Early Proterozoic thrust tectonics east of Ataa Sund, north-east Disko Bugt, West Greenland

Jan C. Escher, Michael J. Ryan and Mogens Marker

The area east of Ataa Sund consists mainly of amphibolite facies grade Archaean gneisses, amphibolites and granites. Intense early Proterozoic deformation led to low-angle ductile imbrication of thrust sheets with movement directions to the west. Late tectonic Proterozoic basic sills with olivine-rich cumulates were intruded along the thrust sheets.

J.C.E., *Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark.* E-mail: *jce@geus.dk*.
M.J.R., *Department of Geology, University of Portsmouth, Portsmouth PO1 3HE, UK.*
M.M., *Geological Institute, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.* Present address: *Geological Survey of Norway, Leiv Erikssonsvei 39, N-7491 Trondheim, Norway.*

Keywords: Archaean rocks, Disko Bugt, Proterozoic, thrust tectonics, West Greenland

The Ataa area, north-east Disko Bugt, lies between the early Proterozoic Nagssugtoqidian and Rinkian orogenic belts of West Greenland (Fig. 1; Escher 1995). Escher & Pulvertaft (1967) proposed the boundary between the two belts to run along a fault zone in the Ataa Sund region, but Kalsbeek *et al*. (1988) believed that the area was hardly or not affected by early Proterozoic deformation, and thus did not belong to either of them. In the present study we describe the structural development of an area east of Ataa Sund, and show that large-scale westward-directed ductile thrusting took place during the early Proterozoic. Similar structures occur west of Ataa Sund (Grocott & Davies 1999, this volume) and on Nuussuaq (Garde & Steenfelt 1999, this volume), and correspond to a phase of early Proterozoic thrusting described by Pulvertaft (1986) in the southern part of the Rinkian belt.

During the Disko Bugt Project the coastal areas were mapped by rubber boat on 1:50 000 scale, and the inland areas by foot traverses in less detail. Five Archaean and six Proterozoic events in the development of the area have been recognised (Table 1).

Archaean rocks

Most of the area east of Ataa Sund consists of late Archaean rocks. Five units have been distinguished (Fig. 2; Table 1).

1. Amphibolites probably represent the oldest rock unit of the area, as they occur as numerous inclusions and boudinaged layers within migmatitic orthogneisses; locally, some of the inclusions show an early discordant foliation (Fig. 3). The thicker sheets often preserve compositional banding, seen as paler varieties of feldspar-hornblende gneiss next to darker, coarser grained, mafic amphibolite and hornblendite. Some of this banding may be original, but some may be due to metamorphic differentiation. The amphibolites were probably derived from basic lavas or tuffs, or differentiated basaltic intrusions. Locally, disseminated fine-grained sulphides give the rocks a rusty weathering appearance.

2. Migmatitic, banded, foliated granodioritic and tonalitic orthogneisses form the bulk of the rocks in

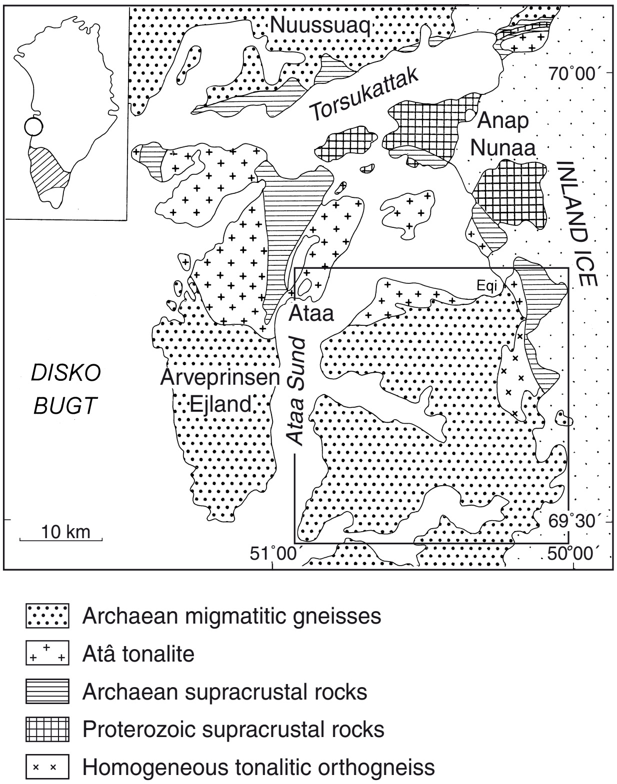


Fig. 1. Geological sketch map of the region north-east of Disko Bugt with the location of the area described in this paper.

