DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1999/80

The evidence for episodic tectono-thermal activity in southern Renland, East Greenland Caledonides

A. Graham Leslie and Allen P. Nutman

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1999/80

The evidence for episodic tectono-thermal activity in southern Renland, East Greenland Caledonides

A. Graham Leslie and Allen P. Nutman

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

G E U S

Frontispiece. *Peak 1882 m viewed along Øfjord from the south-west and showing the dark hypersthene monzonite intrusion on the lower cliffs. Pale augen granite and darker paragneiss layers on the cliff in the foreground.*

Contents

Abstract

Detailed examination of field relationships in the rocks of southern Renland, Scoresby Sund region, East Greenland, reveals a protracted sequence of pre-Caledonian and Caledonian tectono-thermal events. The earliest observed deformation predates presumed ~900–1000 Ma granite generation in Mesoproterozoic metasediments. Non-coaxial contractional deformation and ductile shearing with top-to-the-west sense of displacement took place subsequent to melt generation. Some time later, intrusion of basic sheets was followed by an extensional shearing episode but, allowing for some overlap in the later stages of extension, those intrusions largely pre-date superimposition of high grade metamorphic conditions which reached granulite facies. Renewed thrusting in Caledonian time was associated with retrogression of the high grade parageneses, most pervasively in the east of the region, and was associated with Caledonian acid to intermediate intrusive activity and migmatisation. The latest events to be recognised in the region include brittle–ductile extensional shear and upright late Caledonian folding. Samples have been collected from critical localities for isotopic studies which are intended to provide absolute constraints on the timing of events in the sequence outlined above.

AGL: *Department of Geology, School of Geosciences, The Queen's University of Belfast, Belfast BT7 1NN, Northern Ireland.*
APN: "Melbury", Hensleigh Drive, Exeter, EX2 4NZ, UK.

Introduction

The southern part of the East Greenland Caledonian fold belt is characterised by N–S trending belts of different character, reflecting superimposition of different structural levels during north-westwards transport on major Caledonian thrust systems. In the Scoresby Sund region a 75 km wide migmatite and granite zone can be traced from the northern Stauning Alper through Renland to Gåsefjord, a distance of more than 200 km (Fig. 1). This zone is thought to be an amalgam of two major orogenic cycles, both involving migmatisation, deformation and plutonism (e.g. Henriksen & Higgins 1976; Henriksen 1986). During the first, sheets of augen granite were intruded into metasediments assumed to be the equivalent of the Krummedal supracrustal sequence (Higgins 1988). In southern Renland both units were regarded as folded into major recumbent nappe structures (Chadwick 1975). Rb-Sr whole rock and U-Pb zircon age determinations on the augen granites have yielded ages of 900–1000 Ma (Steiger *et al.* 1979), interpreted as the age of emplacement.

In southern Renland (Fig. 2), late to post-kinematic intrusions are widespread, the oldest of which is a prominent lopolithic Caledonian hypersthene monzonite cutting through strongly deformed and migmatised gneisses and augen granites, but itself affected by later migmatisation and granite injection. The monzonite was believed to have been injected at 475±14 Ma (Steiger *et al.*1979) with the younger migmatisation and granites giving a broad suite of Caledonian ages (Hansen & Tembusch 1979).

