The Germania Land deformation zone and related structures, North-East Greenland

Joseph M. Hull and Jane A. Gilotti

The Germania Land deformation zone in North-East Greenland consists of two subparallel, NW-striking strands of mylonites and cataclasites. The quasiplastic mylonites formed under low grade (biotite zone) conditions following high grade Caledonian metamorphism. Displacements on the Germania Land deformation zone and parallel zones at Danmarkshavn were predominantly dextral strike slip. Along with the similar, but sinistral, Storstrømmen shear zone, these zones record a late Caledonian phase of orogen-parallel movement. The Germania Land deformation zone is also the locus of Carboniferous normal faulting and basin development.

J. M. H., Division of Science & Mathematics, Seattle Central Community College, Seattle WA 98122, U.S.A.
J. A. G., Geological Survey, New York State Museum, Albany, NY 12230, U.S.A.

The gneiss complexes in the Skærfjorden region of North-East Greenland are cut by two deformation zones (zones of concentrated deformation), the NNW-striking Germania Land deformation zone and the NNE-striking Storstrømmen shear zone (Fig. 1). The Storstrømmen shear zone (SSZ) has been discussed in some detail, and is an important element of a transpression model for Caledonian deformation in this region (Holdsworth & Strachan, 1991; Strachan *et al.*, 1991, 1992). The Germania Land deformation zone (GLDZ) was discovered during the 1990 field season, and was briefly described by Friderichsen *et al.* (1991). This paper summarises the structural geometry and kinematics of the GLDZ, as well as the microstructures and metamorphic assemblages in the mylonites. We also include our observations of the SSZ tectonites obtained from a 3 km long traverse across Hertugen af Orléans Land for comparison. Brittle faults and fractures which cut the GLDZ and the SSZ are described as well. Some tectonic models are reconsidered which incorporate the data on timing, geometry and kinematics for these zones.

Location and topology

Germania Land deformation zone

The Germania Land deformation zone (GLDZ) forms two, subparallel topographic lineaments that can be traced from Hagen Ø in southern Jökelbugten through Gamma Ø and Stormlandet to north-eastern Germania Land (Figs 2, 3). The GLDZ is therefore sporadically exposed over 100 km in trace length. The two lineaments, where developed, are separated by about 1–2 km. Both strands are associated with protomylonites, mylonites, ultramylonites and related rocks (mylonite family of high strain tectonites). The eastern strand is also cut by true fault rocks (cataclasite family) of the Chatham Elv fault.

High strain tectonites (both mylonites and cataclasites) are highly concentrated along the two branches of the GLDZ, but are scattered more diffusely between the two branches; the area between the two branches is not predominantly mylonite or cataclasite. High strain tectonites are also found adjacent to the GLDZ to the west and east. The width or thickness of tectonite across either branch is difficult to define, due to variability along strike and lack of traverse data. There are perhaps tens to a few hundred metres of high strain tectonite along each branch of the GLDZ.

Deformation zones in the Danmarkshavn area

The Danmarkshavn area is located in southern Germania Land, south-west of the main trace of the GLDZ (Fig. 1). The rocks in the Danmarkshavn area form a NNW-striking belt of straight gneisses. Strongly deformed gneisses containing mylonites and ultramylonites (Fig. 4) alternate with strike-parallel bands of less deformation on a scale of tens to hundreds of metres. Cross-cutting relationships between metadolerite dykes and gneisses are preserved in the low strain regions, but all structures are transposed into the dominant foliation in the high-strain zones. This belt of straight gneisses with mylonites extends west at least as far as the west coast of Store Koldewey.

Mylonite and ultramylonite zones are abundant, but are rarely more than 1 m thick. These zones are often found

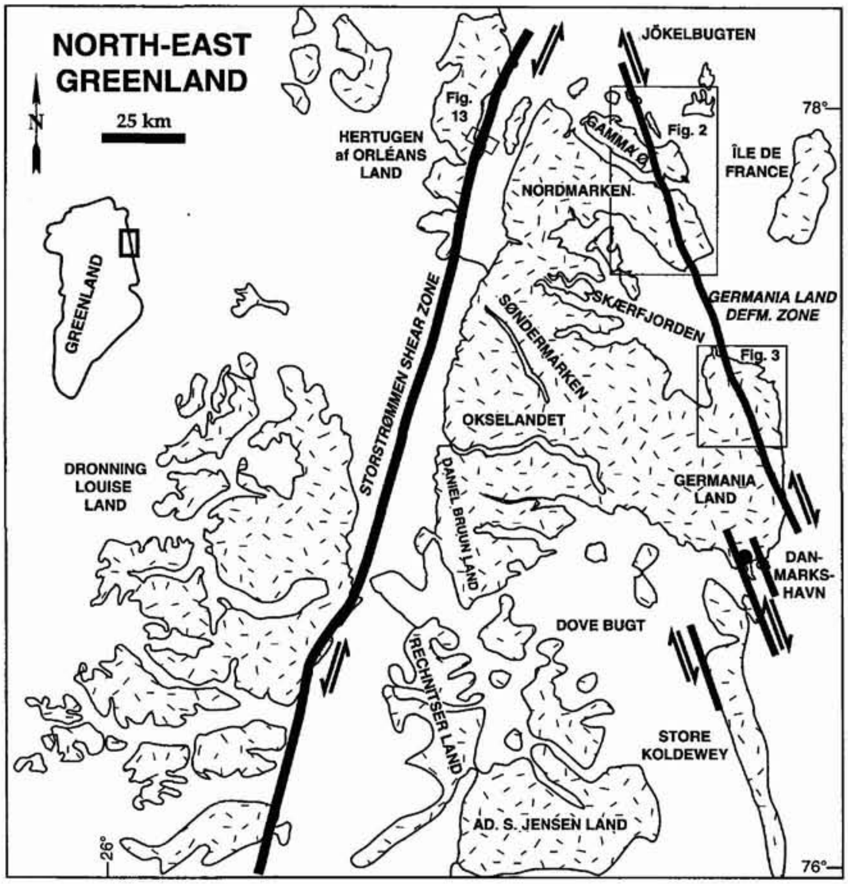

Fig. 1. Sketch map showing North-East Greenland from approximately 76°–78°N. The Storstrømmen shear zone and the Germania Land deformation zone are shown, as well as locations of Figures 2, 3 and 13.

along contacts between two different lithologies (e.g. between concordant metadolerites and quartzofeldspathic gneiss), and many seem to be localized along pegmatites and eclogitic pods.

Storstrømmen shear zone

The Storstrømmen shear zone (SSZ) has been described by Holdsworth & Strachan (1991) and Strachan *et al.* (1992) as "one of the largest Phanerozoic strike-slip shear zones in the Northern Hemisphere". The SSZ is exposed in the south-central portion of easternmost Hertugen af Orléans Land, and in the central and southern parts of easternmost Dronning Louise Land (Fig. 1). Similar tectonites have been reported along strike in Lambert Land (J. D. Friderichsen, personal communication); if these tectonites all belong to the same deformation zone, then the trace length is approximately 500 km. Holdsworth & Strachan (1991) give the width (thickness) of the SSZ as 10 km; however, the actual amount of high strain tectonite measured on our traverse is much less (see below).

Mylonite mineralogy

Protolith gneisses

The protoliths of the mylonites in the Germania Land deformation zone are as varied as the lithologies in the surrounding heterogeneous gneiss complex (Hull *et al.*, 1994). However, the dominant protolith is a quartzofeldspathic orthogneiss ranging from granite to granodiorite in composition. Granulite facies orthogneisses containing garnet + clinopyroxene + plagioclase + quartz ± hornblende ± biotite (Fig. 5a) are widespread, while the less abundant paragneisses consist of garnet + kyanite and/or sillimanite bearing assemblages (Fig. 5b). The protolith gneisses also contain layers and pods of eclogite that indicate medium-temperature, high-pressure peak metamorphic conditions (Gilotti, 1993; 1994). Amphibolite facies gneisses are the most common protolith material; mafic rocks are garnet amphibolites, while quartzofeldspathic gneisses contain feldspars + quartz + hornblende + biotite ± garnet.