the area. The gneisses show a polyphase intrusive origin with several generations of small-scale layering of quartzo-feldspathic and biotite (-hornblende) segregations (Fig. 4). Some of the tonalitic-dioritic layers may represent different phases of intermediate magmatic precursors of the gneisses, some may represent variable degrees of assimilation of basic enclaves, while most of the leucocratic banding seems to be a consequence of migmatitic differentiation. As noted above, the gneisses are typically rich in amphibolite inclusions. Local rusty weathering of the gneisses has been attributed to hydrothermal activity with alteration to muscovite, epidote, chlorite, hematite and occasionally carbonate and small amounts of disseminated sulphides. One sample of the migmatitic orthogneisses has yielded a SHRIMP U-Pb zircon date of 2815 ± 4 Ma (Nutman & Kalsbeek 1999, this volume).

3. Homogeneous, tonalitic orthogneisses occur in the eastern part of the area. In contrast with the migmatitic gneisses, they exhibit little migmatitic vein-

Fig. 2. Geological map of the area east of Ataa Sund, West Greenland. For location, see Fig. 1.

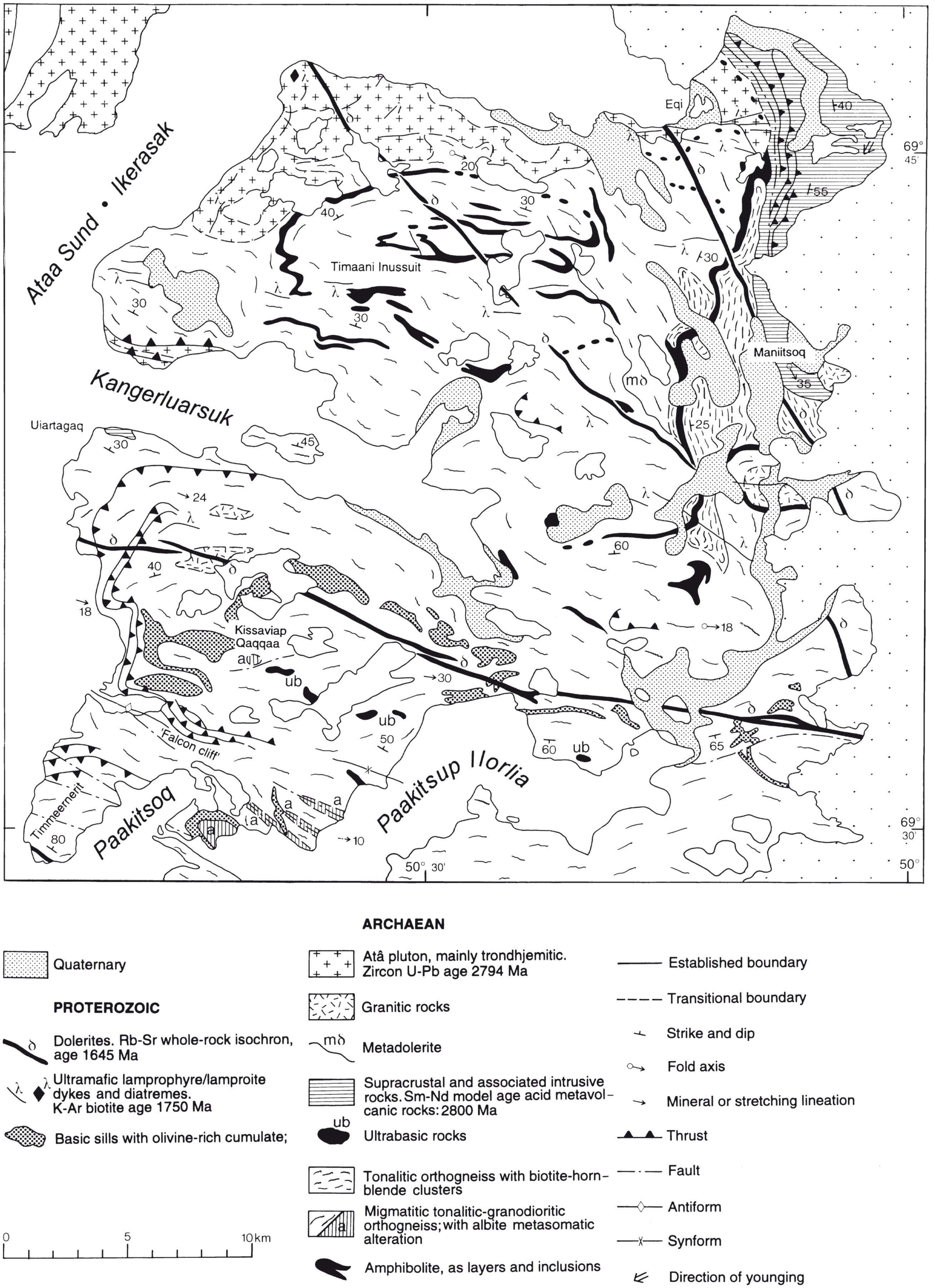
Table 1. Archaean and Proterozoic development of the area east of Ataa Sund; from oldest to youngest

