Episodic tectono-thermal activity in the southern part of the East Greenland Caledonides

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Isotopic data from the Renland augen granites of the Scoresby Sund region (Figs 1, 2) provided some of the first convincing support for relicts of potentially Grenvillian tectono-thermal activity within the East Greenland Caledonides. In Renland, Chadwick (1975) showed the presence of major bodies of augen granite (Fig. 2) interpreted by Steiger *et al.* (1979), on the basis of Rb–Sr whole rock and U–Pb zircon age determinations, to have been emplaced about 1000 Ma ago.

Such pre-Caledonian tectono-thermal activity has recently been unambiguously confirmed by SHRIMP intra-grain zircon and monazite U–Pb geochronology studies farther north in East Greenland (Kalsbeek *et al.* 1993, in press; Strachan *et al.* 1995; Thrane *et al.* 1999; F. Kalsbeek & A.P. Nutman, unpublished data). Magmatic and thermal events of broadly Grenvillian age (930–900 Ma) are now known over a N–S distance in excess of 400 km in East Greenland. The significance of these pre-Caledonian ages is currently under debate, as are similar, although somewhat younger, ages and events in the northern and central Highlands of Scotland (Phillips *et al.* 1999), at this time probably only about 500 km south of the southernmost East Greenland Caledonides on the Laurentian margin (Cambridge Paleomap Services 1998). It has not been clear whether these pre-Caledonian events represent normal orogenic compression, rift-related extension or some other form of thermal activity.

The Geological Survey of Denmark and Greenland (Danmarks og Grønlands Geologiske Undersøgelse) has recently completed field work (1997–98) in the southern part of North-East Greenland (72°–75°N) with a view to compiling Sheet 11 of the Survey's 1:500 000 map series (Henriksen 1998, 1999). These new regional geological investigations have provided an improved understanding of the Caledonian history on this sector of the Laurentian margin of Iapetus, as well as of events associated with construction of the Neoproterozoic supercontinent Rodinia (Dalziel 1997). Caledonian reworking has, however, obscured Proterozoic tectono-thermal relationships in much of the southern part of the East Greenland Caledonides so that no unequivocal record of tectonic events has been recognised between deposition of the Mesoproterozoic Krummedal supracrustal succession (Higgins 1988) and the generation of *c.* 930 Ma old granites intruded into the metasediments.

Southern Renland was revisited in 1999 with the aim of establishing the relationship between the previously described orogenic deformation (Chadwick 1975) and the 900–1000 Ma magmatism (Steiger *et al.* 1979). Critical relationships were examined in south-west Renland augmented by some helicopter reconnaissance work, the latter mainly along Øfjord and in south-east Renland (Fig. 3). Detailed descriptions and accurate mapping of the region by Chadwick (1975) proved invaluable in making the most of a short field season. At the same time, new collections were made for SHRIMP isotopic studies aimed in particular at clarifying the sequence and timing of compressional and extensional events during the period *c.* 1100–430 Ma, prior to top-to-the-NW Caledonian thrusting associated with closure of Iapetus.

Caledonian regional tectonics

The southern part of the East Greenland Caledonian fold belt is characterised by N–S-trending belts of different character (Fig. 1), reflecting superimposition of different structural levels during north-westwards transport on major Caledonian thrust systems (Higgins & Leslie 1999). Windows through lower thrust units reveal foreland successions in parautochthonous settings within the marginal thin-skinned thrust belt; thick-skinned lower and upper thrust sheets overriding the foreland windows comprise allochthonous Palaeoproterozoic or older crystalline complexes overlain by Proterozoic to