The high-grade rocks are moderately to intensely deformed. Gneissosity is typically defined by compositional

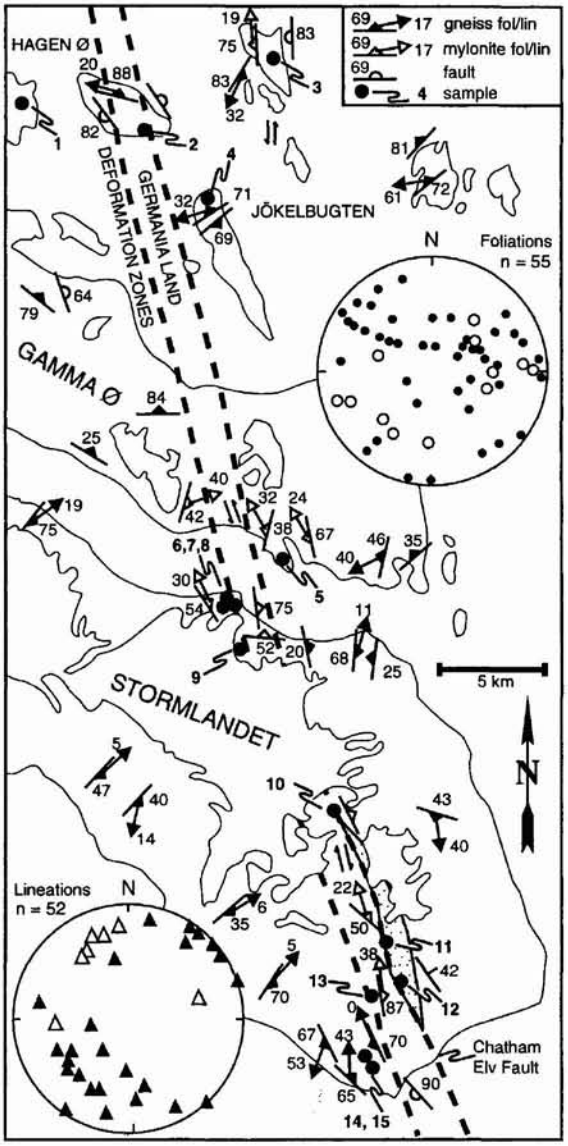

Fig. 2. Structural map of Stormlandet showing the Germania Land deformation zone, the Chatham Elv fault, and Carboniferous sedimentary rocks (stippled). Stereonets are lower hemisphere, equal area projections. Solid symbols are gneisses, open symbols are mylonites.

layering of the high-grade minerals, even though their mosaic texture is granoblastic (Fig. 5a). The high-grade foliation may also be defined by the shape fabric of individual grains, or by the preferred orientation of elongate minerals, such as micas and sillimanite (Fig. 5b). When the gneisses are intensely deformed at high-grades of metamorphism, they tend to have a 'pin-striped' appearance. We have observed rare examples of high-grade mylonites in the gneisses of the Skærfjorden region, mostly from thin deformation zones (< 10 cm) of limited extent. Figure 5a illustrates the upper boundary of a 1.5 cm thick deformation zone where millimeter size grains of clinopyroxene, plagioclase, quartz, garnet and hornblende are recrystallised to a much finer-grained (~ 100 μm) and finely laminated mylonitic fabric.

Mylonite series

Mylonites and related rocks from the GLDZ, the Danmarkshavn area, and the SSZ in Hertugen af Orléans Land are indistinguishable in terms of mineralogy and microstructures, and are retrograde in comparison to the surrounding protolith gneisses. The following descriptions are based on petrographic observations from 42 samples, i.e. 14 protomylonites, 21 mylonites and 7 ultramylonites. Mineral chemistry data were obtained from three mylonite samples. Most of the samples are from the GLDZ; locations are shown on Figures 2 and 3. The description utilises the fault rock terminology of Sibson (1977) and Hull *et al.* (1986).

Table 1 summarises the mineralogy and some textural

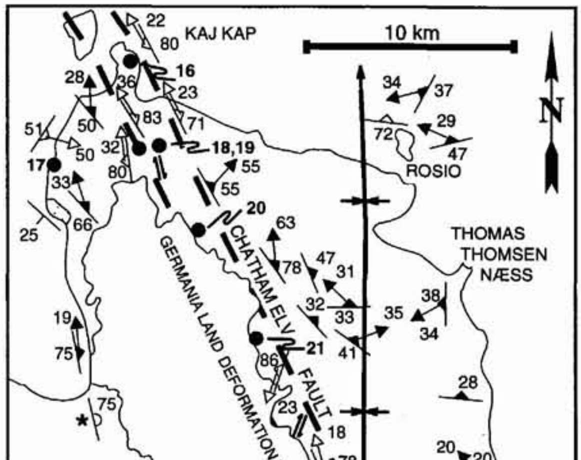

Fig. 3. Structural map of northern Germania Land showing the Germania Land deformation zone and the Chatham Elv fault. The * indicates the fault with the oil seep described by Christiansen *et al.* (1991). Symbols same as Fig. 2.

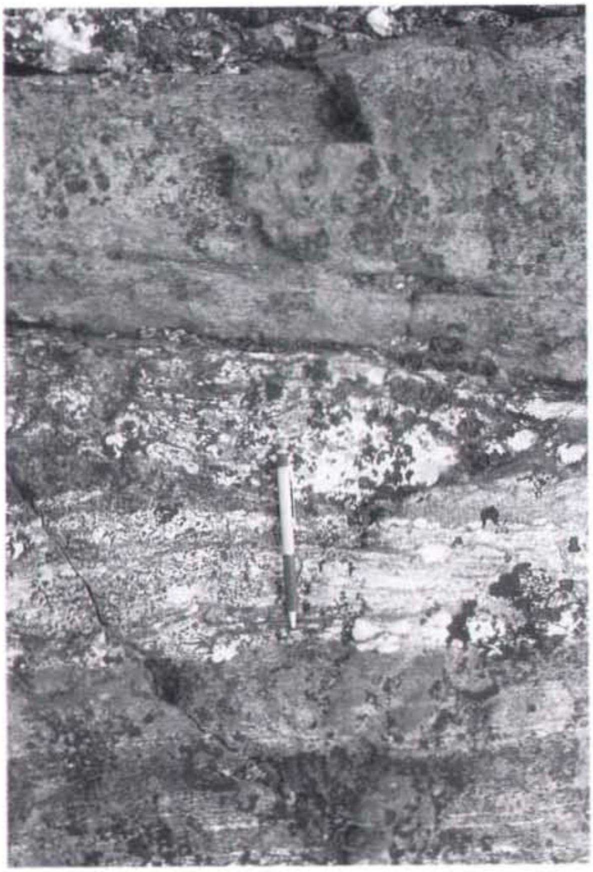

Fig. 4. Pen rests on an augen mylonite derived from a pegmatite vein. Note stringy, black ultramylonite zones typical of the GLDZ. Shear sense is ambiguous in this outcrop. Danmarkshavn area.

features for representative mylonites from the Skærfjorden region. Phases are designated as either augen or matrix to help give an indication of metamorphic grade. The augen in these mylonites are porphyroclasts of the relict high-grade assemblage, not 'porphyroblasts' as originally suggested (Holdsworth & Strachan 1991; Friderichsen *et al.*, 1991). Protomylonites generally contain the same phases as the mylonites, but with better preservation of the parent mineralogy. Most of the protolith grains are destroyed in the ultramylonites. Biotite, quartz and feldspar are the most abundant minerals in the ultramylonites, although the new matrix is often so fine-grained that the mineralogy can be difficult to determine.

Garnet and amphibole are found as relict augen or porphyroclasts in nearly all of the protomylonites and mylonites. Green, calcic amphibole augen are replaced by biotite (Fig. 6a), and only rarely is recrystallised amphibole observed (Fig. 6b). Most of the groundmass amphibole is probably mechanically derived, rather than newly formed neoblasts.

Brown and/or green biotite is the dominant phyllosilicate in these mylonites. The amount of biotite in the groundmass determines the colour of the mylonite in the field. For example, mylonites with abundant biotite tend to have a black, pasty character like those shown in Figure 4. The dark layers of banded mylonites and ultramylonites (e.g. Fig. 6c, d) are always dominated by very fine-grained biotite. Compositions range from Fe/(Fe + Mg) = 0.41–0.53, Ti = 0.09–0.23 per three octahedral sites, and Al^{vi}/11 anhydrous oxygen atoms = 0.14–0.27 in three analysed samples.

Quartz and feldspar are ubiquitous and typically comprise 40–70% of the mylonite modes. Both minerals are important constituents of the fine-grained matrix. Plagioclase is always present, but only some of the mylonites contain K-feldspar. The plagioclase is andesine (An_{34}–An_{48}) in sample 363066, with no marked difference between the average groundmass composition (An_{39}) and the average augen (An_{42}). Plagioclase is oligoclase in

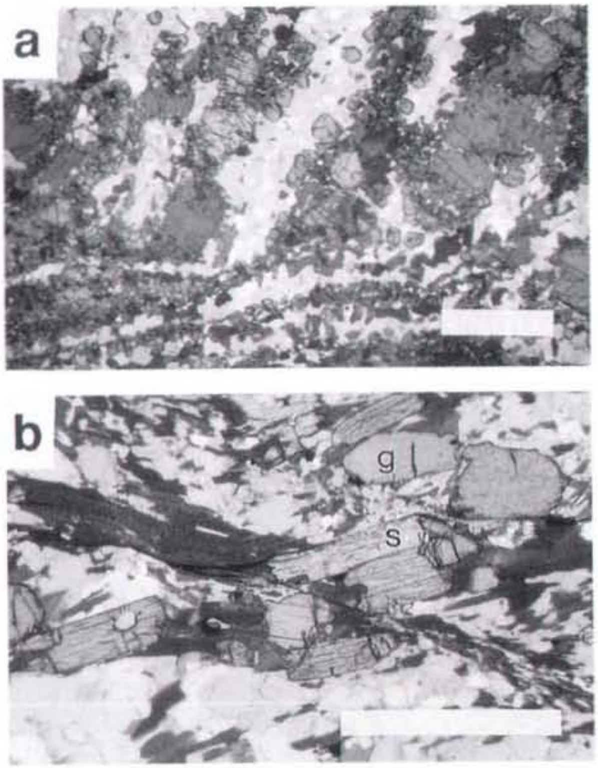

Fig. 5. Photomicrographs of deformed high-grade assemblages in the host gneisses. a: Compositional layers of garnet + clinopyroxene + hornblende + plagioclase + quartz curl into mylonitic foliation defined by finer, recrystallised grains of the same phases; sample GGU 363045 from Nordmarken. b: Schistosity of a garnet + sillimanite + biotite + feldspar + quartz paragneiss cut by biotite rich shear band; s = sillimanite, g = garnet. Sample GGU 407507 from the Danmarkshavn area. Scale bars = 1.0 mm.