ARCHAEAN

1. Amphibolite
2. Migmatitic orthogneiss
3. Homogeneous orthogneiss with biotite-hornblende clusters
4. Supracrustal and associated intrusive rocks (*c.* 2800 Ma)
5. Atâ tonalite (*c.* 2800 Ma)

PROTEROZOIC

6. Major folding and thrusting:
   a. W- to NW-facing recumbent folds; imbricate thrusting during ductile shear deformation with W to NW transport directions; W- to NW-trending mineral stretching lineations; penetrative mylonitic fabric
   b. Open to tight folds with steep E–W- to SE–NW-trending axial surfaces
7. Basic sills with olivine-rich cumulate
8. Minor folding:
   Open, large-scale folds and chevron-type folds; steep SE-trending axial surfaces
9. WNW- to ESE-trending faults in the Paakitsoq region
10. Dolerites and lamprophyres (*c.* 1750 Ma to *c.* 1650 Ma)
11. Albitisation of gneisses


Ataa Sund • Ikerasak
Eqi
Timaani Inussuit
Maniitsoq
Kangerluarsuk
Uiartagaq
Kissaviap Qaqqaa
'Falcon cliff'
Paakitsup Ilorlia
Paakitsoq
Timmeernerit
69° 45'
69° 30'
50° 30'
50°
ARCHAEAN
Quaternary
PROTEROZOIC
Dolerites. Rb-Sr whole-rock isochron, age 1645 Ma
Ultramafic lamprophyre/lamproite dykes and diatremes. K-Ar biotite age 1750 Ma
Basic sills with olivine-rich cumulate;
Atâ pluton, mainly trondhjemitic. Zircon U-Pb age 2794 Ma
Granitic rocks
Metadolerite
Supracrustal and associated intrusive rocks. Sm-Nd model age acid metavolcanic rocks: 2800 Ma
Ultrabasic rocks
Tonalitic orthogneiss with biotite-hornblende clusters
Migmatitic tonalitic-granodioritic orthogneiss; with albite metasomatic alteration
Amphibolite, as layers and inclusions
Established boundary
Transitional boundary
Strike and dip
Fold axis
Mineral or stretching lineation
Thrust
Fault
Antiform
Synform
Direction of younging
0
5
10km

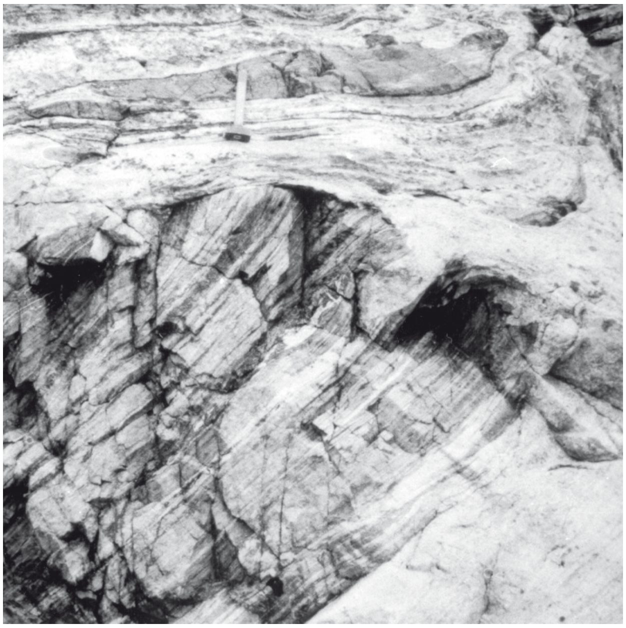


Fig. 3. Foliated amphibolite inclusion within banded migmatitic orthogneiss showing discordant relationship; innermost part of Kangerluarsuk.