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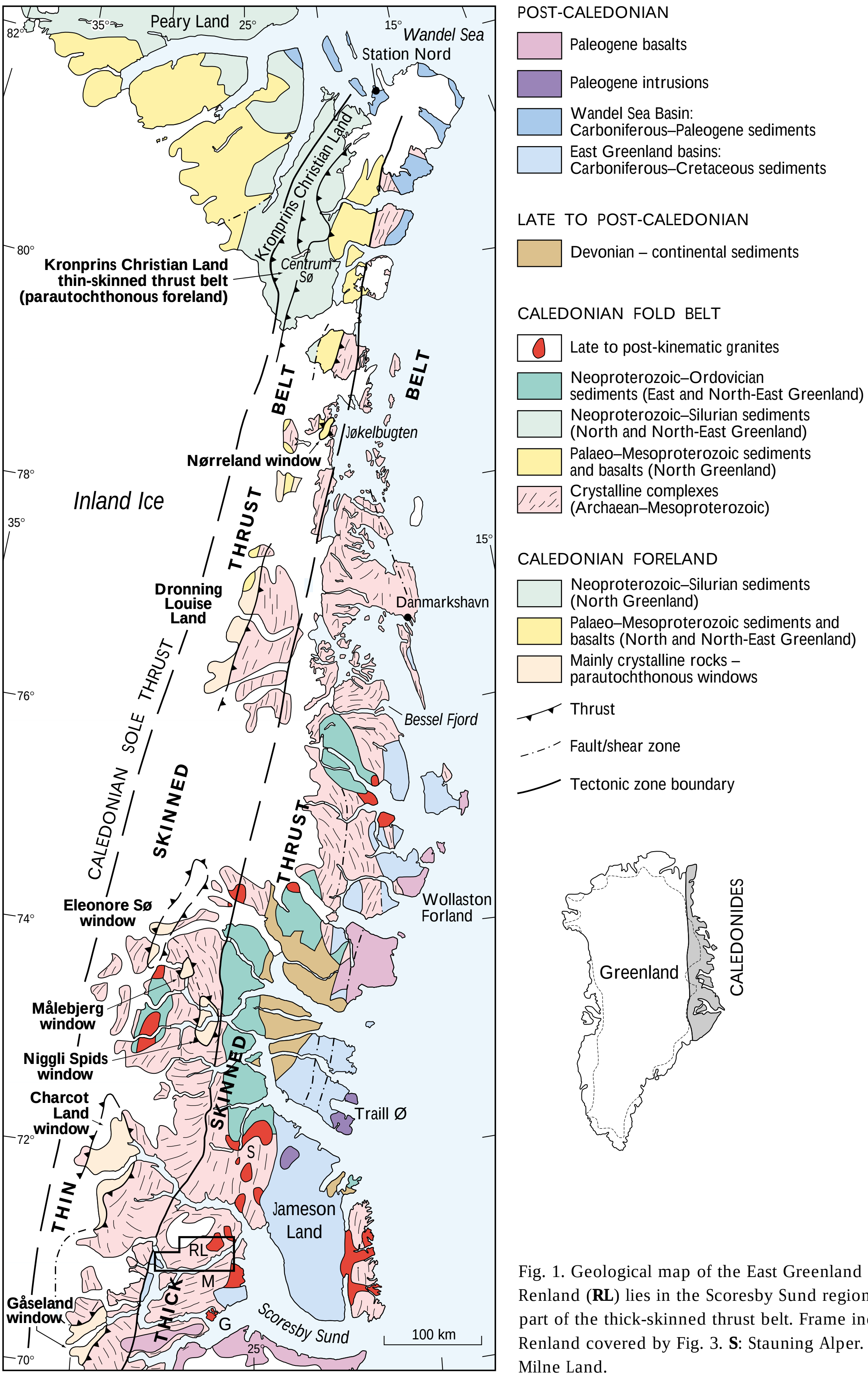
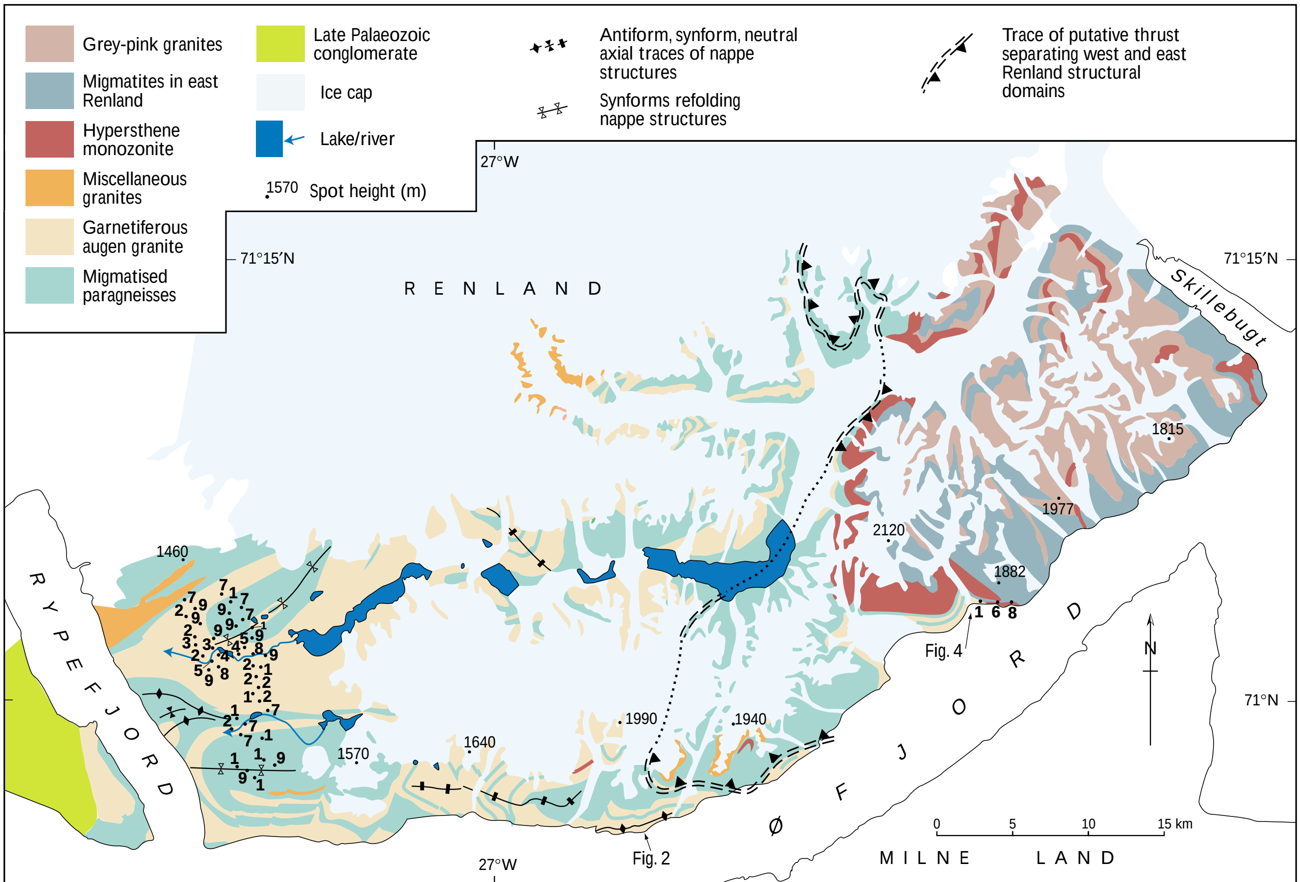