Table 1. Mineralogy of selected mylonites

Area	Stormlandet		Germania Land				Danmarkshavn					Hertugen af Orléans Land			
GGU no	363034	361981	363065*	363066*	363069	364516	407511	407518	407547	407548	407569	363052	363047	363048	363051*
Loc. no	8		21		16	20									
garnet				a				a			a	a			
amphibole	a		a,m		a,m	a	a		a>m	a>m			a	a	
biotite	bm		gm	bm	bm	gm		gm	bm	bm	bm	ba,bm	gm	bm,gm	gm
muscovite		a										a			
chlorite		x,f					x,f	x,f			m	f			
feldspar	pa	a,m	pa,p>km	pa,pm	a,m	pa,m	a,m	a,m	a,m	a,m	a,m	a,m	a,m	a,m	pa,m
quartz	r,m	a,r,m	m	r,m	r,m	a,m>r	a,m	r,m	r,m	m>r	r,m	r,m	m>r	r,m	m>>r
epidote	a		a,m		a	a,m		t	a	a		a	a	a	a
opaques	x	r		x	x	x	x	x	x	x	x		t	t	
sphene	x		m		x		a								
zircon			t	t		a									

Key: a = augen, m = matrix, × = present, t = trace, f = fractures, r = ribbons, b = brown, g = green, p = plagioclase, k = alkali feldspar, * = mineral chemistry data, loc. number on Figures 2 and 3.

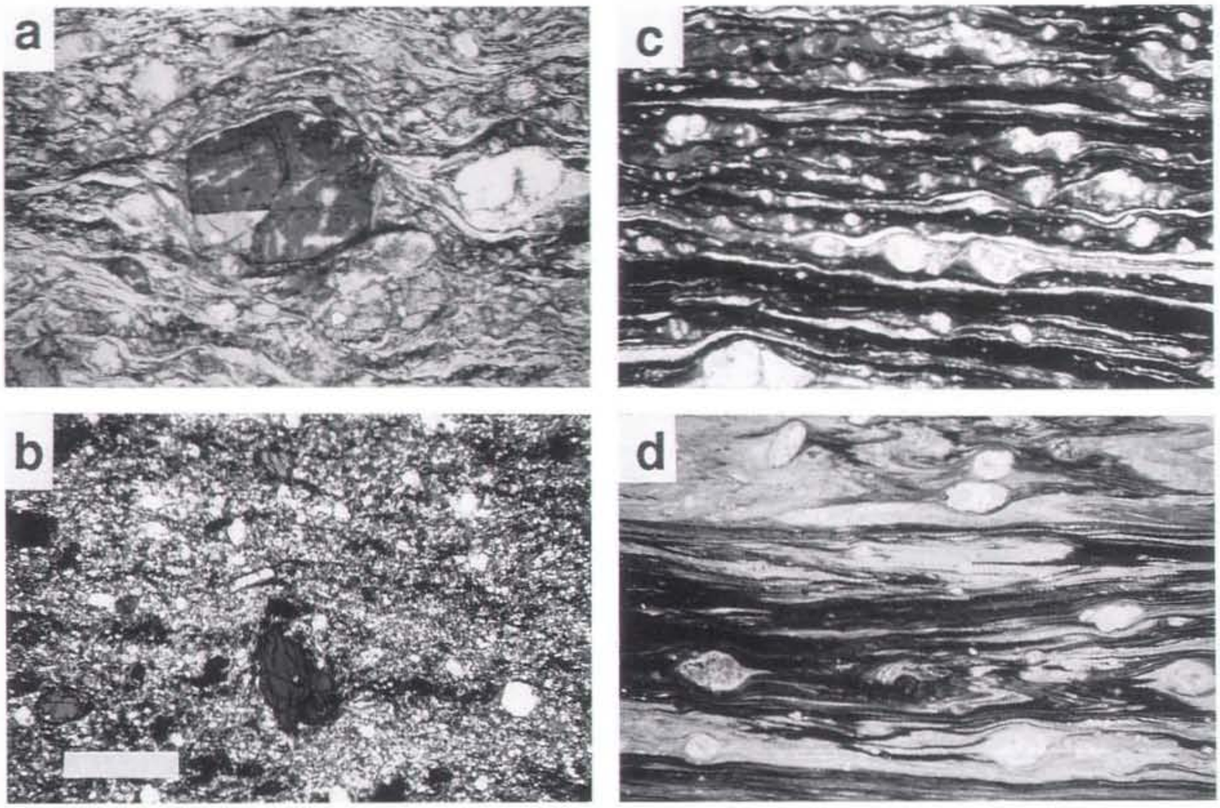

Fig. 6. Photomicrographs of mylonites and ultramylonites. a: Augen mylonite GGU 363048 from the Storstrømmen shear zone; large, sigma-type porphyroclasts are amphibole (dark) and feldspar (light). b: Augen mylonite GGU 363065 (locality 21) from Germania Land; the large, dark delta-porphyroclast is hornblende with recrystallised amphibole forming the dark tails. c: Augen mylonite GGU 363034 (locality 8) from Stormlandet; the dark groundmass is very fine-grained biotite >> quartz + feldspar. d: Ultramylonite GGU 363070 (locality 18) from Germania Land containing mostly feldspar augen in a folded, ultra fine-grained matrix; light quartzofeldspathic domains and dark biotite-rich domains. All sections are perpendicular to the foliation and parallel to the lineation with north on the right. Shear bands, delta and/or sigma-type tails around porphyroclasts indicate a sinistral sense of shear in one example (a) and dextral in the others. Numbers in parentheses are sample locations found in Figures 2 and 3. Scale bar = 1.0 mm is the same for all photographs.

mylonite samples 363065 and 363051 with a range of compositions between An_{20}–An_{28}.

Epidote/clinozoisite is present in some of the more mafic mylonite layers as both large augen and matrix grains. The poikiloblastic epidotes are commonly zoned with complex core-rim structures; some growth may have occurred either during or just after mylonitisation.

Muscovite is nearly absent in these mylonites with the exception of phyllonite 363052, which contains large, folded and kinked muscovite fish. This sample was collected west of the SSZ from a moderately inclined, metre thick mylonite zone that shows top-to-the-west thrusting. Very fine-grained muscovite is a sericitic alteration product of feldspar augen in some samples.

Small amounts of chlorite are also found in the matrix or together with biotite in shear bands. In some cases biotite and chlorite are intergrown. Opaque minerals are present in most of the mylonites. Small amounts of sphene, zircon, and apatite have also been identified, but it is difficult to know how many of these phases are relicts or neoblasts.

Metamorphism

In order to determine the metamorphic grade of mylonitisation, care must be taken to identify those phases that form the new mylonitic fabrics and groundmass. Because these deformation zones are very heterogeneous, high grade protoliths (e.g. the eclogite in Fig. 10a) are well preserved on all scales, and the mylonite mineralogy may include both relict phases (porphyroclasts) and newly grown phases (neoblasts).

The common matrix assemblage of quartz + K-feldspar + green or brown biotite ± oligoclase-albite ± epidote ± chlorite in the more mafic domains of the mylonites points to mylonitisation under predominantly greenschist facies conditions (see Robinson *et al.*, 1982, for facies terminology). Biotite ± chlorite shear bands in the pelitic protomylonites indicate a decrease in grade from sillimanite zone to biotite zone. The persistance of hornblende + oligoclase in some of the mylonites may indicate that mylonitisation began in the epidote-amphibolite facies (i.e. no matrix garnet).

Alternatively, hornblende + oligoclase may represent a metastable assemblage where the change in mineral chemistry and retrograde hydration reactions cannot keep pace with mylonite formation, perhaps for lack of fluids. In a study of a single metadolerite dyke progressively deformed and metamorphosed to a simple shear strain (γ) ~ 100, Gilotti (1989) demonstrated that retrograde reactions could be sluggish even at shear strains in excess of $\gamma = 30$, where hornblende + oligoclase are part of the continuous reactions to a stable greenschist facies mylonite assemblage.

