Metasedimentary rocks, intrusions and deformation history in the south-east part of the c. 1800 Ma Ketilidian orogen, South Greenland: Project SUPRASYD 1996

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The south-east part of the *c.* 1800 Ma Ketilidian orogen in South Greenland (Allaart, 1976) is dominated by strongly deformed and variably migmatised metasedimentary rocks known as the 'Psammite and Pelite Zones' (Chadwick & Garde, 1996); the sediments were mainly derived from the evolving Julianehåb batholith which dominates the central part of the orogen. The main purpose of the present contribution is to outline the deformational history of the Psammite Zone in the region between Lindenow Fjord and Kangerluluk (Fig. 2), investigated in 1994 and 1996 as part of the SUPRASYD project (Garde & Schønwandt, 1995 and references therein; Chadwick *et al.*, in press).

The Lindenow Fjord region has high alpine relief and extensive ice and glacier cover, and the fjords are regularly blocked by sea ice. Early studies of this part of the orogen were by boat reconnaissance (Andrews *et al.*, 1971, 1973); extensive helicopter support in the summers of 1992 and 1994 made access to the inner fjord regions and nunataks possible for the first time. A preliminary geological map covering part of the area between Lindenow Fjord and Kangerluluk was published by Swager *et al.* (1995). Hamilton *et al.* (1996) have addressed the timing of sedimentation and deformation in the Psammite Zone by means of precise zircon U-Pb geochronology. However, major problems regarding the correlation of individual deformational events and their relationship with the evolution of the Julianehåb batholith were not resolved until the field work in 1996.

The SUPRASYD field party in 1996 (Fig. 1) was based at the telestation of Prins Christian Sund some 50 km south of the working area (Fig. 2). In addition to base camp personnel, helicopter crew and the four authors, the party consisted of five geologists and M.Sc. students studying mafic igneous rocks and their mineralisation in selected areas (Stendal *et al.*, 1997), and a geologist investigating rust zones and areas with known gold anomalies.

Fig. 1. The SUPRASYD field party in 1996 at the small quay below the telestation at Prins Christian Sund. Photo: Anne Vibeke Leth.

