Ketilidian structure and the rapakivi suite between Lindenow Fjord and Kap Farvel, South-East Greenland

Brian Chadwick, Adam A. Garde, John Grocott, Ken J.W. McCaffrey and *Mike A. Hamilton*

The southern tip of Greenland is underlain by the Palaeoproterozoic Ketilidian orogen (e.g. Chadwick & Garde 1996; Garde *et al*. 1998a). Field investigations in the summer of 1999 were focused on the structure of migmatites (metatexites) and garnetiferous granites (diatexites) of the Pelite Zone in the coastal region of South-East Greenland between Lindenow Fjord and Kap Farvel (Figs 1, 2). Here, we first address the tectonic evolution in the Pelite Zone in that region and its correlation with that in the Psammite Zone further north. Then, the structure and intrusive relationships of the rapakivi suite in the Pelite Zone are discussed, including particular reference to the interpretation of the controversial outcrop on Qernertoq (Figs 2, 8). Studies of the structure of the north-eastern part of the Julianehåb batholith around Qulleq were continued briefly from 1998 but are not addressed here (Fig. 1; Garde *et al*. 1999).

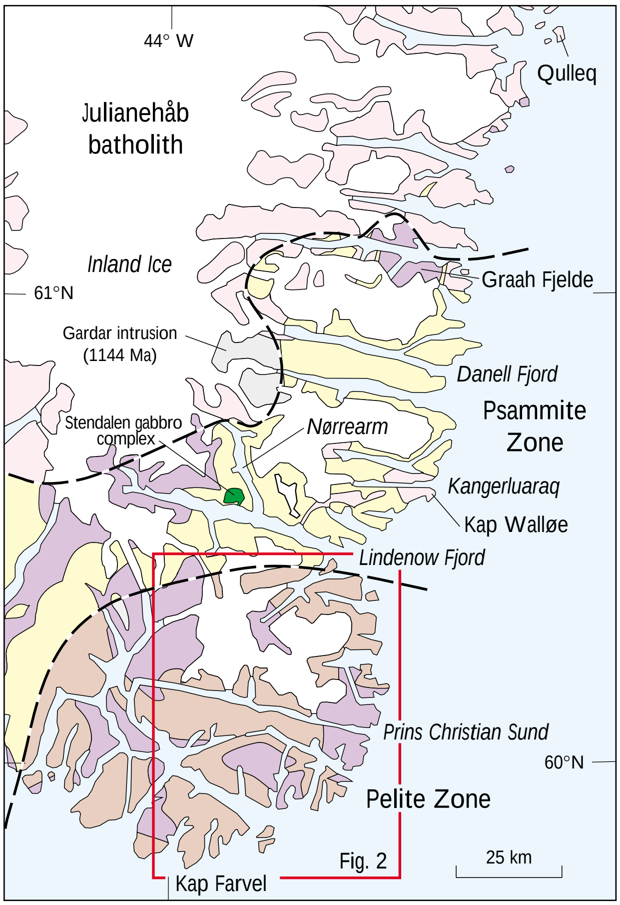

Fig. 1. Geological and location map of South-East Greenland, showing the Julianehåb batholith and other granites (**pink**), the Psammite and Pelite Zones (**yellow** and **brown**) with the rapakivi suite (**purple**), the Stendalen gabbro complex (**green**) and a Gardar intrusion (**grey**).

The field study was keyed to an interpretation of the Ketilidian orogen as a whole, including controls of rates of thermal and tectonic processes in convergent settings. Earlier Survey field work (project SUPRASYD, 1992–1996) had as its principal target an evaluation of the economic potential of the orogen (Nielsen *et al.* 1993). Ensuing plate-tectonic studies were mainly funded in 1997–1998 by Danish research foundations and in 1999 by the Natural Environment Research Council, UK. The five-week programme in 1999 was seriously disrupted by bad weather, common in this part of Greenland, and our objectives were only just achieved. Telestation Prins Christian Sund was the base for our operations (Fig. 2), which were flown with a small helicopter (Hughes MD-500).