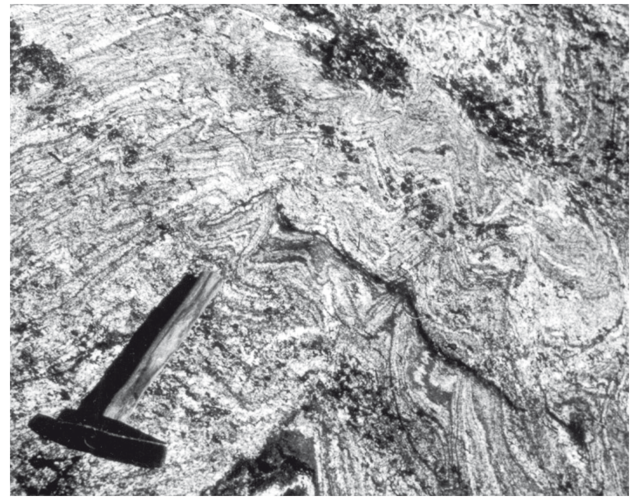


Fig. 4. Small-scale folded, migmatitic orthogneiss; Timaani Inussuit.

ing and contain few amphibolite inclusions. Small clusters of biotite and hornblende give the rock a characteristic spotted appearance. The low degree of migmatisation and the scarcity of basic inclusions may indicate that these gneisses are younger than the migmatitic gneisses. SHRIMP zircon dating (Nutman & Kalsbeek 1999, this volume) did not resolve this age difference.

4. An isolated outcrop (*c.* 1 km^2) of quartzite and structurally overlying grey garnetiferous mica schists occurs along the coast at Uiartagaq (Fig. 2). These metasediments occur in the centre of a westerly-trending, synformal structure. About 35 km to the north-west of Uiartagaq, similar Archaean metasedimentary rocks with a comparable mineralogy have been mapped at Oqaatsut; 69°55′N, 51°25′W (Rasmussen & Pedersen 1999, this volume).

A belt of supracrustal rocks and associated intrusive bodies occurs along the north-eastern margin of the gneiss area in the Eqi–Maniitsoq region. (Fig. 2). The belt consists mainly of micaceous quartz-rich metasediments with a few thin layers of banded iron formation, acid and basic volcanic rocks and gabbroic rocks; they show amphibolite and greenschist facies metamorphic grade (Stendal *et al.* 1999, this volume). The dominant bedding/foliation dips to the north-east at variable angles, but well-preserved pillow structures within the primary stratification indicate a way-up direction to the south-west; the sequence is therefore overturned. Acid metavolcanic rocks in the Eqi region have yielded a Sm-Nd model age of *c.* 2800 Ma (Kalsbeek & Taylor 1999, this volume).

Fig. 5. Migmatitic orthogneiss with intrusive, polyphase, granite sheets and veins (Atâ tonalite); west of Eqi.

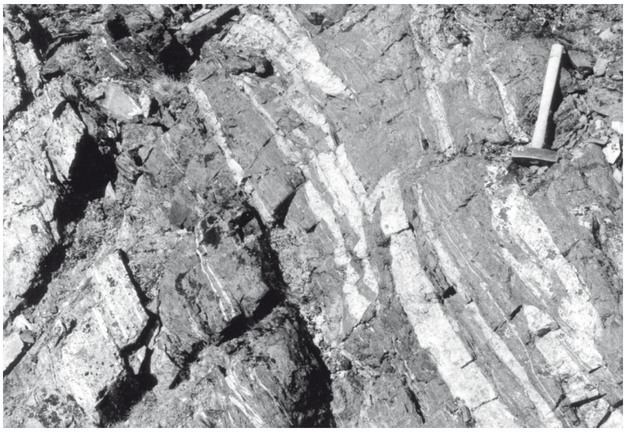


Fig. 6. Intrusive contact relationship between deformed granitoid rocks of the Atâ tonalite (lower left) and Archaean metavolcanic rocks (upper right) with veins of tonalite within amphibolite; Eqi.

5. Weakly-foliated, polyphase trondhjemitic rocks forming part of the Atâ tonalite (Atâ intrusive complex of Kalsbeek & Skjernaa 1999, this volume) occur along the northern margin of the gneiss area. The boundary between the banded migmatitic gneisses and the Atâ tonalite is transitional with a gradual, northwards increase of grey polyphase trondhjemitic veins intruding the migmatitic gneisses (Fig. 5). Although the Atâ tonalite has given about the same radiometric age as the acid volcanic rocks of Eqi, the tonalite is younger as numerous trondhjemitic veins intrude the supracrustal rocks along the contact between the two units (Fig. 6).