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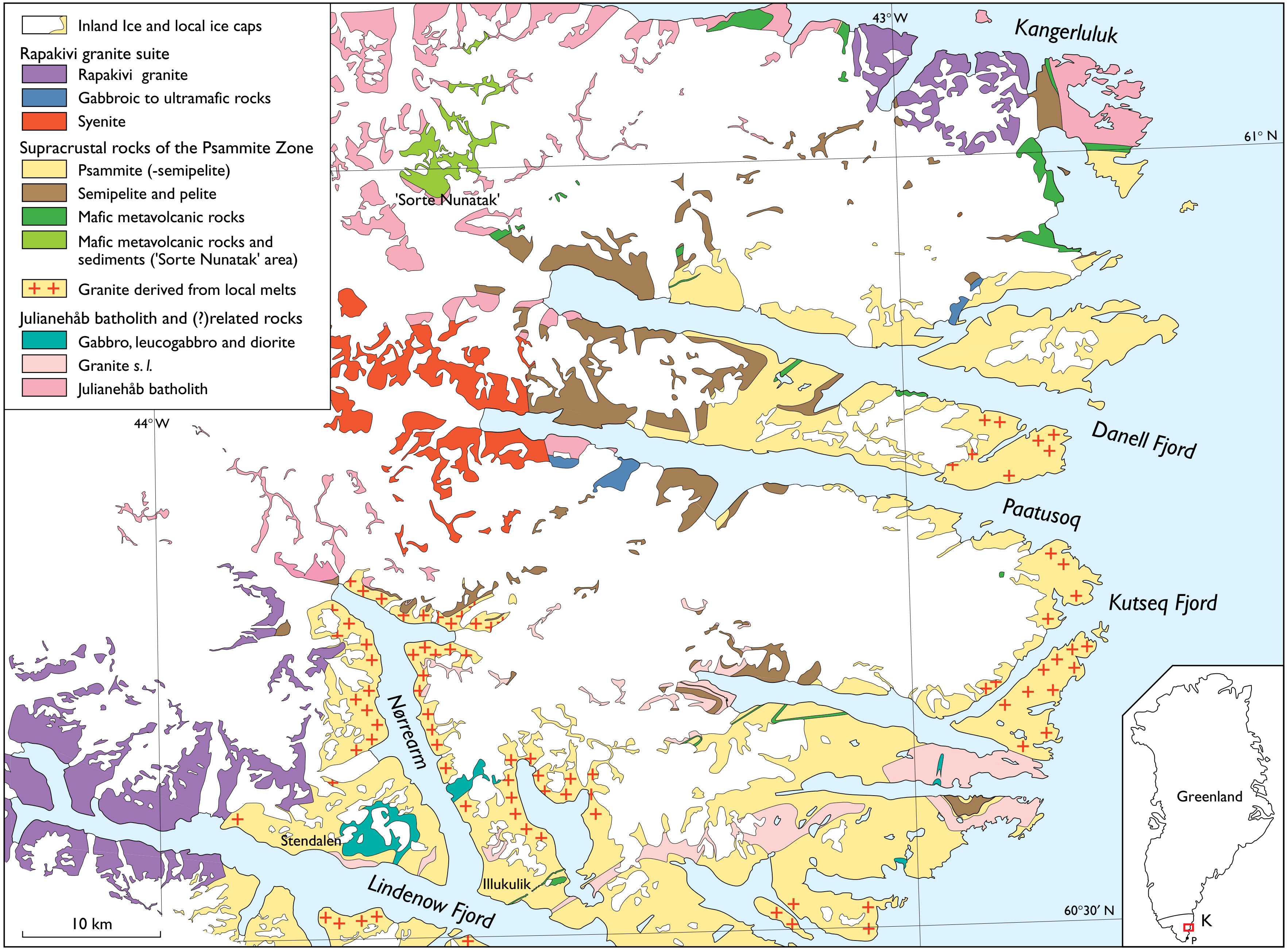

Fig. 2. Simplified geological map showing the Psammite Zone of the Ketilidian orogen between Lindenow Fjord and Kangerluluk. On inset map: K: Ketilidian orogen, P: the telesta-

Fig. 3. Upper limb of major recumbent F3 fold on the north coast of Lindenow Fjord, west of Nørrearm; the hinge zone is visible near sea level (arrowed). The cliff is *c.* 1000 m high. View looking north across Lindenow Fjord.

Metasedimentary rocks

Variably migmatised, strongly deformed, amphibolite facies psammitic, semipelitic and lesser amounts of pelitic rocks are the dominant lithologies in the Psammite Zone; minor metavolcanic and volcaniclastic rocks are also present. In the south-western part of the Psammite Zone a number of intrusive sheets of granodiorite, diorite and gabbro *s.l.* are closely related to the Julianehåb batholith (see below), and heterogeneous leucocratic granites derived from *in situ* or local melting of sedimentary rocks are volumetrically important in the south and east.

The psammitic rocks are generally arkosic and commonly calcareous; local pockets of low deformation preserve primary sedimentary structures indicative of deposition in a shallow subaqueous environment, although incipient melting has taken place in the coarser-grained beds. Polymict conglomerates with granite clasts occur adjacent to the margin of the Julianehåb batholith, both in the Lindenow Fjord region and in the south-western part of the Psammite Zone, as previously reported by Escher (1966), Wallis (1966), Dawes (1970) and Chadwick & Garde (1996). In addition, a vein-quartz pebble conglomerate occurs in the central part of the Lindenow Fjord region. Where best preserved at the head of Danell Fjord, the semipelitic to pelitic rocks display graded beds with psammitic bases and pelitic tops, which are probably indicative of deposition by turbidity currents; individual beds are up to *c.* 50 cm thick. These rocks were deposited below storm wave base but need not indicate deposition in deep water. Semipelitic and pelitic rocks elsewhere in the Psammite Zone, now highly migmatised, are also considered likely to be the products of turbidity currents.