Previous work

Prior to the 1999 season, the regional geology between Lindenow Fjord and Kap Farvel was poorly known, based on reconnaissance mapping of Bridgwater *et al.* (1966) and Sutton & Watterson (1968) for the Survey's 1:500 000 geological map sheet of South Greenland (Allaart 1975). At that time the Kap Farvel region was viewed as a flat-lying migmatite complex mainly consisting of psammitic to pelitic rocks besides the younger rapakivi suite (Allaart 1976). The deformation was believed to be of flattening type, generally lacking a lin-

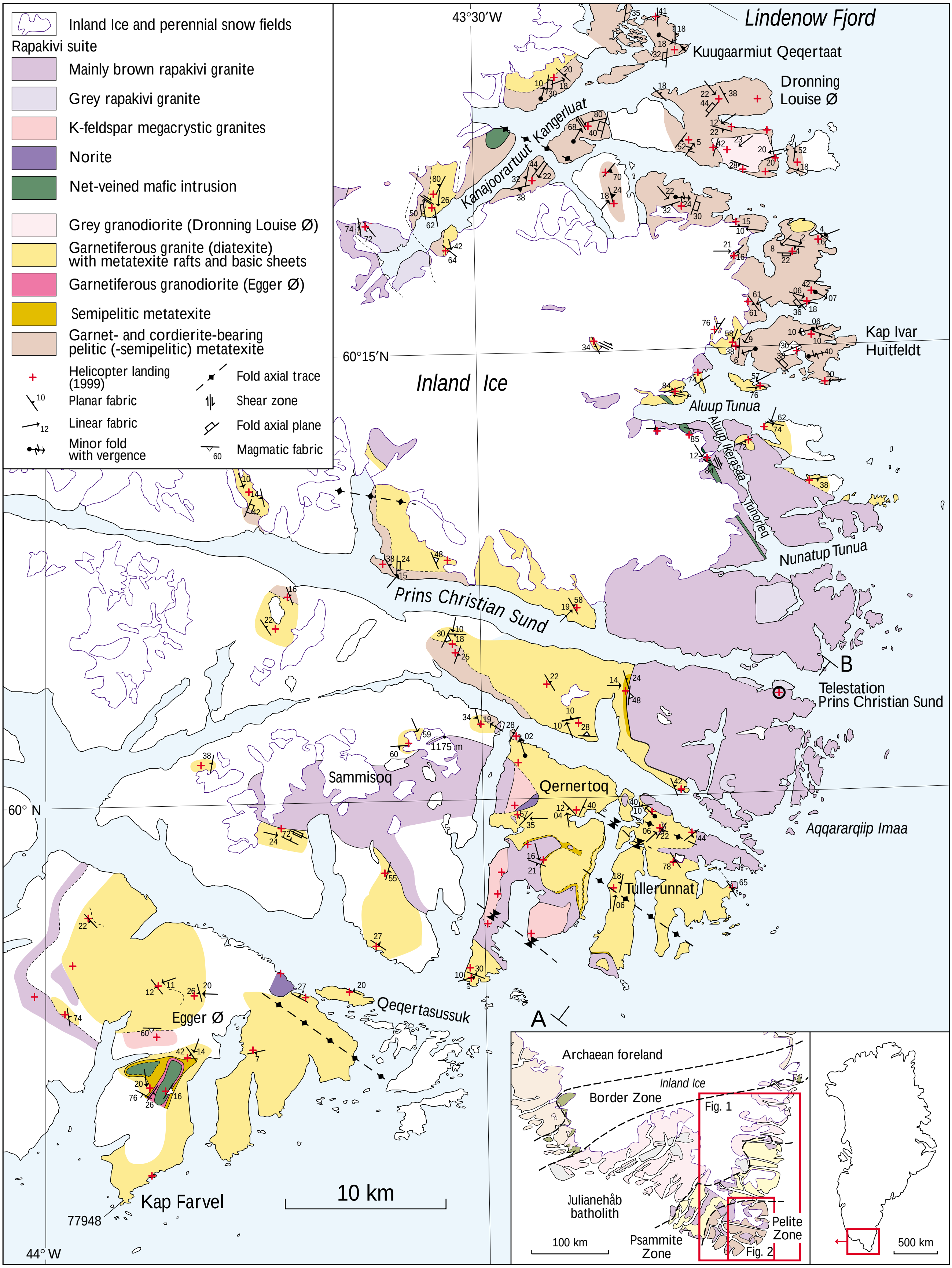

Fig. 2. Geological map of the terrain between outer Lindenow Fjord and Kap Farvel. The positions of sample 77948 from Kap Farvel and **profile A–B** (Fig. 7) are indicated. **Blank**: unmapped areas and, bordered by **dark blue lines,** ice and perennial snow fields. Index maps show the location of the Ketilidian orogen in southern Greenland and its main subdivisions.

Table 1. Summary of the Ketilidian tectonic chronology in the Psammite Zone, South-East Greenland

Deformation phase	Main structure	Contemporaneous event
D5	Large (kilometre-scale) upright folds	?Emplacement of rapakivi granite suite
D4	Kilometre-scale upright folds trending NE or E	
D3	100 m-scale and larger overturned and recumbent folds verging NW with axes trending NE–SW	High temperature / low pressure metamorphism and anatexis
D2 – D1	Coaxial and coplanar large- and small-scale, tight to isoclinal folds with shallow penetrative LS fabric contemporaneous with orogen-parallel top-to-the-NE displacements	

ear component. U–Pb zircon geochronology showed that rapakivi emplacement was separated from the regional metamorphism and migmatisation by some 40 Ma (Gulson & Krogh 1975).

Field work during project SUPRASYD led the present authors and their coworkers to conclude that the structure of the Psammite Zone in South-East Greenland (Fig. 1) was the result of four, and locally five, phases of deformation which took place during high temperature / low pressure metamorphism (Chadwick & Garde 1996; Garde *et al.* 1998a and references therein; Garde *et al.* 1998b); the tectonic chronology is outlined in Table 1. A comprehensive but partly unpublished database of U–Pb zircon ages (e.g. Hamilton 1997) shows that *HT-LP* metamorphism, anatexis and at least the first three phases of deformation occurred between *c.* 1792–1785 Ma ago and long before emplacement of the rapakivi granites, as indicated previously by the work of Gulson & Krogh (1975). Previous work related to the rapakivi suite is discussed below.