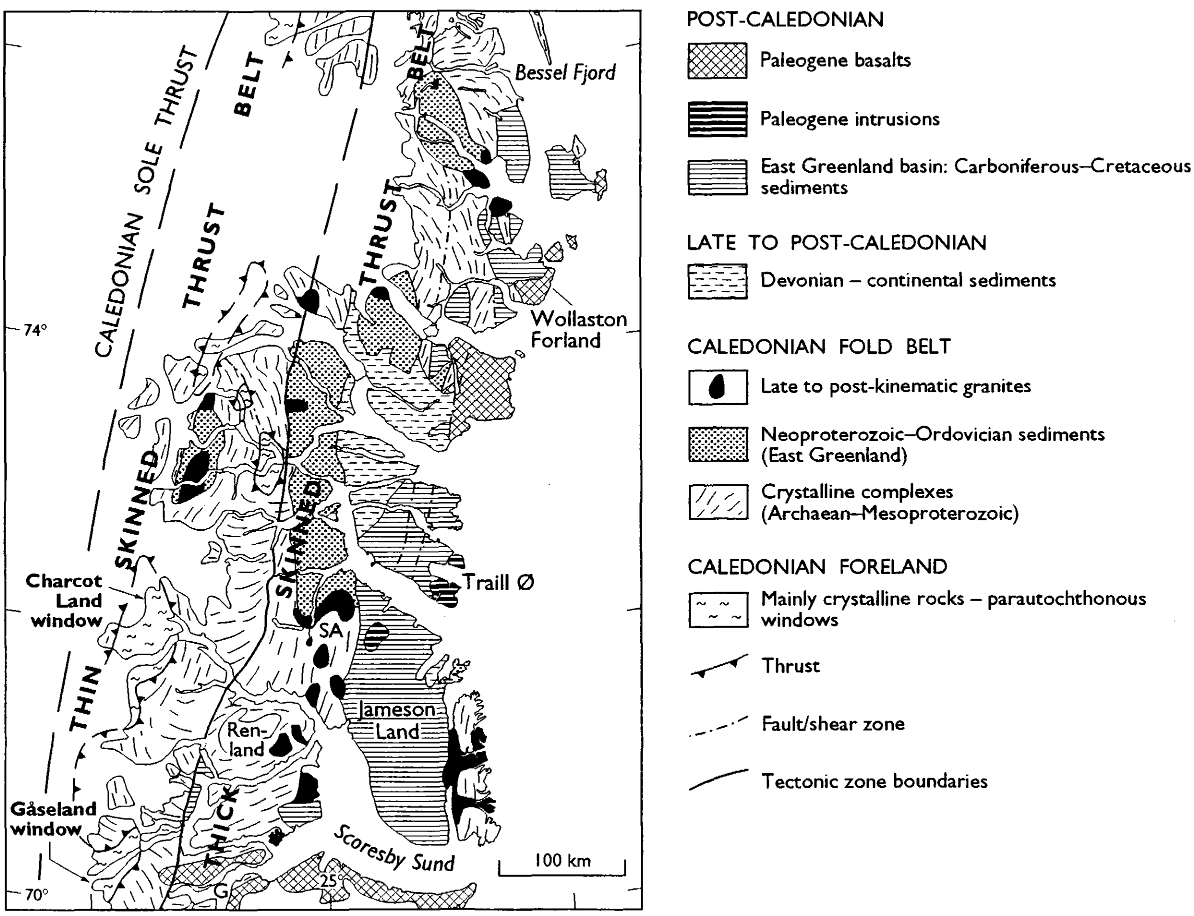


Figure 1. *Geological map of the southern East Greenland Caledonides. Renland lies in the Scoresby Sund region within the thick-skinned zone of the fold belt. SA: Stauning Alper. G: Gåsefjord. A geological map of southern Renland is shown in Fig. 2.*

The isotopic data from the Renland augen granites noted above provided the first convincing support for pre-Caledonian (?Grenvillian) tectono-thermal activity in the broader context of the East Greenland Caledonides, activity which has recently been unambiguously confirmed by SHRIMP intra-grain zircon and monazite U-Pb geochronology studies further north in East Greenland (e.g. Strachan *et al.* 1995; Thrane *et al.* 1999; Kalsbeek *et al.* 1993, in press; F. Kalsbeek & A.P. Nutman unpublished data). The 1999 fieldwork in southern Renland reported here was prompted by the need for new field studies and collections for SHRIMP isotopic studies, aimed in particular at clarifying the nature of the pre-Caledonian event.