Fig. 1. Geological map of the East Greenland Caledonides. Renland (**RL**) lies in the Scoresby Sund region in the southern part of the thick-skinned thrust belt. Frame indicates the area of Renland covered by Fig. 3. **S**: Stauning Alper. **G**: Gåsefjord. **M**: Milne Land.

Fig. 2. Large-scale recumbent fold structures in paragneisses, Øfjord, southern Renland. All the thick white sheets are augen granite which mimic the earlier fold structure and are not, in fact, folded (see discussion in text). Highest summit about 1900 m above sea level; for location, see Fig. 3. Photo: Niels Henriksen.



1 “Early isoclines” in metasediments.

2 Augen granite overprints/cross-cuts “early isoclines”.

3 High-strain top-to-west strongly non-coaxial ductile shear.

4 Emplacement of basic sheets – (dykes?).

5 Top-down-to-east ductile extensional shears.

6 Granulite facies static overprint – events 4 to 6 apparently broadly coeval.

7 Localised amphibolite facies top-to-NW ductile non-coaxial simple shear.

8 Brittle-ductile and brittle top-down-to-east extensional shear fabrics.

9 E–W-trending open upright cylindrical synforms/antiforms.

Fig. 3. Geological map of southern Renland, modified after Chadwick (1975), to show localities where the detailed field relationships of the nine tectono-thermal events discussed in this report can be examined in outcrop (**numbers 1–9** on map). The thrust believed to separate western and eastern parts of the region is discussed further in the text. The tectono-thermal sequence of events is summarised below the map from oldest (1) to youngest (9). Locations of Figs 2 and 4 are shown.

Fig. 4. Peak 1882 m viewed along Øfjord from the south-west and showing the dark hypersthene monzonite intrusion on the lower cliffs. Note pale augen granite and darker paragneiss layers on the cliff in the left foreground. For location, see Fig. 3.

Lower Palaeozoic successions. In the lower thrust units the Mesoproterozoic Krummedal supracrustal sequence has generally escaped granite generation and migmatisation, while Neoproterozoic or younger successions are only locally preserved. In the upper thrust units Mesoproterozoic Krummedal succession rocks are characterised by extensive migmatisation and emplacement of numerous pre- and syn-Caledonian granites; these lie structurally beneath the Neoproterozoic Eleonore Bay Supergroup, Tillite Group and Lower Palaeozoic successions which form the upper levels of the thick-skinned thrust units.

In the Scoresby Sund region (Fig. 1), a 75–100 km wide zone of thick-skinned upper thrust units comprise migmatites and granites which have been traced from the northern Stauning Alper over a distance in excess of 200 km through Renland to Gåsefjord. This zone has for some time been considered to be an amalgam of two major orogenic cycles, both involving migmatisation, deformation and plutonism (e.g. Henriksen & Higgins 1976; Henriksen 1986). During the earlier cycle, sheets of augen granite were intruded into metasediments correlated with the Mesoproterozoic Krummedal supracrustal sequence. Chadwick (1975) believed that both these units, which are well exposed in the deglaciated terrain of south-west Renland, were folded into major recumbent nappe structures.

Both the metasedimentary successions and the augen granites are strongly sheared in places, but have subsequently been sporadically intruded by what now appear as metabasic sheets and pods containing metamorphic orthopyroxene. The metasediments and augen granites are cross-cut by patchy, vein-like or lit-par-lit garnetiferous neosome produced (with the orthopyroxene) during high temperature granulite facies metamorphism. Syn-kinematic and post-kinematic intrusions are widespread in southern Renland (Fig. 3), the oldest of which is a prominent lopolithic hypersthene monzonite intrusion cross-cutting strongly deformed and migmatised gneisses and augen granites (Fig. 4), but itself affected by later migmatisation and granite injection. The monzonite, believed to have been injected at 475 ± 14 Ma (Steiger *et al.* 1979), apparently provided unequivocal evidence for late Proterozoic pre-Caledonian deformation given its cross-cutting relationships with the reported nappe-scale folds of the *c.* 1000 Ma augen granites and Krummedal metasediments (Chadwick 1975).

Younger migmatisation and granites gave ages from 430–400 Ma (Hansen & Tembusch 1979) implying a broad span of Ordovician and Silurian tectono-thermal activity during the Caledonian orogeny in this sector of East Greenland.

The sequence of tectono-thermal events in southern Renland

The geological map of southern Renland shown in Fig. 3 is modified after Chadwick (1975, plate 1). A firm relative chronology of nine distinct events has been established for the tectono-thermal evolution; numbers 1 to 9 on the geological map refer to locations where critical relationships pertaining to the nine events may be observed. The sequence of events is summarised in the inset below the map and the nine events are described below.