More mineral chemistry data, especially from the ultramylonites, is needed to precisely determine the metamorphic grade. The petrographic and structural evidence suggests that an epidote-amphibolite to greenschist facies mylonitic foliation is superimposed on an older, higher grade gneissosity and schistosity. One possible path for this retrograde event is shown in Figure 7. Pressure-temperature estimates for eclogites and related high-pressure rocks are given in Gilotti (1993, 1994). Parageneses in semipelitic gneisses and amphibolites suggest regional metamorphism near the kyanite-sillimanite join subsequent to regional high-grade events. Retrograde mylonitisation took place at moderate to low metamorphic grades, whereas cataclasites (breccia and gouge) formed under very low grade, low pressure conditions. Direct dates (e.g. Gromet, 1991) of the high grade to low grade parageneses are required to distinguish between a continuum or separate metamorphic events.

Mylonite microstructures

The mylonites and related tectonites from the Germania Land deformation zone, the Danmarkshavn area, and the Storstrømmen shear zone in Hertugen af Orléans Land are quasiplastic (Sibson, 1977), exhibiting evidence for simultaneous intracrystalline plasticity and brittle fracture. Mineral type may control the exact micromechanical behaviour. In a quasiplastic tectonite, some minerals may be wholly plastic (such as quartz), some minerals wholly brittle (garnet or zircon) and some minerals may deform by both micromechanisms (e.g feldspars). Grain size also controls the mechanical behaviour; large grains often show more evidence of cracking and fracture than small grains of the same mineral.

Our descriptions are based on petrographic observations using standard light microscopy. We note that some optical features of deformation may be generated by different crystal micromechanisms (Hirth & Tullis, 1992), and that transmission electron microscopy is necessary to confirm our preliminary conclusions.

Garnet and amphibole form relict augen or porphyroclasts in the protomylonites and mylonites we have examined. Both phases are fractured, with the cracks ending at the grain boundaries (i.e. intragranular or stable fractures). Figure 8a shows almandine-rich garnet with cracks filled with biotite and opaque minerals. Amphibole pull-aparts with biotite tails and fracture fill are very common in these mylonites (Fig. 8b). Amphibole also deforms plastically, with dynamically recrystallised grains forming tails on augen (Fig. 6b). Extension across dilated cracks and intracrystalline plasticity both contributed to shape changes; amphibole and garnet are usually elongate parallel to the mylonitic foliation.

Quartz shows the most obvious features of intracrystalline plasticity, including undulose extinction, core-mantle structures, and dynamic recrystallisation to a finer grain size. Progressive deformation of quartz produces pronounced shape changes in the grains and commonly leads to the formation of very long, thin ribbons (Fig. 6a, c). A few of the samples contain ribbons with recrystallised grains consistently oriented with their long dimension oblique to ribbon boundaries, a useful kinematic indicator.

Feldspar deformation is also plastic. Mechanical twinning produces small strains in some of the plagioclase, but recrystallisation-accomodated dislocation creep (Tullis & Yund, 1985) seems to be the main agent of grain size reduction in the feldspars. Feldspar augen are often composed of mosaics of recrystallised grains, and rarely exceed shape factors of 3:1. This type of dynamic recrystallisation may be active at temperatures between 450–650°C (Simpson, 1985; Yund & Tullis, 1991), corresponding to deformation near the greenschist to amphibolite facies transition.

Biotite forms tails around amphibole and garnet porphyroclasts and fills stable fractures, and is the main mineral in most shear bands. Biotite shows no obvious signs of crystal plasticity. Biotite grains are blocky by nature and aligned parallel to the mylonitic foliation or to shear bands (e.g. Fig. 6a). Grain boundary sliding along the biotites (especially in the shear bands) is probably an important strain producing mechanism in these mylonites.

The ultimate product of mylonitisation is a very fine-grained matrix of interspersed phases (Fig. 6c, d), here

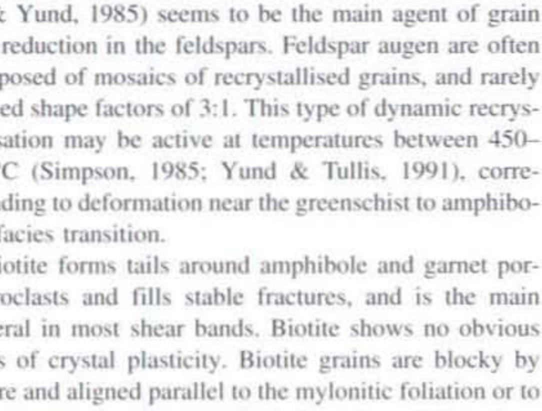

Fig. 7. *P-T* diagram illustrating one possible retrograde metamorphic path (the four stippled areas) for North-East Greenland rocks. Caledonian *P-T* path for central Norway, for comparison, modified from Möller (1988).

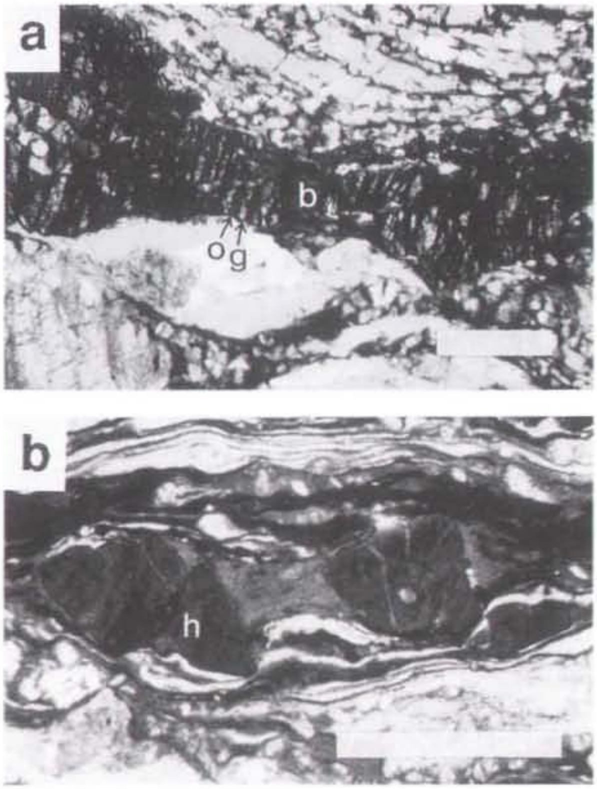

Fig. 8. Photomicrographs showing retrogression of high-grade minerals during mylonitisation. a: Garnet (g) pull-aparts are filled with opaque minerals (o) and biotite (b) in mylonite GGU 363066 from Germania Land. b: Hornblende (h) is fractured and extended in augen mylonite GGU 363034 (locality 8) from Stormlandet; fractures are filled with very fine-grained biotite. Scale bar = 0.5 mm.

dominated by quartz + feldspar + biotite. Although much of the quartzofeldspathic matrix is the result of both fracture and dynamic recrystallisation, some neomineralisation is required by the retrograde reactions to produce the lower grade minerals, particularly biotite. Both diffusional creep and grain boundary sliding are probably important deformation mechanisms in the matrix. The matrix is likely to accomodate a large part of the strain in the mylonites and ultramylonites once a critical amount of fine-grained material is produced (Mitra, 1978; Gilotti, 1992).

The mylonites and related rocks found in these large deformation zones in North-East Greenland are represented on a tectonite diagram in Figure 9. The tectonite diagram uses metamorphic grade, grain size and composition as variables (see Hull *et al.*, 1986). Composition is fixed in this version at quartzofeldspathic (granitic) to represent a common protolith. The tectonites described above form a continuous series in the quasiplastic mylonite field, from relatively coarse-grained protomylonites

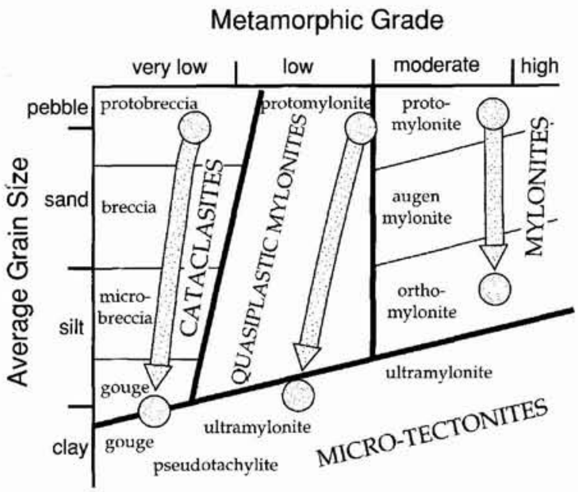

Fig. 9. Tectonite diagram, modified from Hull *et al.* (1986), showing the types of high-strain tectonites as a function of grain size and metamorphic grade, for a granitic bulk composition. Tectonite series for North-East Greenland includes moderate- to high-grade mylonites, quasiplastic mylonites, and cataclasites.

to very fine-grained ultramylonites. We interpret the decrease in grain size as reflecting increasing magnitudes of finite strain. The small decrease in metamorphic grade with increasing strain magnitude is speculative, but consistent with the mineralogic observations; it may also represent increasing fluid access and loss of metastable assemblages, as discussed previously.

Chatham Elv fault

Carboniferous sedimentary strata are juxtaposed against basement gneisses along the Chatham Elv fault in eastern Stormlandet (Fig. 2; Friderichsen *et al.*, 1991; Piasecki *et al.*, 1994). The sedimentary rocks extend for approximately 10 km along the eastern bank of Chatham Elv north of Kap Amélie. The section is composed of a 60 m thick basal conglomerate overlain by 15 m of interbedded conglomerates, sandstones and siltstones; the basal unconformity is not exposed. The section is tilted, dipping away from the fault at a modest angle north-eastwards.

