Carapace schistosity and gneissosity are strongly curved around boudin; some of the scatter in gneiss orientations seen in Figure 8 is due to warping of foliation around boudin. Lineations in the carapace are also strongly deflected around boudin.

Structures within boudin are very variable (Fig. 10c). Earlier structures, including cross-cutting intrusive relationships, are often preserved in competent pods. However, most boudin have some internal gneissosity or schistosity, often discordant with the regional foliation, and many boudin are penetratively deformed, with concordant schistosity. Asymmetric boudinage is common (Fig. 10d), with a gradation between asymmetric boudinage of competent layers, asymmetric foliation boudinage, and individual or isolated shear bands or extension bands. The 'back rotation' of internal foliation gives the sense of asymmetry. Unfortunately, it is difficult to integrate this kinematic information into the regional structural picture, as the age or ages of these structures are not known. A few isolated shear bands are probably Caledonian, as they deflect schistosity in the late metagranitoids, but the rest are equivocal.

The metamorphic history associated with Proterozoic orogenesis is obscure due to subsequent Caledonian activity. However, regional metamorphism probably reached amphibolite to granulite facies. The metamorphic history of this region is discussed more fully in Gilotti (1994) and Hull & Gilotti (1994).

Second fabric and associated structures: Caledonian

Field studies and subsequent isotopic work have established that cross-cutting metagranitoids and metadolerite dykes separate the two main deformational events in the study area (Figs 2, 3). A similar conclusion was reached by Chadwick & Friend (1991) for their detailed study area in north-western Dove Bugt. Penetrative Caledonian deformation superimposed new structures and fabrics on the Proterozoic structural family in the Skærfjorden study area. Caledonian fabrics can be identified unambiguously in the cross-cutting metaporphyries and metadolerite dykes, and are tentatively inferred at a few other localities where a schistosity cuts an older gneissosity at a high angle.

The Caledonian fabrics are typically a simple, planar schistosity or cleavage (rarely gneissic banding), with an associated mineral (hornblende, feldspar) or aggregate (stretching) lineation. Schistosity shows a variety of orientations, but most cleavage dips shallowly to moderately towards the south and south-west (Fig. 11). Mineral lineations are tightly clustered, plunging SSW, and schistosities show a broad, diffuse girdle about the same axis (Fig. 11). The fanning of Caledonian schistosity (as well as gneissosity, Fig. 8) is consistent with a later period of upright folding about a SSW plunging axis, although some of the steeper schistosities may be axial planar fabrics associated with these late folds. These late fabrics are approximately parallel to the regional grain of the Caledonian fold belt, similar to the Caledonian hinterland in west-central Norway (Gilotti & Hull, 1993).

The larger structures associated with the Caledonian fabrics have not been identified in the northern part of the study area. To the south around Dove Bugt, Chadwick & Friend (1991) have identified shallowly to moderately south-east dipping isoclinal folds of the late metagrani-

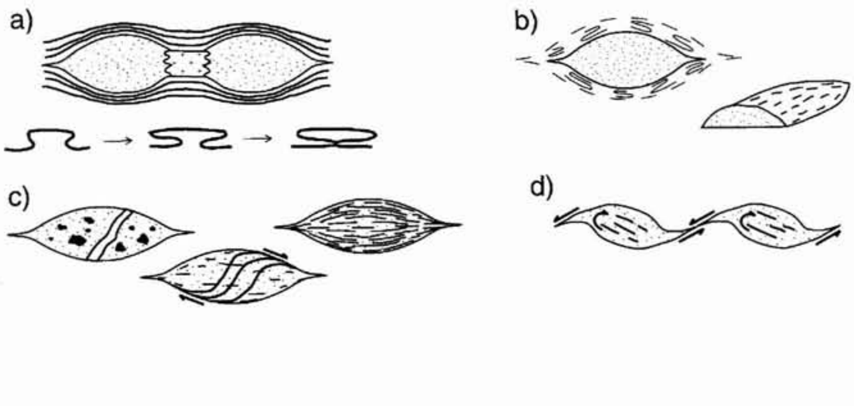
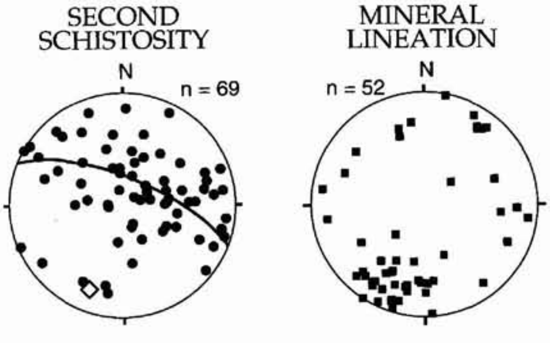