1. *Intrafolial, often rootless, isoclinal folds* are recognised at many locations in pelitic, semipelitic and psammitic metasedimentary gneisses. The axial planes of these structures are coincident with the dominant foliation of the metasediments, essentially a transposed lithological layering. Preferred mineral lineations are rather weakly developed and for the most part the paragneisses display recrystallised granoblastic microtextures so that only geometric evidence for a single phase of folding survives in outcrop. Folding does, however, clearly pre-date generation of the augen granites.

2. *Augen granite generation* is essentially the product of *in situ* partial melting of the deformed metasedimentary rocks; many rafts and vestigial remnants of especially the psammitic lithologies remain in parts and wispy biotitic schlieren are common. Several examples of these metasedimentary relicts preserve outcrop-scale fold structures which have been overwhelmed or overprinted by *in situ* generation of granitic melt. Although the augen granite often carries a fabric relating to the ductile shear described under event 3 below, that fabric is never seen to be geometrically or dynamically linked to folds of the augen granite layers; even the thinnest augen granite sheets are not folded in the isoclinal style of the paragneisses. Granite sheets instead mimic 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 are cross-cutting and 'burst across' pre-existing fold structures, or simply occur as irregular patches. The nappe-scale folds of Chadwick (1975; Fig. 2) must pre-date granite generation, and are the regional expression of the outcrop-scale fold structures in the metasedimentary belts.

3. *Heterogeneous non-coaxial ductile shear* post-dates granite crystallisation. The resulting fabric is strongly partitioned, varying from an intense L-S fabric with clear top-to-west sense of shear to a simple coaxial flattening fabric. Fold axes in the paragneisses and lineations in the augen granite are typically colinear and all cluster around a gentle 15–20° plunge to the east or east-north-east, as observed by Chadwick (1975). Folds preserved in metasedimentary relicts within the granite are typically less attenuated, close to tight rather than isoclinal, and with more variable orientations than occur in those sheared metasedimentary belts where little or no augen granite has been generated. Pre-granite fold axes are largely transposed in the superimposed top-to-the-west shearing event.

4. *Metre-scale basic intrusions* are recognised at a number of locations in the augen granite and clearly cross-cut the ductile shear fabric. Rare basic pods within the paragneisses, which now appear as disrupted metre-scale boudins, must indicate an earlier suite of intrusions since they appear to be disrupted within the main regional foliation and so were emplaced prior to top-to-the-west ductile shearing; intrusion prior to folding is equally possible, as field relationships are insufficiently clear.

5. *Ductile extensional shear zones* deform the basic sheets in the augen granite; each shear zone is typically several to tens of centimetres wide, traceable over a distance of metres to tens of metres and with top-down-to-the-east displacements of the order of a few metres at most. The sheets are rotated into the shear zones along with the augen granite fabric.

6. *Granulite facies metamorphism* produced garnetiferous melt segregations in the augen granite (Fig. 5) and in semipelitic components of the paragneisses, together with localised concentrations of garnetiferous leucogranite ('alaskite' – cf. Chadwick 1975). Like development of the augen granite, formation of these high-grade segregations is clearly lithologically controlled (Fig. 6), with the new segregations faithfully mimicking the recrystallised pre-existing fold

structures, then cross-cutting earlier formed fabrics as melt volumes increase. Metamorphic orthopyroxene is produced in the rare basic lithologies. In augen granites and paragneisses with little or no development of garnetiferous segregations, this high-grade event produces the granoblastic textures which obliterate earlier fabric details in the folded metasediments; much of the recrystallisation appears therefore as a static 'overprint' rather than as the product of tectonic thickening during horizontal shortening.