The sandstones and siltstones are fossiliferous; plant fossils include small tree trunks and *Stigmaria* roots. Sporomorphs from a dark siltstone are somewhat sheared but indicate an Upper Westphalian age (Piasecki *et al.*, 1994), consistent with the *Stigmaria*. It is likely that faulting and sedimentation were concurrent, given the spatial relationships, geometries, and sedimentary facies. In addition, fragments of cataclasite and breccia, identical to tectonites within the fault zone, are found within the conglomerates adjacent to the fault.

The fault zone itself is 100 m thick. The length of the fault is not known. Cataclasis is common along the eastern lineament extending north into Jökelbugten and south into north-east Germania Land. While there is undoubtedly a large component of dip slip, normal displacement on the Chatham Elv fault, to form the sedimentary basin, the orientation and magnitude of the net slip vector is not known.

True fault rocks or cataclasites (Sibson, 1977) are well developed along the Chatham Elv fault, and are also scattered along the GLDZ, in the Danmarkshavn region, and along the SSZ in Hertugen af Orléans Land. In addition, steep faults which are subparallel to the Chatham Elv fault bound the sedimentary basins on Store Koldewey. Relict crude oil has been found in mineralised breccias associated with a steep NNW-striking fault zone in western Germania Land (Christiansen *et al.*, 1991). Minor faulting and cataclasis also widespread throughout North-East Greenland. There were probably several episodes of brittle faulting in this region following the Caledonian orogeny, including Devonian, Carboniferous, and Mesozoic (Friderichsen *et al.*, 1991). The steep faults in Stormlandet and Germania Land belong to a family of fault-bounded graben that are known from the East Greenland shelf (Larsen, 1990).

Cataclasite series

The cataclasites, including those from the Chatham Elv fault, range from very coarse, heterogeneous breccias to very fine grained, pasty gouge (Fig. 9). In fault outcrops, the cataclasites are flinty and often green; fracturing is so pervasive that the cataclasites break into centimetre size phacoids whose surfaces are coated with slickensides. Figure 10 illustrates the variety of brittle microstructures in the region. Fractures cut all lithologies from eclogites (Fig. 10a) to ultramylonites (Fig. 10b). As fracturing becomes more pronounced, cracks coalesce to form the breccia series (Fig. 10c, d).

We feel that it is important to emphasise the differences between the fracture component of the quasiplastic deformation, and the subsequent cataclasis. The two are not necessarily related mechanically or temporally, even though they are associated spatially along Chatham Elv. In this particular locality, the two events are probably separated by a considerable interval of time, about 70 Ma (see discussion below), and reflect entirely different tectonic settings (strike slip versus normal faulting).

Cracks formed during quasiplastic deformation are typically intragranular fractures, terminating at grain boundaries. These stable fractures are distinct from unstable, transgranular cracks that cut across matrix and clasts (see Mitra, 1992; Fig. 10a). Stable fractures are often intimately linked to crystal plastic processes,

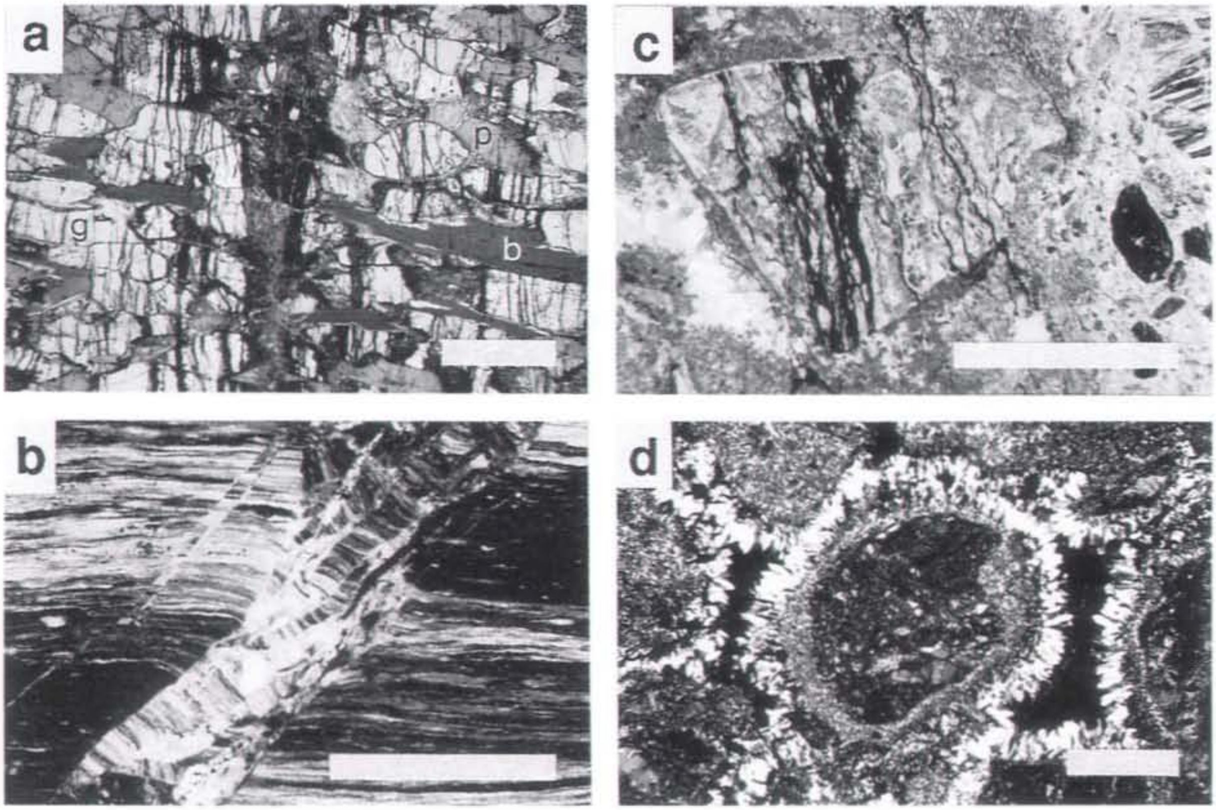

Fig. 10. Photomicrographs of cataclasites. a: Chlorite and calcite-filled fractures cut strongly foliated, garnet (g) – omphacite (p) – biotite (b) eclogite GGU 363050 from the Storstrømmen shear zone. b: Fibre-filled fractures (quartz) cut diagonally through ultramylonite GGU 363036 (locality 8) from Stormlandet. c: Mylonite clast (centre) in fault breccia cut by dark, unstable fracture; sample GGU 361965 (locality 8) from Stormlandet. d: Clasts of gouge in breccia GGU 361965 (locality 8) from Stormlandet overgrown by quartz and zeolites (?), replacing groundmass. Scale bars = 1.0 mm.

whereas unstable fractures are characteristic of brittle, through-going faults.

Dilation or increase in volume is much more pronounced in cataclasis than in quasiplastic deformation of quartzofeldspathic rocks, usually because of the shallow depths and lower pressures. Large voids and mineral-filled fractures (veins) are more common in cataclasis. In quasiplastic mylonites, dilation or cavitation is usually restricted to 'shadows' around rigid augen or mineral pull-aparts. Increased dilation during cataclasis facilitates fluid transport, and results in more extensive and thorough alteration and conversion of minerals. In quasiplastic deformation, relict minerals of earlier, higher grade metamorphic events (such as garnet, pyroxene and amphibole) are often well preserved, even under unfavourable *P-T* conditions.

These differences can be seen in the mylonites and cataclasites of the study region. In addition, the mineral assemblages in these two tectonite series are different: biotite + quartz + feldspar + epidote ± muscovite in the ultramylonites, and chlorite + quartz + calcite + sericite ± zeolites (?) in the cataclasites and fracture fills. The field and petrographic observations support our conclusion that mylonitisation and cataclasis are two separate and distinguishable events in the GLDZ.

Structural analysis

It is important to separate the structures associated with the protolith gneisses, which formed earlier, from the structures associated with the mylonites and cataclasites themselves. We used cross-cutting relationships in the field to separate these structures. It is also important to separate the geometries of the small deformation zones themselves from the geometries of individual fabric and microfabric elements within the mylonite zones, but this was usually not possible due to the reconnaissance nature of our fieldwork. Therefore, we assume that mylonitic schistosity and lineation are essentially parallel to the mylonite zone boundaries and transportation directions, respectively. This assumption is justified because of the apparent high strains within individual mylonite zones.

The trace of the Germania Land deformation zone strikes between 335° and 345°, but the geometries of individual mylonite zones are more variable. In eastern Stormlandet (Fig. 2), most individual mylonite zones strike NW and dip moderately to steeply to the NE and SW. In north-eastern Germania Land, mylonite zones strike NNW to NW with variable dips; mylonitic schistosities are fanned about an axis plunging shallowly to the NNW. In north-eastern Germania Land (Fig. 3), mylonite zones are subparallel to the planar structures in the host gneisses; however, in Stormlandet, mylonites are more oblique to the gneissosity.