Structure of the metatexites and diatexites

Metatexites and diatexites derived from psammites, semipelites and pelites characterise the Pelite Zone on the south-eastern coast of Greenland (Fig. 2). Metatexites primarily occur between outer Lindenow Fjord at Kuugaarmiut Qeqertaat and Kap Ivar Huitfeldt; diatexites predominate southward to Kap Farvel. The generally shallow solid-state fabrics in metatexites and magmatic- and solid-state fabrics in diatexites are gently warped in upright arches and troughs which mainly trend NW–SE. The warping appears to be closely related to the emplacement of rapakivi granites discussed later.

Metatexites

The metatexites are typically banded with palaeosome interleaved with broadly concordant seams of neosome (Fig. 3). Palaeosome with locally preserved bedding and early thin seams of neosome are seen as part of a transposed planar fabric in most outcrops. Thick seams of biotite + garnet ± cordierite neosome (locally alaskitic) were generated *in situ* or emplaced later than the trans-

Fig. 3. Metatexites with broadly concordant pegmatitic neosome, Kap Ivar Huitfeldt. Height of section *c.* 500 m.

Fig. 4. Garnetiferous meta- and diatexite 2 km west of Kap Ivar Huitfeldt. The *D1/D2* planar fabric and concordant neosome are folded by metre-scale folds correlated with *D3*. Note the younger transposed fabric and new neosome (e.g. along the 45 cm long hammer), which are both axial planar to the *D3* folds.

posed neosome. Abundant biotite, garnet, cordierite and fibrolite point to a semipelitic precursor for most metatexites, but psammitic palaeosome is evident in some outcrops. Nodules with hornblende and garnet like those in semipelites north of outer Lindenow Fjord are common. The metatexites also contain disrupted mafic and ultramafic sheets presumed to be relics of early appinitic intrusions, like those in semipelites and psammites north of the fjord.