Fig. 10. Schematic diagram illustrating the varieties of boudinage within the study area. a. Structures associated with boudin necks. b. Carapace structures. c. Structures within boudin. d. Asymmetric boudinage.



Evalue	Evector	
10.00	067	62°
5.95	299	18°
3.33	202	21°

Evalue	Evector	
10.00	204	17°
3.16	109	15°
2.29	339	67°

Fig. 11. Stereonets showing geometries of schistosities and mineral lineations in late metagranitoids and metadiabase dykes.

toids, associated with mylonitic detachments showing NE-directed displacement. These fold-thrust nappes are probably Caledonian in age. If such structures are present in Germania Land, Nordmarken, and adjacent areas, then fold-thrust nappes would dip moderately to the south-west (parallel to cleavage), rather than to the south-east as around Dove Bugt. However, the overall orogen parallel, NE–SW transport direction would be similar to that seen in north-western Dove Bugt.

Late upright folds: Caledonian

The latest major folds in the study area are shallowly plunging structures characterised by upright to strongly inclined hinge planes (Fig. 12). Most of the upright folds have wavelengths of a few kilometres or less, but the large antiform stretching from Gamma Ø to Mørkefjord has a half wavelength of tens of kilometres and a correspondingly high amplitude. Fold morphologies vary; the largest antiform has a rounded hinge and an open to close interlimb angle, whereas small upright folds exposed on cliffs in northern Nordmarken are tight to isoclinal, and polyharmonic. Antiform-synform pairs are common, suggesting asymmetric couples developed in shear, although a consistent sense of shear has not been determined for the Skærfjorden area. An axial planar schistosity is probably associated with the tighter folds. Late upright folds have also been described from the Dove Bugt area; these folds are upright to somewhat inclined to the north-west (Chadwick & Friend, 1991).

Late upright folds in northernmost Nordmarken plunge to the north-east, whereas other folds to the south have a SSW plunge (Fig. 12). Thus the area north of Flyversø represents a culmination for upright folds, although the significance or origin of this culmination is unknown. Minor, outcrop to hand sample scale buckle folds probably of the same generation are common throughout the region. Hinge lines of minor folds plunge shallowly SSW (22° towards 190°), and most hinge planes are upright (Fig. 13). Most of these folds have a mullion-like appearance (Fig. 14), with hinges alternating between rounded and pinched-in morphologies.

Deformation zones

High grade deformation zones or 'shear zones' are not common in the study area, and are generally quite localised. Higher grade deformation zones can be recognised by the intensity of schistosity and lineations, by their straight planar fabrics with uniform orientations, and by fine banding and extreme attenuation or thinning of lithologies (Fig. 15). 'Straight gneisses' are known from the

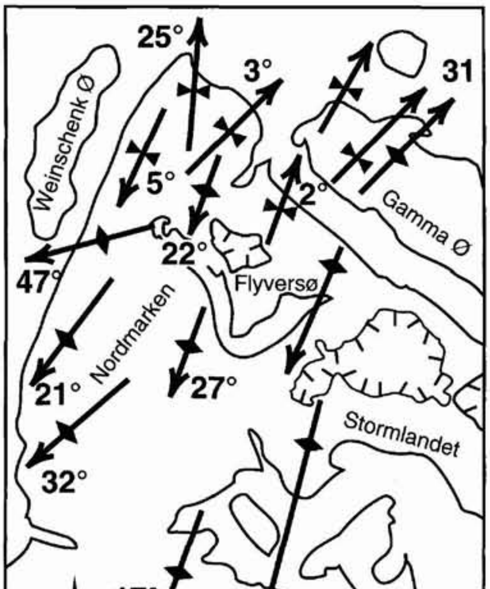
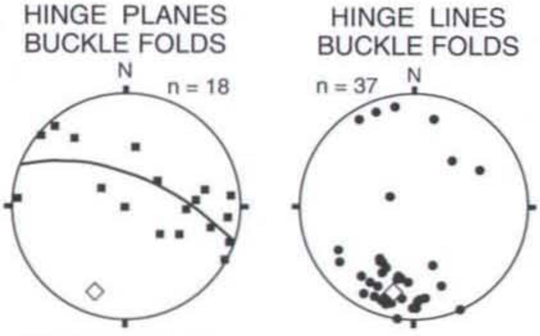


Fig. 12. Map showing locations and geometries of late upright folds. The stereonet illustrates the geometry of fold axes, determined stereographically.