The garnetiferous segregations often simply cross-cut the extensional shear fabric but are also rotated into some shear zones when garnets become lenticular in outline. These relationships suggest that more than one discrete episode of extensional shearing may have occurred during high heat flow conditions or, more likely perhaps, that extensional shearing and the high-grade metamorphic overprint (and intrusion of the basic sheets?) are to some extent contemporaneous. Some extensional shear zones have clearly experienced more brittle reactivation since cm-scale granite veins (which show no evidence of development of granulite facies segregations) are emplaced along the axes of the shear zones.

7. *Retrogression to amphibolite facies* occurs at a variety of structural levels in schistose, muscovite-biotite dominated, high-strain zones within the granulites in southern Renland. A second lineation is 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 and, when

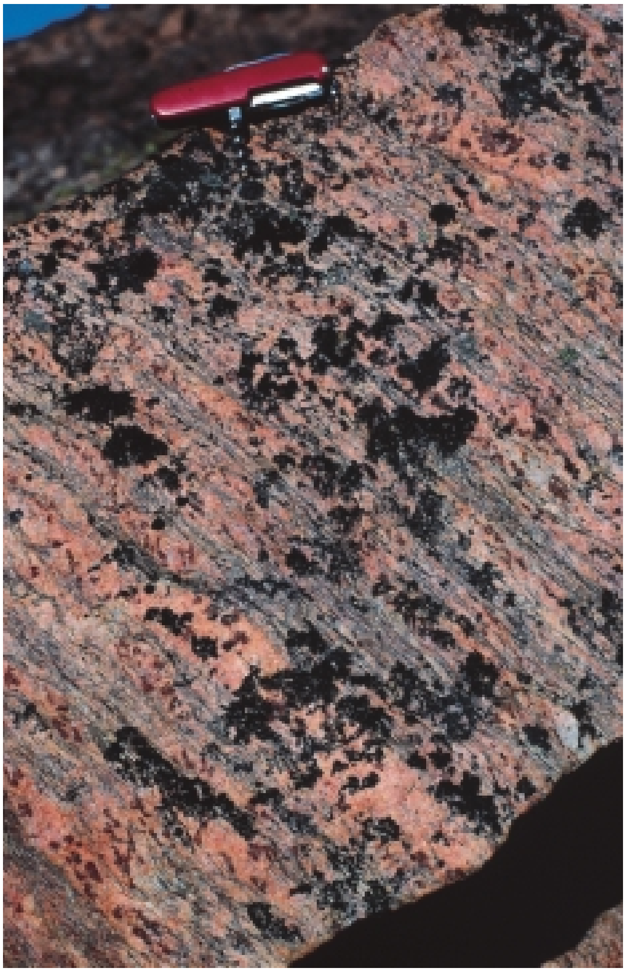


Fig. 5. Intense planar top-to-the-west shear fabric in augen granite cross-cut by garnetiferous melt segregation during static high temperature granulite facies overprint, south-west Renland. Penknife is 10 cm long.

Fig. 6. Distribution of high temperature granulite facies garnetiferous melt segregations constrained by pre-existing folds of compositional layering in the paragneisses, south-west Renland. Pencil for scale.

later folding is taken into account, records transport that is top-to-the-NW, rather than west, during non-coaxial ductile shear. Some of the best examples of this fabric are located at the highest structural levels preserved in the northerly of the two open synformal folds (Fig. 3) recognised by Chadwick (1975) in south-west Renland, but similar fabrics occur at structurally deeper levels on the north-western margin of the augen granite domain where J.D. Friderichsen (in Chadwick 1975, fig. 1 and discussion, p. 27) recorded a possible thrust contact with rocks of basement aspect farther to the north-west.

South-eastern Renland comprises augen granites and paragneisses of very similar aspect to the rocks in the south-western part, except that the originally high-grade metamorphic assemblages in the former appear more pervasively retrogressed to amphibolite facies as well as having experienced Caledonian migmatisation and granite emplacement. In reconnaissance flights along Øfjord, a high strain zone has been identified which may define the boundary between the two domains (Fig. 3), with the retrogressed granulite facies rocks of south-eastern Renland thrust over stable granulite facies rocks in south-western Renland. Structural discordance had already been recognised by Chadwick (1975) along the likely trace of this structure.