Deformation in the metatexites between outer Lindenow Fjord and Kap Ivar Huitfeldt appears to have taken place in three stages. The earliest is represented by disrupted, tight to isoclinally folded mafic sheets which are flanked by psammites with well-preserved bedding. Palaeosome/neosome banding in associated metatectic semipelites forms a transposed fabric which is axial planar to these folds, for example on the mainland south of Dronning Louise Ø. The folds have a locally intense coaxial mineral lineation or ribbing. These characteristics point to correlation with *D2* north of Lindenow Fjord (Table 1). A later phase of folding is represented by common asymmetric folds verging either north or south with axial surfaces dipping 30–40° north or south (Fig. 4). Differences in vergence suggest that large-scale flat-lying folds (nappes) are present, but none were positively identified. Axial planar neosome and *S* fabrics of transposed older palaeosome and neosome are common (Fig. 4). On Dronning Louise Ø, these folds deform the linear fabric and correlate with *D3* north of Lindenow Fjord (Table 1). The refolded lineation is best preserved in competent, non-migmatised psammite and amphibolite lithologies, but is commonly transposed to new *L3* intersection and mineral lineations. In the adjacent metatexites, *F3* folds are characterised by an intense coaxial mineral lineation, and *L2* has been almost universally transposed to *L3*.

South of Dronning Louise Ø, minor folds coaxial with the intense lineation are common. Their shallow SW, W, NE and E plunges suggest that larger scale folds have curving hinge lines. Fold scales vary widely but long limbs of the largest structures preserve the regional shallow dip between Kuugaarmiut Qeqertaat and Kap Ivar Huitfeldt. Shear bands and asymmetric tails to nodules indicate transport of the hanging wall towards the south-west or west, and towards the north-east or east, parallel to the shallow lineation.

Refolding of the *D2* lineation was seen only at a few localities south of Dronning Louise Ø. The paucity of refolding is attributed to transposition of *L2* to *L3* in the metatexites which predominate over competent units that best preserve *L2* further north. Transposition of *L2* to *L3* accounts for the differences in displacement direction observed parallel to the mineral lineation. We infer that the prominent folds of the regional *D1/D2* fabric in the metatexites south of Dronning Louise Ø are most likely of *D3* age.

Diatexites

Garnetiferous granite (diatexite) with rafts of metatexite and xenoliths of psammite and amphibolite dominates west of Kap Ivar Huitfeldt and between Prins Christian Sund and Kap Farvel (Figs 2–4). Most of the diatexites are characterised by high amphibolite facies assemblages, but small areas with granulite facies assemblages occur on Qeqertasussuk. The diatexite boundaries are generally concordant with palaeosome/neosome banding in the underlying metatexites, and the diatexites appear generally to overlie the metatexites. Common garnet, cordierite and subhedral feldspar megacrysts contrast with irregular feldspars and lack of garnet in many diatexites north of Lindenow Fjord. These differences may be effects of either different metasedimentary precursors or movement of the garnetiferous diatexites further from their source rocks, but the extent to which the diatexites are autochthonous or intrusive is unclear. Bridgwater *et al.* (1966) and Sutton & Watterson (1968) highlighted a regionally concordant, subhorizontal sheet of granodiorite up to more than 1 km thick in the eastern part of the region between Lindenow Fjord and Kap Farvel, bounded by veins of aplite and pegmatite in the host metatexites. The exact position and affinity of this sheet are unclear from their descriptions, but outcrops along Prins Christian Sund that we consider likely to belong to this sheet are part of the regional diatexites and not related to the Julianehåb batholith or the rapakivi suite.

The diatexites are dominated by a subhorizontal magmatic-state *LS* fabric indicated by alignment of alkali feldspar megacrysts. Transitions to a coplanar solid-state *LS* fabric are common. Both top-to-the-N or -NE, and top-to-the-S or -SW displacements are indicated by winged feldspars and asymmetric calc-silicate boudins. These conflicting shear senses appear to mirror the hanging wall displacements in the metatexites between Dronning Louise Ø and Kap Ivar Huitfeldt.