Evalue	Evector	
10.00	102	22°
4.72	327	60°
0.95	200	19°

Evalue	Evector	
10.00	193	22°
1.90	313	52°
1.22	090	29°

Fig. 13. Stereonets showing the geometries of hinge planes and hinge lines of minor buckle folds.

Danmarkshavn area, north-eastern Germania Land and Kap Li.

The largest deformation zones in the Skærfjorden study area are the Storstrømmen shear zone, the Germania Land deformation zone and the Danmarkshavn deformation zone (Holdsworth & Strachan 1991; Hull & Gilotti, 1994). All of these zones are characterised by quasiplastic mylonites, low grade assemblages, steep schistosities and shallow lineations, indicating predominantly strike slip displacement late in the structural and metamorphic history (late- to post-Caledonian). The Storstrømmen shear zone shows sinistral movement, whereas the Germania Land and Danmarkshavn deformation zones are predominantly dextral. The petrography, structure and tectonic significance of these shear zones are discussed by Hull & Gilotti (1994).

Low grade, black mylonite zones, typical of the Storstrømmen and Germania Land deformation zones, were found in Hertugen af Orléans Land and northernmost Nordmarken. At the latter locality, a metre thick black orthomylonite contains augen or porphyroclasts of K-feldspar derived from originally cross-cutting pegmatite veins. Kinematic indicators in the west-dipping mylonite support east-directed reverse movement, consistent with asymmetric, outcrop scale folds in the footwall. Given the low grade of mylonitisation and association with upright folds, this black mylonite is probably Caledonian or younger. Low grade mylonites are rarely found in the study area, outside of the strike slip zones.

Discussion and conclusions

There is some isotopic evidence for Archaean crustal material in the Skærfjorden study area around Danmarkshavn (Steiger *et al.*, 1976; Nutman & Kalsbeek, 1994), but the extent of Archaean crust in this region is uncertain. Kalsbeek *et al.* (1993) concluded that an Archaean crustal component is present in many of the Proterozoic gneisses between latitudes 75°–78°N, based upon Sm-Nd model ages. Tucker *et al.* (1993) report concordant Archaean zircons from Zebra Series arenites in Dronning Louise Land; however the provenance of these zircons is unknown.

Field relationships, petrography and geochemistry of gneisses from North-East Greenland implicate large,

Fig. 14. Mullion-like folds of gneissosity producing a strong rodding fabric in northern Nordmarken. Map board towards left-centre for scale.

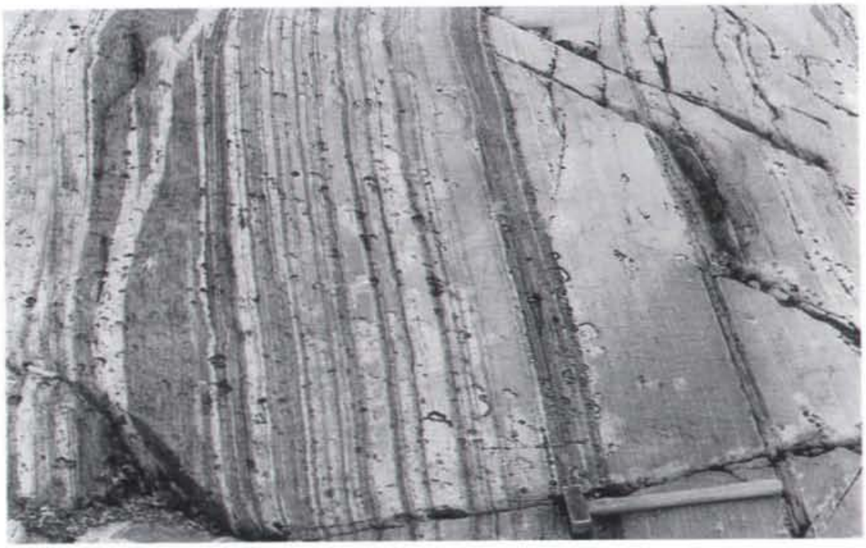


Fig. 15. Straight gneisses from the Danmarkshavn area. Hammer for scale.