Proterozoic rocks

A basic sill complex with olivine cumulate layers occurs within the gneisses of the southern part of the area. Many of the sills have been emplaced within thrust faults during a late stage of the ductile regional thrusting. They show well-developed pinch and swell structure or boudinage (Fig. 7). The centres of the thicker sills show generally little deformation, while the margins have been variably altered. Most of this alteration is attributed to shear movements along the thrusts perhaps during injection of the magma. The sills show in many localities well-preserved intrusive contacts with the host gneisses and dark coloured fine-grained chilled margins; secondary chloritisation occurs along joints.

Although layering or colour banding of the sills are not apparent in the field, variations in mineral assemblages and composition are shown by thin section study and chemical analyses. These variations are either the result of *in situ* differentiation or separate injection pulses of magmas with different compositions.

Thin sections show generally a medium- to coarse-grained rock of ultramafic composition, with 1–2 mm olivine crystals enclosed by larger 5–10 mm orthopyroxene, occasionally with minor interstitial plagioclase. However, the sill situated near the narrow entrance of Paakitsoq is a micronorite, with abundant basic plagioclase and orthopyroxene, a little clinopyroxene and interstitial quartz. The lowest sill in the Kissaviap Qaqqaa region, occurring about 150 m above sea level, has a similar composition.

Some 125 km further to the north, Schiøtte (1988) has described a swarm of discordant metabasic sills within Archaean migmatitic gneisses, which show comparable composition and style of emplacement. Based on the occurrence of normal and inversed igneous layering, Schiøtte recognised inversion of the bodies relative to each other after their intrusion, and concluded that Rinkian (*c.* 1800–1900 Ma) recumbent folding postdated the intrusion of the metabasites. East of Ataa Sund, it has not been possible to establish the direction of younging of the igneous layering; however, the tectonic development of the region does not indicate any major recumbent folding of the sills. Therefore it is not clear whether the two swarms of metabasic sills can be correlated.

A few NNW-trending metadolerite dykes occur in the eastern part of the area (Fig. 2). They have been subjected to moderate deformation, shearing and boud-

Fig. 7. Boudinaged basic sill (about 20 m thick), intruded along a thrust fault; east of Kissaviap Qaqqaa.

Fig. 8. 'Falcon cliff' (view to the north) with imbricated thrust sheets of banded gneiss. Transport direction to the west. West-facing recumbent folds with related small-scale folds in upper part of cliff section near 460 m high mountain summit. Thrust planes accentuated with black lines.

inage. The foliated margins consist of amphibolite and often preserve discordant relationships with the surrounding gneisses. Cores of less-deformed dykes show relict ophitic textures or early metamorphic textures, with garnet formed by reaction between igneous pyroxene and plagioclase. One metabasic dyke, more than 10 km long, cuts through the fold interference pattern of Timaani Inussuit (described below). The age of the Timaani Inussuit structure is, however, poorly constrained, and the age of these metadolerites may be either Archaean or Proterozoic.

Main Proterozoic structural development

Proterozoic E–W compression in the Disko Bugt region led to widespread ductile deformation of the crystalline rocks. Large-scale recumbent isoclinal folds and imbricated low-angle thrust sheets, with overall westerly transport directions, have been mapped in different parts of the region. For example on northern Nuussuaq, about 65 km north of the area described here, a major recumbent west-facing fold and associated thrust sheets, formed by low-angle fault movements, deform a marble unit correlated with the early Proterozoic Mârmorilik Formation (Garde & Steenfelt 1999, this volume). Similar deformation occurred on Arveprinsen Ejland, where a series of low-angle, generally SE-dipping ductile shear zones have been described by Grocott & Davies (1999, this volume). The area east of Ataa Sund has undergone similar intense deformation during westerly-directed ductile overthrusting combined with west-verging recumbent folding. Two examples are described in detail.