Large-scale recumbent folds with uncertain vergence deform layering in the diatexites north and south of Prins Christian Sund. Numerous large-scale folds with northerly vergence are marked by dark sheets of amphibolite or metatexite in diatexites in eastern Qernertoq (Fig. 5) and elsewhere. These folds also appear to deform the fabric in the diatexites, but their vergence is consistent with top-to-the-NE shear sense in the main *LS* fabric. A few of the folds in eastern Qernertoq have shallow-dipping dark sheets (possibly including norites contemporaneous with the rapakivi granites and older appinites) parallel to axial surfaces of the N-verging folds (Fig. 5).

The recumbent and N-verging folds in the metatexites and diatexites, for example those along Prins Christian Sund and on eastern Qernertoq, appear on the one hand to be consistent with orogen-parallel top-to-the-NE displacement on low-angle magmatic- and solid-state fabrics and could therefore be *D1/D2* structures like those in the Psammite Zone (Table 1). On the other hand, the folding of diatexite fabrics suggests a *D3* age for the recumbent and N-verging folds (such as those visible on Fig. 5). This correlation implies that *D3* had a significant impact as far south as Kap Farvel.

A sample of diatexite collected by D. Bridgwater from Kap Farvel has yielded a U–Pb zircon age of 1790 ± 1 Ma (GGU 77948 on Fig. 2; Hamilton 1997), whereas the rapakivi granite exposed at Prins Christian Sund yielded a U–Pb bulk zircon age of *c.* 1734 Ma (Gulson & Krogh 1975). Since diatexite 77948 was collected within the Pelite Zone where rocks of the rapakivi suite are common, its age provides important additional evidence to show that the regional metamorphism and extensive partial melting are *much* older than the emplacement of the rapakivi suite, contrary to the interpretation by Dempster

Fig. 5. South–north profile of south-eastern Qernertoq (cf. Fig. 8). The dark S-dipping horizon to the left and its flat-lying continuation on the high tops in the centre is the basal part of the rapakivi sheet overlying shallow-dipping garnetiferous meta- and diatexites. These steepen towards the north and south over a major arch. The rapakivi sheet steepens in accord with this structure at the southern end of the profile to the left, where it is also discordant (see main text). Note the N-verging folds in metatexites (e.g. where marked by **arrow**), which predate the arch. Peak on the right is 1081 m high.

et al. (1991). It also supports a close temporal relationship between high-grade metamorphism and deformation, specifically *D1/D2*, in the Psammite and Pelite Zones: in the Psammite Zone *D1/D2* coincides with the emplacement of a hornblende granite sheet dated at 1792 ± 1 Ma (Hamilton 1997; Garde *et al.* 1998a).

Grey granodiorite sheet on Dronning Louise Ø

A *c.* 500 m thick sheet of biotite granodiorite *sensu lato* was emplaced into the metatexites on south-eastern Dronning Louise Ø (Fig. 2). Large feldspars and ellipsoidal enclaves of darker grey granodiorite have a strong linear preferred orientation within a weak magmatic-state *S* fabric. The *LS* fabric is broadly parallel to the pervasive palaeosome/neosome banding in the host metatexites. The grey granodiorite is cut by irregular pegmatites and thin lenses of neosome associated with diffuse small-scale shear zones dipping steeply north-east. Extensional shear bands dropping down to the south-west are also common. At the contact with the metatexites the granodiorite has an intense magmatic-state *S* fabric broadly concordant with the *S* fabric in the adjacent metatexites. Later sills of granite were emplaced along the boundary. The outcrop points to large-scale folding of the sheet by *D3*. Isotopic age determination is in hand to establish whether the sheet on Dronning Louise Ø is contemporaneous with the above mentioned hornblende granite emplaced during *D1/D2* deformation north of Lindenow Fjord.