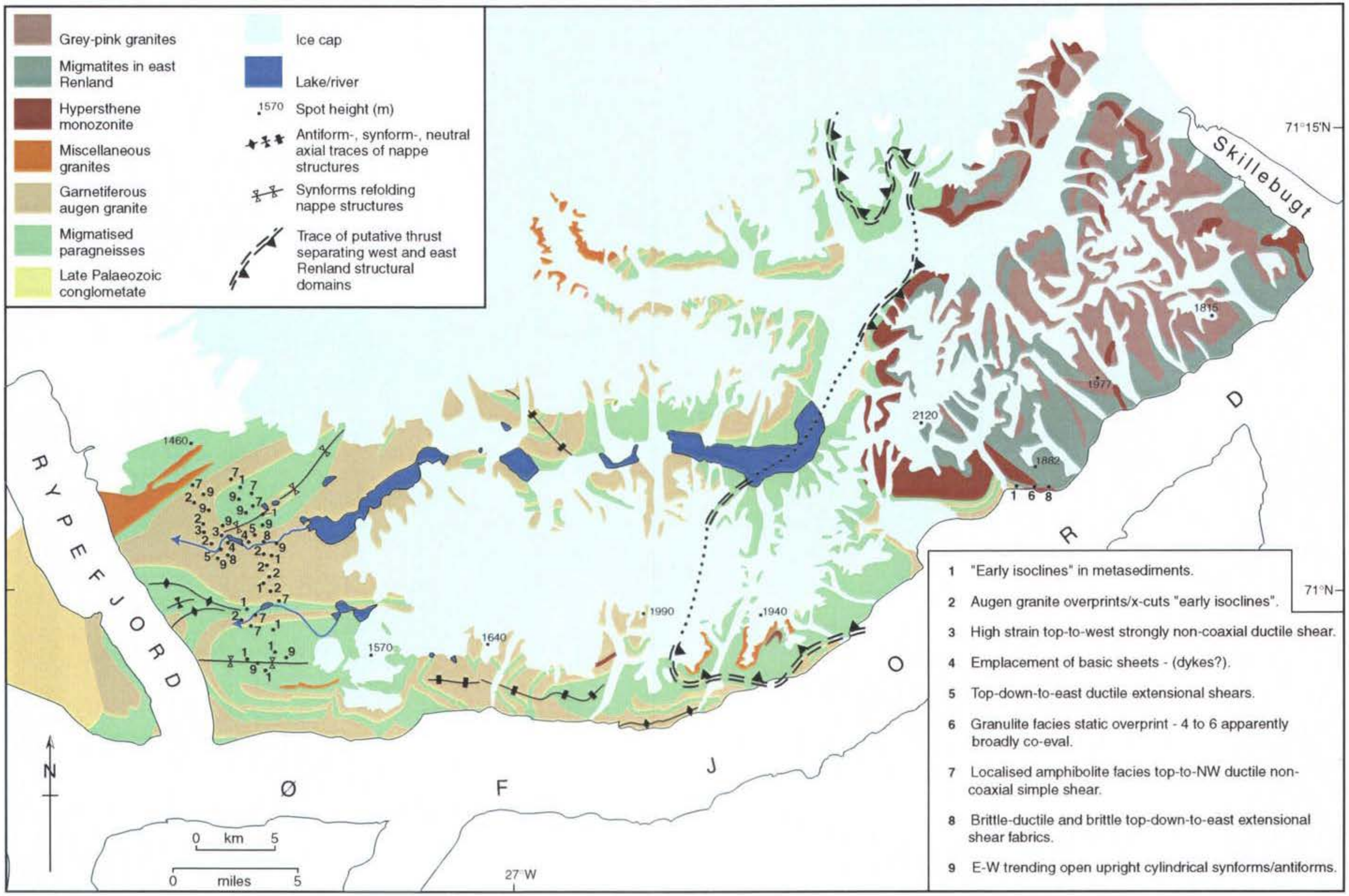
Review of the isotopic data and objectives of the Renland project

In the southernmost exposures of the East Greenland Caledonides in the Scoresby Sund region, augen granites in the Stauning Alper – Gåsefjord migmatite and granite zone have yielded bulk zircon upper concordia intercepts of 900–1000 Ma and lower concordia intercept ages of *c.* 440 Ma (Steiger *et al.* 1979). Steiger *et al.* interpreted the 900–1000 Ma intercept ages as the time of zircon growth when the granite magmas were emplaced and 440 Ma as the time of Caledonian disturbance. The more recent SHRIMP studies further north were carried out on a widespread suite of augen granite intrusions, which have yielded presumed intrusion ages of ~930 Ma (Kalsbeek *et al.* 1993; Thrane *et al.* 1999), and also on metasedimentary rocks presumed equivalent to the Krummedal supracrustal sequence, where new zircon growth indicates a significant metamorphic event at ~930–950 Ma (Strachan *et al.* 1995; Thrane *et al.* 1999). Thus there would appear to be evidence for 900–1000 Ma thermal event(s) throughout a large portion of the crystalline rocks exposed beneath the Neoproterozoic sequences (Eleonore Bay Supergroup) of the East Greenland Caledonides. However, there is less certainty as to whether the 900–1000 Ma event was simply thermal (e.g. in response to underplating) or whether there was (orogenic?) deformation associated with it.