polyphase calc-alkaline batholiths as the protoliths for the major part of the Early Proterozoic gneiss complexes (Friderichsen *et al.*, 1991). Early Proterozoic (~ 2000–1900 Ma) magmatism in North-East Greenland involved a region of at least 30 000 km^2. We conclude that these calc-alkaline complexes of batholithic dimensions represent subduction zone magmatism. If the Early Proterozoic gneisses of North-East Greenland are contaminated with Archaean crustal material, as suggested by Kalsbeek *et al.* (1993), then the Early Proterozoic intrusive complexes were formed along an active continental margin. Comparable Early Proterozoic plutonic activity is widespread in Greenland, Canada, and Scandinavia (e.g. Kalsbeek, 1981, 1986; Hoffman, 1988; Lindh & Persson, 1990).

The Early Proterozoic intrusive suites and older xenoliths were subsequently deformed and metamorphosed into polyphase gneiss complexes before intrusion by ~ 1750 Ma metagranitoids. This orogenic event is broadly coeval with the Nagssugtoqidian and Ketilidian orogenies of Greenland (~ 1850 Ma), the Svecofennian of Scandinavia (~ 1800–1850 Ma) and the Hudsonian of Canada (~ 1750 Ma).

The gneiss complexes were subsequently intruded (around 1750 Ma) by sheets of granite and monzonite. The pink metagranitoids of North-East Greenland are similar to other suites of crustal-derived melts, such as the 1.79–1.74 Ga epizonal granites of Canada (summarised in Hoffman, 1988), the 1.76–1.74 Ga, post-metamorphic rapakivi granites of southern Greenland (e.g. Brown *et al.*, 1992), and the 1.80–1.75 Ga Revsund granites of northern Sweden (reviewed in Weihed *et al.*, 1992). All of these late- to post-orogenic plutons followed Early Proterozoic (2.0–1.8 Ga), massive crustal additions (subduction related) and subsequent orogenic events.

There are two and perhaps three periods of Middle to Late Proterozoic basin development in North-East Greenland, based on assumptions about field relationships and the ages of cross-cutting dolerite dykes. Friderichsen *et al.* (1990) suggested that metadolerite dykes cutting the Trekant Series in Dronning Louise Land correlate with the Midsommersø dolerites and Zig Zag Dal Basalt Formation of North Greenland (Jepsen *et al.*, 1980). The dolerite sills of eastern North Greenland have been dated at ~ 1250 Ma using Rb-Sr, whole rock measurements (Kalsbeek & Jepsen 1983). If the Dronning Louise Land dykes are indeed Helikian, then the Trekant Series is at least as old as Middle Proterozoic. Unfortunately, none of the mafic dykes in North-East Greenland have been dated. The cross-cutting metadolerite dykes of Dronning Louise Land and the Skærfjorden region could correlate with one or more of the five major periods of Middle to Late Proterozoic mafic magmatism seen elsewhere in Canada, Greenland and Scandinavia. If the Skærfjorden region and Dronning Louise Land dykes are related to the formation of the Iapetus ocean around 700–600 Ma, then the Trekant Series may be much younger (Late Proterozoic).

Central to most models for the tectonic evolution of the Arctic Caledonides is the development of an Andean-type destructive margin along the eastern flank of Laurentia, specifically East Greenland, prior to Caledonian collision (e.g Hodges *et al.*, 1982; Hossack & Cooper, 1986). Pre-Caledonian subduction along East Greenland in the Cambro-Ordovician should have produced pre-orogenic batholiths of calc-alkaline, I-type, Group I affinity (Harris *et al.*, 1986). However, there is no evidence for subduction-related magmatism in North-East Greenland during the Early Palaeozoic. In addition, there is little evidence of subduction zone magmatism of batholithic dimensions in the Early Palaeozoic anywhere in East Greenland. In the Scoresby Sund region (Milne Land, Stauning Alper, and Liverpool Land), individual plutons are of limited extent, and exhibit variable compositions (Steiger *et al.*, 1979; Hansen & Tembusch, 1979; Rex & Gledhill, 1981).