8. *Brittle-ductile and brittle-extensional (top-down-to-east) shear zones* cross-cut the migmatites and granites. While geometrically similar to the extensional shears closely linked with the granulite facies overprint, these new structures are often observed to reactivate the pre-existing ductile shears, deform the now retrogressed high-grade garnetiferous segregations, have a more brittle style, and may consist largely of dark greenish-black cataclasite seams reworking earlier schistose fabrics. North-west directed Caledonian thrusting followed by extension has clear parallels with events farther north in East Greenland, where Caledonian thrusting predates extensional collapse (e.g. Hartz & Andresen 1995; Leslie & Higgins 1999).

9. *East–west-trending open upright folds* deform all of the earlier structures with the possible exception of the shear zones of event 8. These folds, together with the late N–S-trending 'warps' recognised by Chadwick (1975) as late Caledonian, are the only structures observed to deform the augen granite sheets.

Discussion

Field relationships in southern Renland provide a firm relative chronology for an episodic sequence of folding, thrusting, extensional, metamorphic and magmatic events, as well as providing evidence for the origin of the abundant augen granites. Preliminary SHRIMP U–Pb zircon and monazite results based on our new collections demonstrate that the augen granites are *c.* 910 Ma old (Nutman, provisional SHRIMP data) and thus part of the *c.* 930 Ma suite recognised elsewhere in East Greenland (Kalsbeek *et al.* 1993; Strachan *et al.* 1995; Thrane *et al.* 1999); the hypersthene monzonite sheet was emplaced between 430 and 420 Ma, significantly later than proposed by Steiger *et al.* (1979). Full results and an evaluation of the data obtained will be published elsewhere.

Metasediments of the Krummedal supracrustal sequence in south-western Renland record an episode of intense ductile deformation and regional nappe-scale folds. Consequent crustal thickening resulted in the *in situ* generation of augen granites with S-type chemistry (F. Kalsbeek, personal communication 2000) at around 910 Ma ago. Subsequent top-to-the-west ductile shearing was responsible for deforming the augen granite and pervasive transposition and attenuation of earlier folds in the metasediments; crustal thickening, granite generation and shearing were all closely linked around 900 Ma and record a collisional orogenic sequence.

These observations suggest that late Proterozoic Grenvillian construction of Rodinia (Dalziel 1997) was still taking place around 900 Ma ago in the East Greenland sector, clearly somewhat later than the 1300 to 1100 Ma tectono-thermal activity ascribed to the Grenvillian orogeny farther south-west in the United States and Canada. Grenvillian orogenic deformation, magmatism and metamorphism must now be given consideration when assessing the complex record of events preserved farther north in the East Greenland Caledonides. Approximately colinear transport directions during non-coaxial ductile shearing at *c.* 900 Ma (top-to-the-west) soon after augen granite generation, and much younger, pervasive top-to-the-NW Caledonian displacements some 470 Ma later, may do much to obscure the identification of the earlier orogenic episode on purely structural geometric grounds in much of the East Greenland Caledonides. Nevertheless, the widespread occurrence of 930–900 Ma magmatic and metamorphic events implies that the orogenic events recognised in Renland will have been much more widespread throughout the region.

I-type magmatism in Renland and nearby Milne Land (Henriksen 1986; F. Kalsbeek, personal communication

2000) in the interval 430–420 Ma ago (Nutman, provisional SHRIMP data) is spatially and temporally associated with high temperature granulite facies anatexis before the onset of top-to-the-NW Caledonian thrusting in the Scoresby Sund region. These lower parts of the upper thrust units in the Caledonian nappe stack (Higgins & Leslie 1999) record contemporaneous high temperature melting, ductile extensional shearing and I-type magmatism and suggest that westward closure of Iapetus had been initiated by this time. Caledonian events on the East Greenland margin will have included at least one episode of subduction-related high heat flow and magmatism following on from events on the Scandinavian margin of Baltica (Stephens & Gee 1989).

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