Steiger *et al.* (1979) reported a Rb-Sr isochron age of 475±14 Ma (one point omitted and then apparently all within error) for a thick sheet of hypersthene monzonite cutting previously deformed rocks in eastern Renland. *If* this age, and the assigned error, are correct, then that would be evidence for pre- *c.* 475 Ma deformation which could be construed to have been associated with a 900–1000 Ma thermal event in the country rocks to the monzonite. However, at this juncture it should be noted that with more comprehensive error analysis (program ISOPLOT, Ludwig 1997) the same data yields a model 1 solution of 475± 29 Ma (MSWD = 1.05). Thus it is entirely feasible that the monzonite could be indistinguishable in age from most other Caledonian granitoids in East Greenland which have ages of 430–440 Ma.

Detailed field studies in Renland (Chadwick 1975) noted that presumed Krummedal supracrustal sequence metasediments and "interlayered" augen granites were deformed prior to upper amphibolite/granulite facies metamorphism and intrusion of "Caledonian" monzonites. This represented a further possibility that there was evidence in this area for pre-Caledonian 900–1000 Ma deformation. In the course of this new investigation, critical relationships were examined during 12 days field work in south-west Renland combined with some helicopter reconnaisance work, mainly along Øfjord and in south-east Renland.

Figure 2. Geological map of south Renland, modified after Chadwick (1975), to show localities (numbered on map) where the detailed field relations discussed in this report can be examine at outcrop. The thrust believed to separate western and eastern parts of the region is discussed further in the text. Key to numbered localities inset below right.



Use of Chadwick's detailed descriptions and his accurate mapping of the region (Chadwick 1975) proved invaluable in making the most of a short field season aimed at a review of the chronology of structural, metamorphic and plutonic events. Samples have been collected from key localities for age determination and geochemical analysis as well as detailed fabric analysis.

The following specific objectives have been addressed:

- Did some rocks in the Caledonian orogen suffer deformation associated with 900–1000 Ma thermal events?
- Are the metasediments of southern Renland the same general age and provenance as the Krummedal sequence farther west and north in the orogen?
- To obtain an accurate age on the augen granites which Steiger *et al.* (1979) proposed were intruded between 900 and 1000 Ma ago.
- To obtain an accurate age for the "post-kinematic" high grade metamorphism described by Chadwick (1975).
- To produce a detailed relative sequence of tectonic and thermal events in Renland in order to compare and contrast with events known farther north in the Kong Oscar Fjord region. Identification of the relative importance of compressional and extensional tectonics during the period 1000–400 Ma is important in this respect.
- To examine the possibility of a major tectonic discontinuity between the migmatites of south-eastern Renland and the augen granite and paragneiss terrain of south-western Renland.

This report concentrates on the latter two of these objectives. We detail here a set of nine distinct events, illustrated by examples from "key" localities. A selection of such localities is shown on the detailed geological map in Figure 2 (modified after the commendable Plate 1, Chadwick 1975); complementary field photographs illustrating the main aspects of this sequence of events are presented here in Plate 1. These observations provide, we believe, a firm relative chronology for the tectonothermal evolution of Renland. Geochronological work which aims to place absolute constraints on the relative chronology is in hand (APN) and will be reported upon fully elsewhere; brief statements on some of the provisional findings are incorporated below.

The sequence of tectono-thermal events in southern Renland

The following relative chronology of events can be recognised:-

1. Deformation of presumed Krummedal type metasediments

Intrafolial, often rootless, isoclinal folds (see Plate 1.01) are recognised at many locations throughout the metasedimentary belts (see Fig. 2). Only one phase of deformation is evident prior to event 2. Fold axes in general now plunge gently to moderately east, or east-north-east (see further below).

2. Formation of the augen granite

Although seen to be locally cross-cutting, the augen granites are essentially the product of *in situ* partial melting of metasedimentary rocks; many rafts and vestigial remnants of especially psammitic lithologies remain in parts and wispy biotitic schlieren are common. Granite sheets mimick large fold structures on the Øfjord cliffs and generally tend to follow gross, and sometimes fine-scale, lithological layering, all of which has constrained generation of the granitic melt. Locally however, the granitic melts "burst across" the pre-existing fold structures and even the thinnest of augen granite sheets were never observed to be folded in the style of the isoclines noted under event 1 above. The nappe-scale folds of Chadwick (1975) are therefore believed to pre-date granite generation, being the regional scale expression of the rootless isoclines of event 1. It can generally be seen that where outcrop scale fold structures have been overwhelmed or overprinted by granite generation (Plate1.02 & 1.03) the former are often more open, less attenuated structures than ever occur in those segments of the metasedimentary belts where little or no augen granite was generated (cf. Plate 1.01); see also below under event 3.