Isotopic dating of detrital zircons in three sediment samples and of primary zircons in a granitic clast from a conglomerate were made by ion probe and conventional U-Pb methods (A. P. Nutman, personal communication, 1995; Hamilton *et al.*, 1996). These analyses demonstrate that the metasediments in various parts of the Psammite Zone are largely erosion products derived from the evolving Julianehåb batholith; the ages of the youngest detrital zircons indicate that in some areas sedimentation did not begin before *c.* 1793 Ma ago.

Intrusive igneous rocks

Intrusive sheets of diorite, tonalite and hornblende-biotite granodiorite, often with dioritic inclusions or enclaves, are common in the western part of the Psammite Zone around Nørrearm and inner Kutseq Fjord (rock names based on visual estimates of mineralogical compositions). The outcrop area of a related hornblende granite body, discovered east of Nørrearm in 1994, which is associated with a magmatic complex of gabbro, diorite and porphyritic biotite granite, was greatly extended in 1996 (Fig. 2). The intrusive rocks closely resemble typical components of the nearby Julianehåb batholith, which suggests a close genetic relationship. They were emplaced as subconcordant sheets in the metasediments towards the end of the second phase of regional deformation (see below) and confirm previous indications of an overlapping temporal and spatial relationship between batholith evolution, deposition of batholith-derived sediments and deformation of the Psammite Zone (Hamilton *et al.*, 1996); this scenario has important implications for the geotectonic interpretation of this part of the Ketilidian orogen, which will be considered elsewhere.

A folded, sheet-like body of layered gabbro, leucogabbro and diorite at least 8 km in length and several hundred metres thick occurs at Stendalen, west of outer Nørrearm (Fig. 2; Stendal *et al.*, 1997). Another body comprising similar lithologies, together with homogeneous dolerite or microgabbro, crops out east of Nørrearm and may be part of the same magmatic complex. Two other gabbroic sills up to tens of metres thick occur at the north coast of Nørrearm and south of inner Lindenow Fjord. Parts of all these intrusions exhibit penetrative tectonic S fabrics, and were folded during the third and fourth phases of deformation (see below); i.e. they were emplaced broadly at the same time as the granites (*s.l.*) described above. It is at present uncertain whether this suite of rocks is genetically related to the Julianehåb batholith.

Deformation

Four phases of regional deformation are recognised in the Psammite Zone, which were accompanied by high temperature, low pressure metamorphism and associated partial to extensive melting of sedimentary rocks of appropriate compositions.

The two earliest phases, D1 and D2, were essentially coaxial and coplanar and resulted in overall flat-lying structure, tight to isoclinal folds and strong penetrative LS fabrics. The scale of the folds varies generally from centimetres to tens of metres, with larger folds in places. In an extensive area north-east of Nørrearm the S1–S2 surfaces have shallow primary orientations, with ENE to NE-trending mineral and extension lineations parallel to the strike of the orogen. Sense of shear indicators show that transport was to the north-east. Close to the Julianehåb batholith at the head of Danell Fjord, a prominent younging upwards succession of graded turbidites outlines a tight F1–F2 syncline with a shallow NE-trending fold axis, steep bedding and steep S1–S2 cleavage. Although modified by later deformation, the present geometry in the latter area appears to reflect an originally steep orientation of S1–S2 planar fabrics, broadly parallel to steep shear zones common in the adjacent batholith (Chadwick *et al.*, 1994; Garde & Schønwandt, 1995).

Fig. 4. Bedding in psammitic metasediment, overprinted by S1 and S2 cleavages. The early seams of migmatite neosome are coplanar with S1 cleavage. The field of view is *c.* 80 cm across.

We regard phases D1 and D2 as stages of the same progressive deformation; D1 and D2 can locally be distinguished from each other (for example south of outer Paatusoq and south of inner Lindenow Fjord), and it can be seen that the earliest (S1) cleavage was accompanied by thin cleavage-parallel seams of partial melting (Fig. 4). In pelitic lithologies, andalusite porphyroblasts were formed along early cleavage planes, and were succeeded by widespread growth of sillimanite during the second phase of deformation.