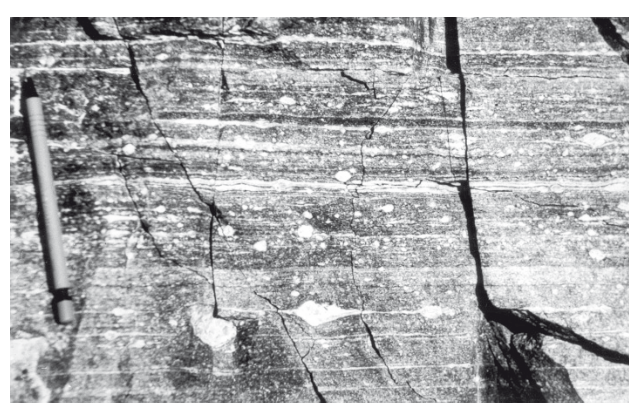


Fig. 9. Penetrative mylonitic foliation with elongated quartz and feldspar aggregates; 'Falcon cliff'.

Fig. 10. Lower part of *S*-shaped fold (view to the north) with E-dipping axial surface; 'Falcon cliff'. Person on right as scale.

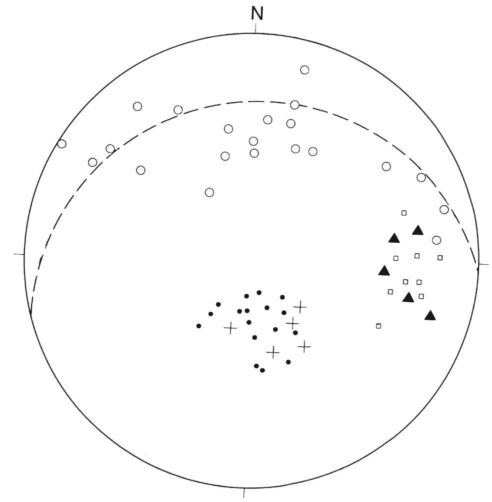


Fig. 12. Lower hemisphere Schmidt projection of measured structural data from 'Falcon cliff. (1) Event 6a (Table 1): open circles = fold axes of recumbent and related small-scale folds; dots = poles to the axial surfaces of the folds; crosses = poles to mylonitic foliation; squares = mineral stretching lineations; great circle (stippled) = 'best fit' of axial surfaces. (2) Event 6b (Table 1): filled triangles = axes of open to tight folds with steep westerly-trending axial planes.

'Falcon cliff'

About 2.5 km south of Kissaviap Qaqqaa (Fig. 2), a steep, south-facing mountain cliff, nearly 400 m high, was given the informal name of 'Falcon cliff' because of nesting Gyr falcons. The cliff represents a well-exposed, E–W cross-section through a series of imbricate thrust sheets (Fig. 8). At least eight thrust units of migmatitic gneisses have been distinguished. The upper part of the cliff section shows a number of large westerly-facing recumbent folds which are related to the thrusting. A well-developed penetrative mylonitic foliation (Fig. 9) seen within all the thrust sheets was developed during the thrust event. Quartz-feldspar-biotite stretching lineations dip to the east and south-east. The recumbent folds are associated with *S*-shaped, asymmetric, parasitic folds (Fig. 10). All folds have tight to isoclinal shapes with their axial surfaces parallel to the thrust faults. The westerly vergence of the recumbent folds and the low-angle, east-dipping imbrication are consistent with the top-to-the-west sense of movement of the thrust sheets, which is demonstrated by numerous asymmetric K-feldspar porphyroclast systems (Fig. 11). Similar shear-sense indicators within thrust structures from other localities of the mapped region also indicate a westerly sense of transport.

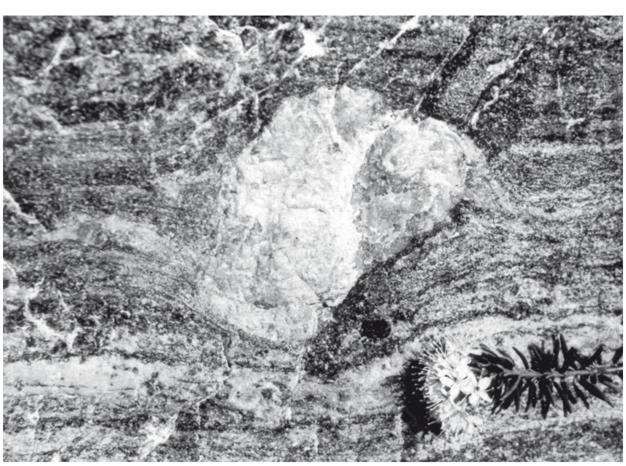


Fig. 11. Rotated, asymmetric K-feldspar porphyroclast (view to the south) indicating top to the west sense of shearing; 'Falcon cliff'. Largest diameter of porphyroclast about 8 cm.