3. Deformation (top-to-west) of the augen granite

The augen granite frequently carries a variably penetrative, strongly partitioned, fabric (cf. Plate 1.04 & 1.05) which varies from an intense non-coaxial simple shear (LS fabric) with clear top-to-west sense of shear to a simple coaxial flattening fabric. There is clear partitioning of strain; high strain shear fabrics are relatively uncommon in any observed section. Never-the-less this deformation is probably responsible for much of the attenuation of the folds in the more siliceous refractory metasediments interlayered with the augen granite belts. Fold axes in the paragneisses and lineations (L_r) in the deformed augen granite are typically co-linear, and all cluster around a gentle 15–20° plunge to the east or east-north-east (cf. Chadwick, 1975). Pre-granite fold axes are probably largely transposed in L_r.

4. Emplacement of basic sheets

Metre-scale basic intrusions are recognised at a number of locations, with the clearest original relationships preserved where emplacement occurs within the augen granite (Plate 1.06). The basic sheets are clearly seen to be cross-cutting with respect to the high strain top-to-west fabric in the augen granite. Rare basic intrusions emplaced into the paragneisses, and now present as disrupted boudinaged pods at metre scale, were probably emplaced prior to these intrusions and before the top-to-west shearing in event three above.

5. Top-down-to-east ductile extensional shear zones

Extensional shear zones (Plate 1.07) are widespread in the central area of augen granite, typically each a few centimetres to tens of centimetres wide, traceable over a distance of a few metres to tens of metres and with maximum displacements of the order of a few metres. The basic sheets are rotated into these shear zones along with the augen granite fabric; on occasion *en echelon* basic bodies exhibit top-to-the-east shear fabrics in zones where the adjacent top-to-west augen granite fabric shows reactivation in the same top-to-east sense.

6. Granulite (or transitional amphibolite/granulite) facies static overprint

High grade metamorphism produced garnetiferous melt segregations in the augen granite (Plate 1.05) and semipelitic (mainly) paragneisses along with localised concentrations of garnetiferous leucogranite ("alaskite" – c.f. Chadwick, 1975). Like development of the augen granite, formation of these high grade segregations is clearly lithologically controlled (Plate 1.08), with segregations mimicking pre-existing fold structures as well as cross-cutting earlier formed fabrics as melt volumes increase (Plate 1.09). Metamorphic orthopyroxene is produced in rare basic lithologies. The garnetiferous segregations are often seen to cross-cut the extensional shear fabric (Plate 1.07) but are also seen to be rotated into some examples of these shear zones. Garnets overgrow the rotating, attenuating neosome and in some cases become lenticular in outline indicating that extensional shearing and the high grade metamorphic overprint (and emplacement of the basic sheets?) are to some extent contemporaneous. Elsewhere in the granites and paragneisses and away from the extensional shear zones, this high grade event appears to produce granoblastic textures which tend to wipe out earlier fabric details in the metasediments; much of the recrystallisation appears therefore in the rocks of south-west Renland as a static overprint.

7. Localised zones of amphibolite facies, top-to-north-west ductile shear

At a number of locations, and at a variety of structural levels, the granulite facies assemblages are retrogressed to amphibolite facies assemblages (muscovite-biotite dominated) in schistose high strain zones (Plate 1.10 & 1.11). A second lineation is commonly developed in these rocks, typically more steeply plunging (*c.* 45–50°) to the east than the fabric associated with the top-to-west augen granite fabrics and earlier fold hinges. This second lineation has been identified as developing within zones of non-coaxial simple shear in high strain sectors where transport was towards the north-west, rather than west, when late Caledonian folding (see under 9) is taken into account.

Some of the best examples of the fabric are located at the highest structural levels preserved in the northerly of the two synformal folds recognised by Chadwick (1975; see Fig. 2), but similar fabrics occur at structurally deeper levels on the north-western margin of the augen granite domain. J.D. Friderichsen (fig. 1 & discussion (p. 27) in Chadwick 1975) recorded a possible thrust contact with rocks of basement aspect in this region.