Most mylonitic lineations plunge shallowly to the NNW in both Stormlandet and Germania Land. The shallow plunge of mylonitic lineations suggests that much of the displacement on these deformation zones is strike-slip in character, with only a small dip-slip component. The predominance of strike-slip is reminiscent of the Storstrømmen shear zone (Strachan *et al.*, 1992).

The mylonitic lineations of the GLDZ are also parallel to the fan axis for mylonitic schistosities. Gneissosity in the country rocks is also fanned around this same axis. One interpretation is that both gneissosity and mylonitic schistosity have been folded about an axis that plunges approximately 20° towards 340°. The dip directions of gneissosities in north-eastern Germania Land indicate that this fold, if present, would be a synform (Fig. 3).

Folding of the mylonitic schistosity on a map scale implies that the GLDZ is folded as well. Small folds of mylonitic schistosity have been observed in the field, but minor folds of mylonitic schistosity are also very common within *planar* shear zones. No marker horizon was traceable in the field to confirm the presence of a major fold. An alternative explanation for the apparent folding of the country rock is progressive rotation of gneissosity into the GLDZ. In north-eastern Germania Land to the east of the GLDZ, gneissosity dipping shallowly to the north is rotated clockwise and steepened into the GLDZ. This rotation is consistent with dextral displacement on the GLDZ.

The variability or fanning of mylonitic fabrics is probably related to heterogeneous deformation within the GLDZ itself. A common characteristic of heterogeneous deformation is an inosculating or braided pattern of high strain zones surrounding low strain pods (e.g. Bell, 1981). Mylonite zones are 'wrapped around' low strain augen, producing a fanned geometry (e.g. Sørensen, 1983). The augen are elongate parallel to the fan axis, such that in north-eastern Germania Land and Stormlandet, the exposed traces of the deformation zones are relatively straight, as observed in the field.

The geometries of fabric elements are much more uniform in the Danmarkshavn area (Fig. 11). Mylonitic schistosity is sub-parallel to gneissosity; both strike about 340° and dip vertically. Aggregates of quartz and feldspar form stretching lineations in the mylonitised gneisses that plunge shallowly (10°–20°) towards the NNW. The geometries of mylonitic fabric elements in the Danmarkshavn area are very similar to those of the GLDZ. Strike-slip also dominates displacement on deformation zones around Danmarkshavn.

Kinematics

The displacement sense on the Germania Land deformation zone is somewhat problematic, because kinematic indicators either were not well developed or were ambiguous in outcrop. Some ambiguity is expected in these mylonites, as well as in the Storstrømmen shear zone, due to mesoscopic folding of mylonitic schistosity. Delta- and sigma-type porphyroclasts (Passchier & Simpson, 1986) and shear bands comprise the best shear sense criteria in these mylonites (e.g. Fig. 6). Four widely spaced, representative samples from the main GLDZ give a dextral sense of shear, while one sample shows sinistral offset. Two localities east of the GLDZ, on smaller, subsidiary mylonite zones, also give a sinistral shear sense.

Ideally, a statistically significant number of observations and a variety of different shear sense indicators should be used to check for kinematic consistency at a given locality. Then the data for each locality can be compiled to interpret the movement sense of the larger structure. Although our current kinematic data set for the GLDZ is less than ideal, our new microstructural observations show that the shear sense is not 'consistently sinistral' as previously reported from field observations alone (Friderichsen *et al.*, 1991). Our new microstructural results illustrate the importance of petrographic studies of kinematic indicators. The predominant movement sense on the GLDZ is right-lateral, with components of left-lateral slip on subsidiary zones.

In contrast to the GLDZ, asymmetric features were well-developed in the sub-vertical, highly strained gneisses of the Danmarkshavn area. Many of the smaller (< 1 m) mafic pods form sigma-shaped augen with wedge-shaped tails that are commonly filled with pegmatitic material (Fig. 12a). Fist-sized pegmatite augen with both delta- and sigma-type tails were observed in pin-striped gneisses. Markers, such as veins and dykes, are offset along the NNW-striking foliation (e.g. Fig. 12b). Asymmetric boudinage also gave unambiguous information on the movement sense. The vast majority of mesoscale features indicate dextral displacement. Microstructural observations from oriented mylonite samples gave eight with a dextral shear sense, one sinistral sample, and two samples with symmetric microstructures. A mylonite with dextral microstructures was collected from a similar zone on the west coast of Store Koldewey.

Strike-slip displacement on the mylonites of the Storstrømmen shear zone was determined to be left-lateral primarily on the basis of macroscopic field observations (Holdsworth & Strachan, 1991; Strachan *et al.* 1991, 1992). Strachan & Tribe (1994) augment these data with microstructural observations that also indicate sinistral movement on the SSZ. Our field and microstructural observations from a traverse across Hertugen af Orléans Land support this conclusion.

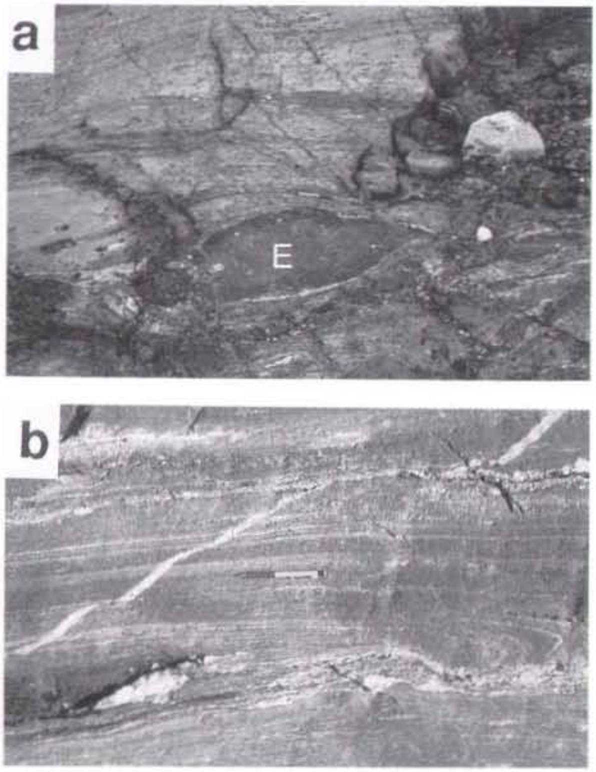

Fig. 12. Highly-strained, straight gneisses in the Danmarkshavn area commonly show dextral asymmetry on horizontal outcrops. a: Sigma-type eclogitic pod (E). b: Offset feldspar vein, an asymmetric fold, and sigma-type pegmatite augen.

Discussion

An ensemble of major strike slip deformation zones in North-East Greenland includes the Germania Land deformation zone extending from Germania Land to Jökelbugten, deformation zones around Danmarkshavn of unknown length, and the Storstrømmen shear zone (SSZ) on the east flank of Dronning Louise Land and Hertugen af Orléans Land (Holdsworth & Strachan, 1991). The SSZ probably extends north of Lambert Land (J. D. Friderichsen, personal communication). These zones are characterised by retrograde, quasiplastic mylonites with late, brittle overprints, and are dominated by strike-slip components of displacement. These zones formed late in the dynamothermal history of the region.

Timing

The age or ages of displacement along these strike-slip zones is difficult to constrain precisely. The last regional, penetrative deformation in this part of North-East Greenland is thought to be Caledonian in age (Chadwick & Friend, 1991; Friderichsen *et al.*, 1991; Tucker *et al.*, 1993; Hull *et al.*, 1994). As the strike-slip system postdates these penetrative fabrics, the Caledonian orogeny provides a lower limit. Unfortunately, the timing of Caledonian deformation is not well known in this region. The U-Pb work of Steiger *et al.* (1976), Kalsbeek *et al.* (1993) and Tucker *et al.* (1993) indicates metamorphism around ~420–400 Ma (Late Silurian). Eclogite facies parageneses have been dated using the Sm-Nd system (Brueckner & Gilotti, 1993; H. Brueckner, personal communication), and give ages ranging from 435–375 Ma (Siluro-Devonian). Rb-Sr mineral isochron ages obtained from the same samples as the Sm-Nd dates yield Carboniferous ages between 360–300 Ma (Brueckner & Gilotti, 1993; H. Brueckner, personal communication), consistent with the earlier Rb-Sr work of Steiger *et al.* (1976).

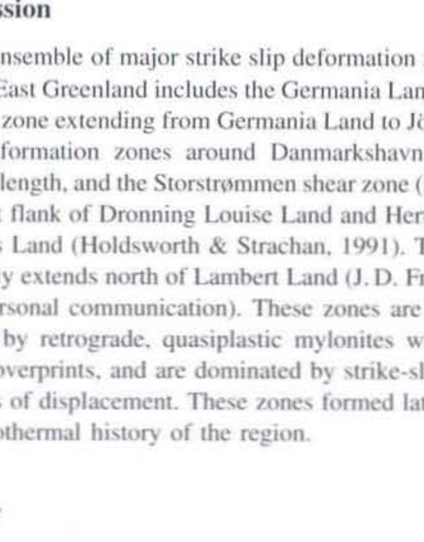

Fig. 11. Lower hemisphere, equal area stereonet of structural elements from the Danmarkshavn area.