A lower hemisphere Schmidt net projection of structural data from 'Falcon cliff' (Fig. 12) shows: (1) mineral and stretching lineations plunging about 20° to the ESE, (2) axial surfaces of parasitic folds parallel to the mylonitic foliation of the thrust sheets, both with an average dip of about 30° to the NNW (indicated as the 'best fitting' great circle) and (3) NW to NE fanning of the axes of parasitic folds.

It was not possible to recognise the basal thrust detachment zone of the imbricates, nor to appraise distances of displacement of the individual thrust sheets. The ductile folding and thrusting of the rocks and the amphibolite facies mineral assemblages indicate that deformation took place at mid-crustal depth.

Following the intense E–W regional shortening (Table 1, 6a), the region east of Ataa Sund endured a

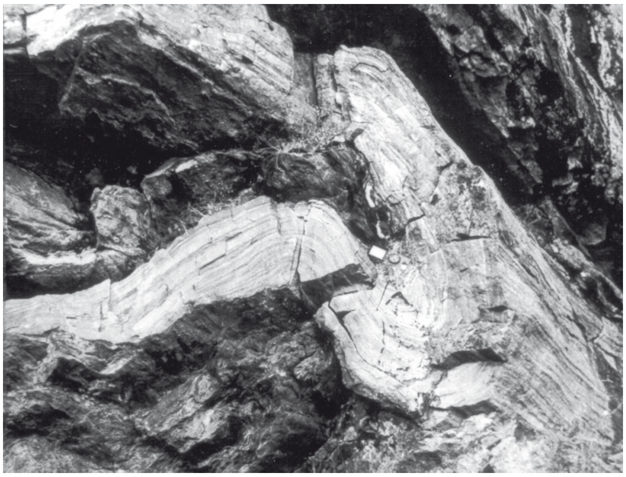


Fig. 13. Recumbent fold refolded by vertical E–W-trending fold; 'Falcon cliff'. See text for explanation. Compass 20 cm in

period of more moderate deformation during N–S contraction (Table 1, 6b). In the 'Falcon cliff' area, a few folds related to the latter event have been recorded (Figs 12, 13).

Timaani Inussuit

A large fold structure in the Timaani Inussuit area (Fig. 2) is outlined by a string of basic inclusions and boudinaged layers of amphibolite which resemble a Ramsay type 2 mushroom-shaped interference pattern. Although no conclusive indications for the age of this structure are found, it is suggested that it was formed by interference between a major, west-facing recumbent fold (Table 1, 6a) and a few E–W-trending upright folds (Table 1, 6b); this would mean that the structure is Proterozoic in age. On the other hand, the intense isoclinal folding and refolding are reminiscent of the fold style of parts of the Archaean craton further to the south.

Later Proterozoic deformation

The youngest Proterozoic deformation recorded in the area east of Ataa Sund is of relatively weak intensity and is characterised by open, large-scale folds and smaller-scale chevron-style folds with steep NW–SE-trending axial planes and variably dipping fold axes. The chevron folds have a well-developed micaceous crenulation cleavage.

A good example of later Proterozoic large-scale folding occurs on the peninsula of Timmeernerit. In general the thrust faults of the mapped area dip eastwards. On Timmeernerit, however, a pile of thrust sheets has been folded by a large open NW–SE-trending antiform, and the thrust sheets as a consequence dip to the south. The antiform of Timmeernerit has the same trend as the Quvnerssuaq–Kugssuk antiform on Arveprinsen Ejland (Grocott & Davies 1999, this volume) and can be envisaged as a south-eastern extension of that structure.

The gneisses north and south of Paakitsoq fjord are cut by a series of parallel, sub-vertical, ESE–WNW-trending faults (Fig. 2). Some of the faults can be traced for about 42 km through the Disko Bugt region from Arveprinsen Ejland (Grocott & Davies 1999, this volume) to the Inland Ice. Although it has not been possible to measure displacement on the faults due to a lack of suitable marker horizons, the impression is that only minor displacement has occurred. The faults are characterised by 2–15 m wide brittle crush zones consisting of brecciated unfoliated epidote-quartz-feldspar rock; the breccia has locally been albitised (Ryan & Escher 1999, this volume). The brittle nature of the fault rock and the undisturbed linear shape of the faults indicate that movement took place at high crustal level during a late stage of the regional deformation.

Escher & Pulvertaft (1976) proposed that the Paakitsoq fault system formed the tectonic boundary between the Nagssugtoqidian and Rinkian mobile belts. A detailed mapping of the region south of Paakitsoq was not included in the mapping program of the Disko Bugt region, but the work on Arveprinsen Ejland by Grocott & Davies (1999, this volume) and the present authors suggests that these faults do not represent a structure of crustal dimensions.