In regional terms the eastern part of Renland comprises augen granites and paragneisses observed and confirmed to be of very similar aspect to the rocks of the western part of Renland, except in that the high grade metamorphic assemblages in the former are retrogressed to amphibolite facies as well as having experienced Caledonian migmatisation and granite emplacement. A high strain zone was recognised (Fig. 2) in reconnaissance flights along Øfjord which may define the boundary between the two domains, acting as a thrust to place the rocks of south-eastern Renland and their retrogressed granulite facies rocks tectonically over the rocks of south-western Renland. A discordance in the structural form lines marked by Chadwick (1975) on his Plate 1 marks the likely trace of this structure.

8. Brittle–ductile & brittle extensional (top-down-to-east) shear zones

In many respects these later shear zones (Plate 1.12) are similar to the extensional shears closely linked with the granulite facies overprint. However, although they are often seen to reactivate the pre-existing ductile shears (Plate 1.07), they always deform the garnetiferous segregations, have a more brittle style, and may consist largely of dark greenish-black cataclasite seams reworking earlier schistose fabrics. Stable garnet is never apparently present, muscovite and biotite are typical. These structures are often associated with granite pegmatite and/or fine- to medium-grained grey granite veins injected along the shear zones. Similar, coplanar veins also occur in rocks where no extensional displacement is evident. Where reactivation of pre-existing ductile shears occurs the brittle behaviour is confined to a narrow discrete zone in the centre of the earlier shear zone.

The relative age of this later extensional shearing with respect to the NW-directed thrusting has not been established with certainty in the field. To regard both events as Caledonian would clearly have parallels with events farther north in East Greenland, where Caledonian thrusting pre-dates extensional collapse (e.g. Leslie & Higgins & 1999; Hartz & Andresen 1995).

9. E–W trending upright open folds

East–west trending open folds deform all of the above tectono-thermal elements and are regarded as late-Caledonian. It would be with regard to this event only that we would recommend a minor modification to Chadwick's (1975) map, in that the region of augen granite lying between the two synformal structures in south-western Renland clearly constitutes the complimentary and intervening antiform (see Fig. 2). These structures, along with the late N–S trendings "warps" recognised by Chadwick (1975) are the only folds observed to deform the augen granite sheets.

Discussion

We have produced a firm relative chronology for a sequence of folding, thrusting, extensional, metamorphic and magmatic events, as well as providing evidence on the origin of the abundant augen granites of western Renland. Much of our work is essentially in accord with that reported by Chadwick (1975); however, with the benefit of his earlier studies we have been able to add more depth and understanding to structures observed.

At this stage, commonly held views would favour that the augen granites were formed, and that the high grade metamorphism occurred, in the interval between 900–1000 Ma. Furthermore, it would be likely that Caledonian activity in western Renland is restricted to relatively low grade top-to-the-NW shear zones followed possibly by easterly directed extensional collapse and certainly by open, upright E–W trending cylindrical folds. Support for the age of the augen granites as *c.* 900–1000 Ma comes from two fronts: (a) broadly similar but non-granulite facies augen granites that occur further north in the East Greenland Caledonides (between Andreé Land and Bartholin Nunatak; 73°–74°30'N) have been dated at ~930 Ma (Kalsbeek *et al.* 1993, in press; Thrane *et al.* 1999), and; (b) Steiger *et al.* (1997) suggested that the 900–1000 Ma upper concordia intercept ages for zircons in the Renland augen granites gives the magmatic age. With respect to the former, it should be remembered that augen granites are a rather common lithology and similar rocks of *different* age might be expected in such a large area. There is no conclusive evidence that the ~930 Ma augen granites in western and central Andrée land post-date any episode of folding as is so clearly demonstrated by the augen granites in southern Renland. In the second case it should be remembered that all the measured bulk zircon aliquots from augen granites analysed by Steiger *et al.* (1979) have strongly discordant ages. Therefore, until detailed and full analysis becomes available from the new studies of within-crystal chronology, fully supported by grain imaging, and undertaken in Canberra in October 1999, it has by no means been certain that these granites are 900–1000 Ma old. The existing zircon data (could) support the interpretation that they were emplaced at *c.* 440 Ma but are rich in inherited zircons (they are, after all, low temperature melts derived from metasediments).