$^{40}Ar/^{39}Ar$ incremental heating ages give information on cooling and provide upper limits for the ages of metamorphism. Several hornblende analyses from North-East Greenland yield plateaus or isotope correlation ages cor-

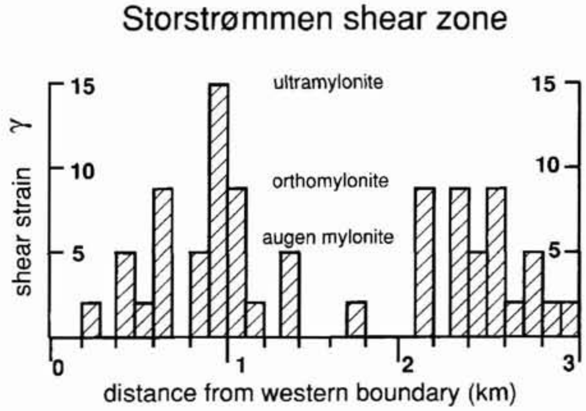

Fig. 13. Mylonite type and estimated angular shear strain (γ) versus distance across part of the Storstrømmen shear zone, south-central Hertugen af Orléans Land.

responding to ~ 390–380 Ma (Dallmeyer *et al.*, 1994), consistent with the U-Pb work. Corresponding muscovite ages ranged from ~420–370 Ma. These data support uplift and cooling through the Middle Devonian.

The development of fault-bounded basins in the Late Palaeozoic provides an upper limit to the mylonitisation. New biostratigraphic data (Stemmerik *et al.*, 1991) indicate that basin formation was initiated in the latest Devonian (~ 360 Ma) throughout the North Atlantic region. These initial red beds are overlain by Early Carboniferous (~ 360–330 Ma) flood plain deposits. Following a mid-Carboniferous uplift event, renewed widespread rifting began in the Westphalian, characterised by alluvial fans along fault-bounded half grabens (Collinson, 1972). The Chatham Elv sedimentary section is comparable to Upper Carboniferous rocks 450 km to the south in Hudson Land (Stemmerik *et al.*, 1991).

The mylonitisation along the Germania Land deformation zone is therefore bracketed by the peak of the Caledonian orogeny at ~430–400 Ma and the formation of fault-bounded, Upper Carboniferous basins at ~300 Ma. The retrograde, quasiplastic mylonites probably formed during cooling and dissection of the orogenic wedge in the Middle to Late Devonian (~380–360 Ma). Mylonitisation along the Storstrømmen shear zone in Hertugen af Orléans Land is probably the same age, because of similar cross-cutting relationships, retrograde tectonites, and argon data. However, Holdsworth & Strachan (1991) concluded that mylonitisation and displacement along the SSZ was synchronous with thrusting during the main phase of the Caledonian orogeny, rather than later in the history. Muscovite from mylonitised pegmatites from the SSZ in Hertugen af Orléans Land gave argon plateau ages of ~375–370 Ma (Dallmeyer & Strachan, 1991; Dallmeyer *et al.*, 1994). We believe that retrograde mylonitisation along this part of the SSZ was late in the orogenic history, and not during the peak of the Caledonian orogeny.

Displacement

The role that strike slip deformation zones play in any tectonic model depends in large part on the magnitude of slip or displacement along the zones. It is very difficult to determine the magnitude of slip without regional markers, and such markers have not yet been recognized in the key areas in North-East Greenland.

One approach to estimating the amount of total slip is integration of simple shear strain across the deformation zone from margin to margin (e.g. Ramsay & Graham, 1970; and discussion in Hull, 1988). As numerical values of shear strain are often difficult to acquire at all points on the traverse, a further approximation is introduced with the surrogate method. The surrogate method involves measuring the thickness of individual mylonite zones or bands across the traverse, and assigning a single numerical value of shear strain to each band depending upon the type of mylonite (protomylonite, orthomylonite, etc.). For example, Grocott & Watterson (1980) used fold topology in each mylonite type as a measure of angular shear strain.

We logged a 3 km traverse across the SSZ in south-central Hertugen af Orléans Land, from the exposed western boundary of the SSZ to the fjord in the east. We found approximately 1800 m of protomylonite, augen mylonite, orthomylonite and ultramylonite on this traverse (Fig. 13); slightly less than half the rocks on our traverse were unmylonitised protolith. Using liberal values of shear strain for each of these tectonite types (Fig. 13), we estimate that the total displacement on this traverse is ~ 9.2 km. Another 2.5 km of SSZ may be hidden under the fjord; if so, then the total displacement along the SSZ in this area is approximately 17 km. Our qualitative estimate of 9–17 km of net slip contrasts with Holdsworth & Strachan (1991), who speculated that displacement across the SSZ "is likely to be tens to hundreds of kilometres".

The displacement across the Germania Land deformation zone is even more problematical, as we were not able to log a continuous traverse across the zone. From the amount and type of tectonites observed in the field, we approximate the total displacement associated with retrograde mylonites as a few kilometres.

The Germania Land deformation zone, the zones around Danmarkshavn, and the Storstrømmen shear zone are important structural elements in North-East Greenland. However, the displacement magnitudes and regional geology suggests that transcurrent deformation zones in North-East Greenland are not terrane boundaries with large displacements, contrary to the assertions of Holdsworth & Strachan (1991) and Dallmeyer & Strachan (1991). In addition to modest displacements, the rock sequences on either side of these deformation zones are very similar (e.g. Friderichsen *et al.*, 1991; Hull *et al.*, 1994); there is no lithologic or geochronologic evidence for 'terranes' (cf. Strachan *et al.*, 1992).

Strike slip in collision

There are many different tectonic models that incorporate strike slip deformation into collisional orogenies (e.g. Atwater, 1970; Molnar & Tapponier, 1977; Bell, 1981; Beck, 1983; Woodcock, 1986). Oblique slip on shear zones can be partitioned into pure dip slip and strike slip components (Jarrard, 1986). Conversely, discrete transcurrent zones have been interpreted as the product of oblique continental collision (e. g. Beck, 1983; Ellis & Watkinson, 1987). This model of slip partitioning in oblique collision has been applied to the Caledonian fold belt of North-East Greenland by Holdsworth & Strachan (1991).

Deformation associated with an *orthogonal* collision can be partitioned among a variety of coeval to sequential deformation zones, including some strike slip, reverse and normal faults. A modern example is the collision between India and Asia with partitioning of the Tibetan Plateau (Molnar & Tapponnier, 1977; Mercier *et al.*, 1987). Salients and recesses along plate margins can also produce local complexities, including orogen-parallel transcurrent faults (e.g. Woodcock, 1986). The presence of strike-slip deformation zones in orogens is therefore not proof of oblique collision.

In heterogeneous deformation, high strain zones of predominantly simple shear will enclose less deformed phacoids or augen exhibiting pure shear (Bell, 1981). These shear zones are stretching faults (Means, 1989); geometrically necessary deformation zones that maintain compatibility between blocks with different magnitudes and/or orientations of finite strain. If strain magnitude varied discontinuously from foreland to hinterland in North-East Greenland, then orogen-parallel strike slip deformation zones would be required to maintain compatibility between crustal blocks.

We have only a few constraints on the transcurrent deformation zones in North-East Greenland that may help us evaluate these and other competing models. The GLDZ and SSZ are not parallel, striking NNW and NNE, respectively. We have argued that displacements on the GLDZ and the SSZ are modest; a few kilometres and about 10–20 kilometres, respectively. The sense of displacement is not uniform; sinistral on the SSZ, and predominantly dextral on the GLDZ and the zones around Danmarkshavn. The quasiplastic mylonites within these zones probably formed late in the collisional history, associated with cooling and retrogression, rather than during the main Caledonian orogenesis.

The history, geometries, and kinematics of Caledonian structural elements in North-East Greenland have similar counterparts in the Scandinavian Caledonides. For example, late, greenschist facies mylonite zones with predominantly strike-slip displacements are present in the hinterland gneisses of central Norway (Piasecki & Cliff, 1988; Seranne, 1992; Gilotti & Hull, 1993). These transcurrent zones are orogen-parallel, and as in North-East Greenland, follow a period of penetrative, ductile, orogen-parallel extension during the Caledonian collision.

The timing of deformational events, the magnitudes of strain and displacement, and the kinematic history of Caledonian structures in North-East Greenland all require further investigation.

Acknowledgements. We are grateful to J. D. Friderichsen, A. K. Higgins, and N. Henriksen whose field observations are included in this report.

References

Atwater, T. 1970: Implications of plate tectonics for the Cenozoic tectonic evolution of western North America. *Geol. Soc. Am. Bull.* **81,** 3513–3536.

Beck, M. E., Jr. 1983: On the mechanism of tectonic transport in zones of oblique subduction. *Tectonophysics* **93,** 1–11.

Bell, T. H. 1981: Foliation development: the contribution, geometry and significance of progressive bulk inhomogeneous shortening. *Tectonophysics* **75,** 273–296.