The timing of Caledonian events in North-East Greenland, such as deformation phases and metamorphism, are not well constrained; metamorphic assemblages or parageneses have not yet been dated. Nearly concordant sphenes from the Archaean gneiss at Danmarkshavn yielded a U-Pb age of ~370–360 Ma (Steiger *et al.*, 1976). In the U-Pb work of Kalsbeek *et al.* (1993) and Tucker *et al.* (1993), some concordant spot analyses of zircons and lower intercepts indicate metamorphism around 420–400 Ma. ^{40}Ar-^{39}Ar incremental heating ages give information on cooling and provide upper bounds for the ages of metamorphism. Few hornblendes from North-East Greenland yield usable plateaus; three different samples showed plateaus corresponding to ~415–390 Ma (Tucker *et al.*, 1993). Corresponding muscovite ages ranged from ~400–370 Ma. These isotopic data support regional deformation and metamorphism in the Late Silurian to Early Devonian, with uplift and cooling through the Middle Devonian.

In order to evaluate Caledonian tectonics and structural settings in North-East Greenland, one must first isolate known Caledonian structures, which can be accomplished by examining younger supracrustal and intrusive rocks, such as the Proterozoic to Early Palaeozoic Trekant and Zebra Series in Dronning Louise Land, or the ~ 1.75 Ga metagranitoids in the Skærfjorden and adjacent regions (cf. Chadwick & Friend, 1991; Strachan *et al.*, 1992). However, these rocks are relatively few and far between, necessitating significant inference and extrapolation.

The portion of the Caledonian mobile belt described in this study lies to the east of the Storstrømmen shear zone (Holdsworth & Strachan, 1991), an important structural element that formed late in the tectonic history of the belt (Hull & Gilotti, 1994). In Dronning Louise Land to the west of the Storstrømmen shear zone, Caledonian lineations rotate from an orogen-transverse attitude in the western foreland, to a more orogen-parallel orientation as the Storstrømmen shear zone is approached (Peacock, 1958; Holdsworth & Strachan, 1991). To the east of the Storstrømmen shear zone in the hinterland, Caledonian lineations are approximately parallel to the orogenic grain, trending NNE and SSW (Fig. 10). Rotation of stretching lineations from an orogen-transverse orientation in the foreland, to an orogen-parallel geometry in the hinterland, has been observed in the south-central Appalachians (Bryant & Reed, 1970) and the central Scandinavian Caledonides (Gilotti & Hull, 1993).

Orogen parallel extension and orogen normal shortening were probably synchronous during Caledonian deformation in North-East Greenland, corresponding to a large component of approximately pure shear. This geometry of pure shear would produce upright folds with hinge lines parallel to the longitudinal stretching direction, corresponding to the later Caledonian structures in the Skærfjorden region (Figs 12, 13). The pure shear was superimposed on early shallow to flat dipping, nappe related structures and fabrics of Caledonian age (e.g. Chadwick & Friend, 1991). Similar geometries and sequences of events have been described by Gilotti & Hull (1993) from the hinterland of the Scandinavian Caledonides in central Norway.

Holdsworth & Strachan (1991) and Strachan *et al.* (1992) proposed that a subhorizontal décollement underlies the Skærfjorden region and adjacent areas in North-East Greenland. In central Norway, a sub-horizontal detachment exposed in a tectonic window (Möller, 1988) is also thought to underlie much of the hinterland (Gilotti & Hull, 1993). In the tectonic model of Gilotti & Hull (1993), the décollement played an important role in developing the longitudinal, orogen-parallel structures that dominate much of the Caledonian hinterland.

A large number of important questions about the geologic evolution of North-East Greenland remain unresolved. What is the extent of Archaean crust in this region? What are the geometries of subduction and accretion during the Early Proterozoic? How many Proterozoic orogenic events did this region enjoy? What are the ages of mafic magmatism? What were the physical conditions of metamorphism, particularly during the Caledonian? Is the North-East Greenland eclogite province comparable to that of central Norway? And what was the tectonic architecture, from foreland to hinterland, throughout the Caledonian orogeny?

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