References

Escher, A. & Burri, M. 1967: Stratigraphy and structural development of the Precambrian rocks in the area north-east of Disko Bugt, West Greenland. Rapport Grønlands Geologiske Undersøgelse **13**, 28 pp.

Escher, A. & Pulvertaft, T.C.R. 1976: Rinkian mobile belt of West Greenland. In: Escher, A. & Watt, W.S. (eds): Geology of Greenland, 104–119. Copenhagen: Geological Survey of Greenland.

Escher, J.C. 1995: Geological map of Greenland, 1:100 000, Ataa 69 V.3 Nord. Copenhagen: Geological Survey of Greenland.

Garde, A.A. & Steenfelt, A. 1999: Precambrian geology of Nuussuaq and the area north-east of Disko Bugt, West Greenland. In: Kalsbeek, F. (ed.): Precambrian geology of the Disko Bugt region, West Greenland. Geology of Greenland Survey Bulletin **181**, 6–40 (this volume).

Grocott, J. & Davies, S.C. 1999: Deformation at the southern boundary of the late Archaean Atâ tonalite and the extent of Proterozoic reworking of the Disko terrane, West Greenland. In: Kalsbeek, F. (ed.): Precambrian geology of the Disko Bugt region, West Greenland. Geology of Greenland Survey Bulletin **181**, 155–169 (this volume).

Kalsbeek, F. & Skjernaa, L. 1999: The Archaean Atâ intrusive complex (Atâ tonalite), north-east Disko Bugt, West Greenland. In: Kalsbeek, F. (ed.): Precambrian geology of the Disko Bugt region, West Greenland. Geology of Greenland Survey Bulletin **181**, 103–112 (this volume).

Kalsbeek, F. & Taylor, P.N. 1999: Review of isotope data for Precambrian rocks from the Disko Bugt region, West Greenland. In: Kalsbeek, F. (ed.): Precambrian geology of the Disko Bugt region, West Greenland. Geology of Greenland Survey Bulletin **181**, 41–47 (this volume).

Kalsbeek, F., Taylor, P.N. & Pidgeon, R.T. 1988: Unreworked Archaean basement and Proterozoic supracrustal rocks from northeastern Disko Bugt, West Greenland: implications for the nature of Proterozoic mobile belts in Greenland. Canadian Journal of Earth Sciences **25**, 773–782.

Nutman, A.P. & Kalsbeek, F. 1999: SHRIMP U-Pb zircon ages for Archaean granitiod rocks, Ataa area, north-east Disko Bugt, West Greenland. In: Kalsbeek, F. (ed.): Precambrian geology of the Disko Bugt region, West Greenland. Geology of Greenland Survey Bulletin **181**, 49–54 (this volume).

Pulvertaft, T.C.R. 1986: The development of thin thrust sheets and basement-cover sandwiches in the southern part of the Rinkian belt, Umanak district, West Greenland. Rapport Grønlands Geologiske Undersøgelse **128**, 75–87.

Rasmussen, H. & Pedersen, L.F. 1999: Stratigraphy, structure and geochemistry of Archaean supracrustal rocks from Oqaatsut and Naajaat Qaqqaat, north-east Disko Bugt, West Greenland. In: Kalsbeek, F. (ed.): Precambrian geology of the Disko Bugt region, West Greenland. Geology of Greenland Survey Bulletin **181**, 65–78 (this volume).

Ryan, M.J. & Escher J.C. 1999: Albitised gneisses in the area between Paakitsoq and Kangerluarsuk, north-east Disko Bugt, West Greenland. In: Kalsbeek, F. (ed.): Precambrian geology of the Disko Bugt region, West Greenland. Geology of Greenland Survey Bulletin **181**, 113–117 (this volume).

Schiøtte, L. 1988: Field occurrence and petrology of deformed metabasite bodies in the Rinkian mobile belt, Umanak district, West Greenland. Rapport Grønlands Geologiske Undersøgelse **141**, 36 pp.

Stendal, H., Knudsen, C., Marker, M. & Thomassen, B. 1999: Gold mineralisation at Eqi, north-east Disko Bugt, West Greenland. In: Kalsbeek, F. (ed.): Precambrian geology of the Disko Bugt region, West Greenland. Geology of Greenland Survey Bulletin **181**, 129–140 (this volume).