The vein quartz pebble conglomerate which crops out in the central part of the Psammite Zone occurs in long flat-lying overturned limbs of F1–F2 or F2 folds. Bedding-cleavage relationships show that the overturning took place before the development of penetrative cleavage, and it is therefore possible that a pre-D1 tectonic event at a high crustal level was responsible, although unaccompanied by the development of any penetrative fabrics.

While the D1 and D2 events mainly seem to reflect orogen-parallel (NE–SW) extension, the subsequent deformation took place during NW-directed crustal shortening. In the third phase of deformation (D3), major recumbent folds commonly with north-facing fold closures, and monoclines with long flat-lying limbs and short steep to vertical limbs, were superimposed on the D1–D2 structures. A prominent recumbent third phase fold is exposed west of Nørrearm on the north coast of Lindenow Fjord (Fig. 3). This fold affects the eastern margin of the gabbro complex at Stendalen. The third phase of deformation was accompanied by extensive migmatisation to the east and south, where strongly migma-

Fig. 5. Open F4 anticline folding highly migmatised psammitic and semipelitic rocks and underlying S-type granite; the granite is presumed to have been derived from melting of the local metasediments. North-east Nørrearm, looking north-east. The prominent double peak (centre left) is 1510 m high.

tised psammitic and semipelitic rocks grade into areas with widespread heterogeneous biotite-bearing and locally garnet-bearing granites. Field observations suggest that these granites were derived by more or less *in situ* melting of local country rocks. Cordierite and garnet are common in the leucosome of the extensively migmatised semipelitic to pelitic rocks, and also in pockets within the local granites. The thorough migmatisation and recrystallisation in the metasediments associated with D3 deformation has commonly obscured D1–D2 fabrics; a new S3 cleavage can only locally be recognised parallel to axial surfaces of minor F3 folds.

During the fourth phase of deformation (D4) large upright to inclined anticlines and less conspicuous synclines were developed; they have shallow E to NE-trending axes and wavelengths of up to several kilometres. Most F4 folds are open warps (Fig. 5), which generally lack penetrative fabrics. However, a tight, angular F4 anticline south of inner Kutseq Fjord shows that D4 deformation could locally be quite intense and give rise to penetrative fabrics. This fold is outlined by a supracrustal amphibolite (see also Stendal *et al.*, 1997); it refolds D1–D2 lineations, and abundant new minor folds with axial planar cleavage occur in its hinge zone.

The superposition on D1–D2 structures of recumbent F3 folds and subsequently upright F4 folds of variable scale commonly resulted in complex refolded geometries. A conspicuous example occurs in the Illukulik area east of Nørrearm.

Conclusions and perspectives

Four main phases of regional deformation have now been established in the Psammite Zone east of the Julianehåb batholith between Lindenow Fjord and Kangerluluk, and the occurrence of significant volumes of batholith-related intrusive igneous rocks has been documented in the western part of the area. However, evidence was found in 1996 that the structural evolution within the mapped area was locally more complex than outlined above. In addition, reconnaissance work was carried out in a major mylonitic boundary zone north of Kangerluluk. These topics will be discussed elsewhere. Field studies of the post-tectonic rapakivi suite of plutonic rocks were also carried out, and a new mechanism for their emplacement has been developed (Garde *et al.,* in press).

Despite local complications, the field data now available from the Lindenow Fjord region form a sound basis for tectonic modelling in the south-eastern part of the Ketilidian orogen, and for studies of the igneous activity and metamorphic/thermal evolution of the region; ongoing isotopic age determinations (Hamilton *et al.*, 1996) are of particular relevance in this context. Furthermore, the regional insight allows understanding of the local structural setting of gold mineralised mafic igneous rocks in various parts of the area, a subject of detailed studies by other members of the SUPRASYD project (Stendal *et al.*, 1997).

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