At this stage in the programme, our preliminary SHRIMP U/Pb zircon results do, in fact, demonstrate that the augen granites are part of the 900-1000 Ma old suite recognised elsewhere in East Greenland; full results and an evaluation of the data obtained on the augen granites, garnetiferous melt segregations, migmatites and other rock units will be published elsewhere. Thus, it seems clear that the events 1 to 9 documented above did indeed start as early as 900–1000 Ma. Full regional implications will only be resolved once the geochronology is completed. However, at this stage in the investigation, our current preferred model, when the geology of Renland is considered in the broader context of the East Greenland Caledonides, is that we have evidence for deformation prior to and during 900–1000 Ma thermal event(s), with Caledonian tectono-thermal events superimposed. Significant extensional tectonics in the interval between cannot be discounted.

References

Chadwick, B. 1975: the structure of south renland, Scoresby Sund – with special reference to the tectonothermal evolution of a southern internal part of the Caledonides of East-Greenland. Bulletin Grønlands Geologiske Undersøgelse **112**, 67pp. (also Meddelelser om Grønland **201**(2)).

Hansen, B.T. & Tembusch, H. 1979: Rb-Sr isochron ages from east Milne Land, Scoresby Sund, east Greenland. Rapport Grønlands Geologiske Undersøgelse **95**, 96–101.

Hartz, E. & Andresen, A. 1995: Caledonian sole thrust of central East Greenland: A crustal scale Devonian extensional detachment. Geology **23**, 637–640.

Henriksen, N. 1986: Descriptive text to geological map of Greenland 1:500,000, Scoresby Sund, sheet 12 – The regional geology of a segment of the Caledonian fold belt, adjacent Upper Palaeozoic – Mesozoic sediments of Jameson Land basin, and Tertiary volcanics, 27 pp. Copenhagen: Geological Survey of Greenland.

Henriksen, N. & Higgins, A.K. 1976: East Greenland Caledonian fold belt. In: Escher, A. & Watt, W.S. (eds): Geology of Greenland, 182–246. Copenhagen: Geological Survey of Greenland.

Higgins, A.K. 1988: The Krummedal supracrustal sequence in East Greenland. In: Winchester, J.A. (ed.) Later Proterozoic stratigraphy of the northern Atlantic regions, 86–96. Glasgow & London: Blackie and Son Ltd.

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

Kalsbeek, F., Thrane, K., Nutman, A.P. & Jepsen, H.F. in press: Late Mesoproterozoic metasedimentary and granitic rocks in the Kong Oscar Fjord region, East Greenland Caledonian fold belt: evidence for Grenvillian orogenesis? Journal of the Geological Society, London.

Leslie, A.G. & Higgins, A.K. 1999: On the Caledonian geology of Bartholin Land, Ole Rømer Land and adjacent nunataks, East Greenland. In: Higgins, A.K. & Frederiksen, K.S. (eds): Geology of East Greenland 72°–75°N), mainly Caledonian: preliminary reports from the 1998 expedition. Danmarks og Grønlands Geologiske Undersøgelse Rapport **1999/19**, 11–26.

Ludwig, K. 1997: Isoplot/Ex. Berkeley Geochronology Center, Publication **1**.

Steiger, R.H., Hansen, B.T., Schuler, C., Bär, M.T. & Henriksen, N. 1979: Polyorogenic-nature of the southern Caledonian fold belt in East Greenland. Journal of Geology **87**, 475–495.

Strachan, R.A., Nutman, A.P. & Friderichsen, J.D. 1995: SHRIMP U-Pb geochronology and metamorphic history of the Smallefjord sequence, NE Greenland Caledonides. Journal of the Geological Society, London **152**, 779–784

Thrane, K., Kinny, P.D. & Watt, G.R. 1999: Age relationships in the crystalline basement-complexes of the East Greenland Caledonides. In: Higgins, A.K. & Frederiksen, K.S. (eds): Geology of East Greenland 72°–75°N), mainly Caledonian: preliminary reports from the 1998 expedition. Danmarks og Grønlands Geologiske Undersøgelse Rapport **1999/19**, 43–58.