Brueckner, H. K. & Gilotti, J. A. 1993: Preliminary age constraints on the timing of eclogite facies metamorphism, North-East Greenland Caledonides. *Geol. Soc. Am. Abst. Prog.* **25,** 340 only.

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.

Christiansen, F. G., Bojesen-Koefoed, J., Jensen, S. M. & Stemmerik, L. 1991: Oil seep in basement, Germania Land, North-East Greenland. *Grønlands geol. Unders. Open File Ser.* **91/7,** 18 pp.

Collinson, J. D. 1972: The Røde Ø conglomerate of inner Scoresby Sund and the Carboniferous (?) and Permian rocks west of Schuchert Flod. *Meddr Grønland* **192**(6), 48 pp.

Dallmeyer, R. D. & Strachan, R. A. 1991: Chronology of terrane accretion in the East Greenland Caledonides (76°–79°N): evidence from $^{40}Ar/^{39}Ar$ mineral ages. *Terra Nova Suppl.* **4,** 21 only.

Dallmeyer, R. D., Strachan, R. A. & Henriksen, N. 1994: $^{40}Ar/^{39}Ar$ mineral age record in the North-East Greenland Caledonides. *J. geol. Soc. Lond.* **151,** 615–628.

Ellis, M. & Watkinson, A. J. 1987: Orogen-parallel extension and oblique tectonics: the relation between stretching lineations and relative plate motions. *Geology* **15,** 1022–1026.

Friderichsen, J. D., Gilotti, J. A., Henriksen, N., Higgins, A. K., Hull, J. M., Jepsen, H. F. & Kalsbeek, F. 1991: The crystalline rocks of Germania Land, Nordmarken and adjacent areas, North-East Greenland. *Rapp. Grønlands geol. Unders.* **152,** 85–94.

Gilotti, J. A. 1989: Reaction progress during mylonitization of basaltic dikes along the Särv thrust, Swedish Caledonides. *Contrib. Mineral. Petrol.* **101,** 30–45.

Gilotti, J. A. 1992: The rheologically critical matrix in arkosic mylonites along the Särv thrust, Swedish Caledonides. *In* Mitra, S. & Fisher, G. (ed.) *Structural geology of fold and thrust belts,* 145–160, Baltimore: Johns Hopkins University Press.

Gilotti, J. A. 1993: Discovery of a medium-temperature eclogite province in the Caledonides of North-East Greenland. *Geology* **21,** 523–526.

Gilotti, J. A. 1994: Eclogites and related high-pressure rocks from North-East Greenland. *Rapp. Grønlands geol. Unders.* **162** (this volume).

Gilotti, J. A. & Hull, J. M. 1993: Kinematic stratification in the hinterland of the central Scandinavian Caledonides. *J. struct. Geol.* **15,** 629–646.

Grocott, J. & Watterson, J. 1980: Strain profile of a boundary within a large ductile shear zone. *J. struct Geol.* **2,** 111–117.

Gromet, L. P. 1991: Direct dating of deformational fabrics. *In* Heaman, L. & Ludden, J. N. (ed.) Applications of radiogenic isotope systems to problems in geology. *Mineral. Assoc. Canada, Short Course Handbook* **19,** 167–189.

Hirth, G. & Tullis, J. 1992: Dislocation creep regimes in quartz aggregates. *J. struct. Geol.* **14,** 145–159.

Holdsworth, R. E. & Strachan, R. A. 1991: Interlinked system of ductile strike slip and thrusting formed by Caledonian sinistral transpression in northeastern Greenland. *Geology* **19,** 510–513.

Hull, J. M. 1988: Thickness-displacement relationships for deformation zones. *J. struct. Geol.* **10,** 431–435.

Hull, J. M., Koto, R. and Bizub, R. 1986: Deformation zones in the Highlands of New Jersey. *Proc. Geol. Assoc. New Jersey* **3,** 19–66.

Hull, J. M., Friderichsen, J. D., Gilotti, J. A., Henriksen, N., Higgins, A. K. & Kalsbeek, F. 1994: Gneiss complex of the Skærfjorden region, North-East Greenland. *Rapp. Grønlands geol. Unders.* **162** (this volume).

Jarrard, R. D. 1986: Relations among subduction parameters. *Rev. Geophys.* **24,** 217–284.

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

Larsen, H. C. 1990: The East Greenland shelf. *In* Granz, A., Johnson, L. & Sweeney, J. F. (ed.) The Arctic Ocean region. *The geology of North America* **L,** 185–210.

Means, W. D. 1989: Stretching faults. *Geology* **17,** 893–896.

Mercier, J.-L., Armijo, R., Tapponnier, P., Carey-Gailhardis, E. & Han, T.-L. 1987: Change from Late Tertiary compression to Quaternary extension in southern Tibet during the India-Asia collision. *Tectonics* **6,** 275–304.

Mitra, G. 1978: Ductile deformation zones and mylonites: the mechanical processes involved in the deformation of crystalline basement rocks. *Am. J. Sci.* **278,** 1057–1084.

Mitra, G. 1992: Deformation of granitic basement rocks along fault zones at shallow to intermediate crustal levels. *In* Mitra, S. & Fisher, G. (ed.) *Structural geology of fold and thrust belts,* 123–144, Baltimore: Johns Hopkins University Press.

Möller, C. 1988: Geology and metamorphic evolution of the Roan area, Vestranden, Western Gneiss Region, Central Norwegian Caledonides. *Bull. Norges geol. Unders.* **413,** 1–31.

Molnar, P. & Tapponnier, P. 1977: Relation of the tectonics of Eastern China to the India-Eurasia collision: application of slip-line field theory to large-scale continental tectonics. *Geology* **5,** 212–216.

Passchier, C. W. & Simpson, C. 1986: Porphyroclast systems as kinematic indicators. *J. struct. Geol.* **8,** 831–843.

Piasecki, M. A. J. & Cliff, R. A. 1988: Rb-Sr dating of strain-induced mineral growth in two ductile shear zones in the Western Gneiss Region of Nord-Trøndelag, central Norway. *Bull. Norges geol. Unders.* **413,** 33–50.

Piasecki, S., Stemmerik, L. & Friderichsen, J. D. 1994: Stratigraphy of the post-Caledonian sediments in the Germania Land area, North-East Greenland. *Rapp. Grønlands geol. Unders.* **162** (this volume).

Ramsay, J. G. & Graham, R. H. 1970: Strain variation in shear belts. *Can. J. Earth Sci.* **7,** 786–813.

Robinson, P. R., Spear, F. S., Schumacher, J. C., Laird, J., Klein, C., Evans, B. W. & Doolan, B. L. 1982: Phase relations of metamorphic amphiboles: natural occurrence and theory. *In* Veblen, D. R. & Ribbe, P. H. (ed.) Reviews in mineralogy. *Mineralogical Society of America* **9B,** 1–227.

Seranne, M. 1992: Late Palaeozoic kinematics of the Møre-Trøndelag fault zone and adjacent areas, central Norway. *Norsk geol. Tidsskr.* **72,** 141–158.

Sibson, R. H. 1977: Fault rocks and fault mechanisms. *J. geol. Soc. Lond.* **133,** 191–213.

Simpson, C. 1985: Deformation of granitic rocks across the brittle-ductile transition. *J. struct. Geol.* **7,** 503–511.

Sørensen, K. 1983: Growth and dynamics of the Nordre Strømfjord Shear Zone. *J. geophys. Res.* **88,** 3419–3437.

Steiger, R. H., Harnik-Šoptrajanova, G., Zimmermann, E. & Henriksen, N. 1976: Isotopic age and metamorphic history of the banded gneiss at Danmarkshavn, East Greenland. *Contrib. Mineral. Petrol.* **57,** 1–24.

Stemmerik, L., Vigran, J. O. & Piasecki, S. 1991: Dating of late Paleozoic rifting events in the North Atlantic: new biostratigraphic data from the uppermost Devonian and Carboniferous of East Greenland. *Geology* **19,** 218–221.

Strachan, R. A. & Tribe, I. R. 1994: Structure of the Storstrømmen shear zone, eastern Hertugen af Orléans Land, North-East Greenland. *Rapp. Grønlands geol. Unders.* **162** (this volume).

Strachan, R. A., Jepsen, H. F. & Kalsbeek, F. 1991: Regional Caledonian structure of Hertugen af Orléans Land, North-East Greenland. *Rapp. Grønlands geol. Unders.* **152,** 95–102.

Strachan, R. A., Holdsworth, R. E., Friderichsen, J. D. & Jepsen, H. F. 1992: Regional Caledonian structure within an oblique convergence zone, Dronning Louise Land, NE Greenland. *J. geol. Soc. Lond.* **149,** 359–371.

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

Tullis, J. & Yund, R. A. 1985: Dynamic recrystallization of feldspar: a mechanism for ductile shear zone formation. *Geology* **13,** 238–241.

Woodcock, N. H. 1986: The role of strike-slip fault systems at plate boundaries. *Phil. Trans. R. Soc.* **A317,** 13–29.

Yund, R. A. & Tullis, J. 1991: Compositional changes of minerals associated with dynamic recrystallization. *Contrib. Mineral. Petrol.* **108,** 346–355.