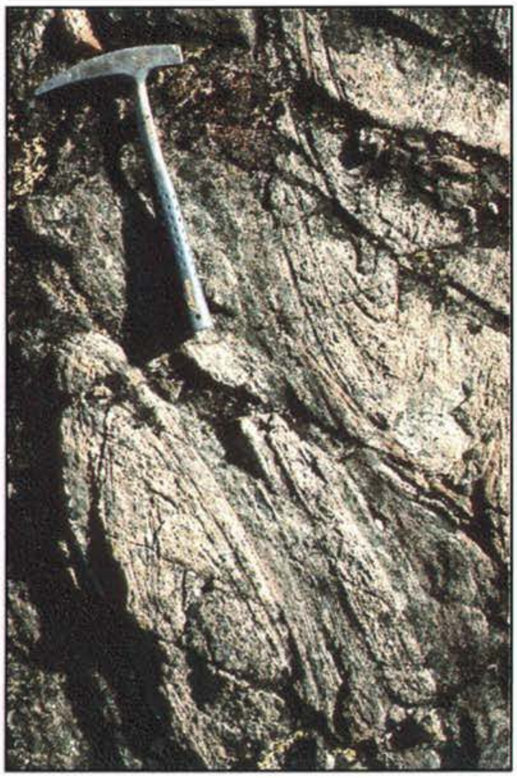


Plate 1.01 *Rootless isoclinal folds in psammitic paragneisses, hammer head to east.*

Plate 1.02 *Gross scale lithological banding and minor close to tight folds in metasediments overprinted by augen granite generation. Pale psammitic band on right, banded psammite/semipelite on left.*

Plate 1.03 *Relict folds of metasedimentary layering preserved in augen granite.*

Plate 1.04 *Typical foliated augen granite, K-feldspar megacrysts are more generally oblate and only strongly asymmetrical in partitioned zones of high non-coaxial strain.*

Plate 1.05 *Intense planar fabric in augen granite cross-cut by garnetiferous melt segregation during upper amphibolite/granulite facies overprint.*

Plate 1.06 *Typical example of the basic sheets emplaced into foliated augen granite.*

Plate 1.07 *Top-down-to-east extensional shear zone in augen granite, disrupted basic sheet in lower left. Central part of shear zone shows planar zone of discrete, more brittle reactivation with the same top-down-to-east sense.*

Plate 1.08 *Distribution of garnetiferous melt segregations constained by pre-existing folds of compositional layering in paragneisses.*

Plate 1.09 *Cross-cutting vein networks and irregular patches of garnetiferous leucogranite.*

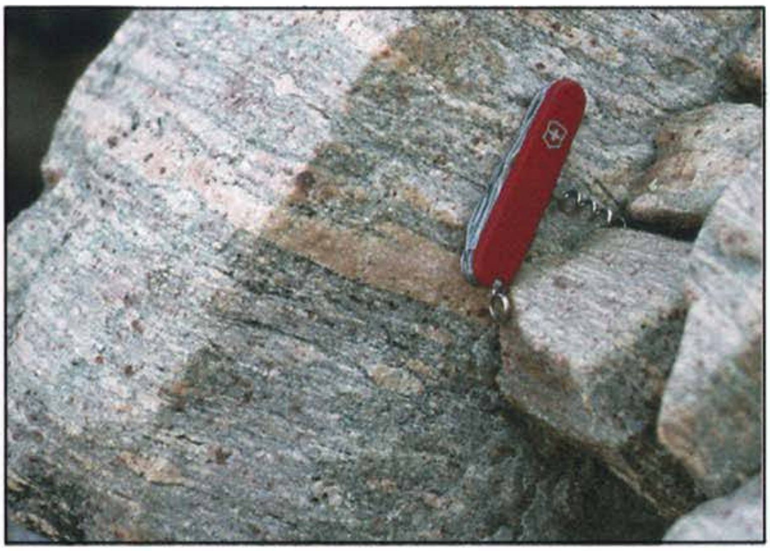


Plate 1.10 *Top-to-NW ductile shear fabric in foliated augen granite. Garnets in granulite facies segregations above penknife show retrogressive overgrowths of biotite.*

Plate 1.11 *Top-to-NW shearing of garnetifeous segregations showing lenticular streaked form of modified, partially retrogressed, garnets.*

Plate 1.12 *Top-down-to-east brittle shear zone in retrogressed amphibolite facies augen granite and paragneisses from east Renland. Illustrates seams of dark chloritic cataclasite in the shear plane. Camera case is 16 cm wide.*