Rapakivi suite including mafic dykes

Spectacular exposures of rapakivi and related granites in the Prins Christian Sund – Kap Farvel region, ranging in size from small outcrops to entire mountains, provided new insight into their contact relationships, states of deformation and overall shapes. These observations have important bearings on the emplacement mechanisms and geotectonic setting of the rapakivi suite, which have been much debated in the literature and are addressed below.

Lithologies, regional extent and contact phenomena

The rapakivi suite comprises different varieties of rapakivi granite (i.e. with mantled K-feldspar megacrysts), other facies of granites, noritic bodies and mafic dykes. The two rapakivi granites distinguished on the map are both coarse-grained; the most common is a brown variety that predominates the rapakivi suite south of Aluup Tunua (Fig. 2). Basal contacts of brown rapakivi granite with metatexites are commonly knife-sharp and discordant, and the granite lacks internal strain, for example in eastern Tullerunnat. Xenoliths of hornfelsed metatexites are common in the basal parts of the granites (Fig. 6; Grocott *et al.* 1999). Hornfelsed metatexites below the contacts are locally folded irregularly, presumably as an effect of thermally induced deformation (rheomorphism). Hornfelsing, with sheaves of secondary dark red biotite, is also prominent beneath the sheet in central Qernertoq, north of Sammisoq and in north-western

Fig. 6. Knife-sharp basal contact of the rapakivi granite sheet overlying hornfelsed metatexites, north-eastern Tullerunnat. Note the angular xenoliths of psammite. Ken McCaffrey for scale, pointing at the contact.

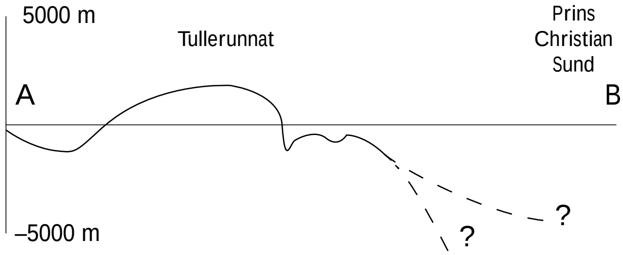

Fig. 7. Profile A–B of the undulating base of the rapakivi granite sheet south-west of Prins Christian Sund. The position of the profile is shown on Fig. 2.

Tullerunnat. West of Telestation Prins Christian Sund the base of the rapakivi intrusion is cut by rheomorphic veins and shows localised brittle shearing. The contact in eastern Tullerunnat is cut by garnetiferous pegmatite.

Structure of the rapakivi sheet between Aluup Tunua and Sammisoq

The outcrops of brown rapakivi granite and related rocks between Aluup Tunua and Sammisoq–Qernertoq suggest that they once formed a continuous sheet at least 1 km thick. The sheet is arched over large-scale antiformal structures in the host diatexites and occupies complementary synformal structures between the arches, some of which are below sea level. Most of these structures trend NW–SE with shallow NW- or SE-plunging axes, but the regional outcrop on Qernertoq and western Sammisoq indicates superimposed or contemporaneous arches trending NE–SW (Figs 2, 5, 8). Whereas most antiforms and synforms are gentle or open structures, the base of the rapakivi intrusion on Tullerunnat occupies a tight synformal cusp (Fig. 7). Sharp steepening of the diatexite foliation below the near-vertical base of the rapakivi sheet is evident in central, southern and north-eastern Sammisoq; see Fig. 2 and Bridgwater *et al.* (1974, fig. 7), a view from the east towards peak 1175 m in north-eastern Sammisoq.

The large-scale domes and basins which control the overall rapakivi outcrop have much in common with *D4* and *D5* structures north of Lindenow Fjord (Table 1), including Graah Fjelde, the Stendalen gabbro complex and the Kangerluaraq interference structure (Fig. 1; Garde *et al.* 1998c; Grocott *et al.* 1999). In the last area an E–W-trending intermediate dyke which appears to be contemporaneous with the interference structure has yielded a U–Pb zircon age of *c.* 1736 Ma (Hamilton, unpublished data). Accordingly, the domes and basins controlling the structure of the rapakivi sheet south of Aluup Tunua are tentatively correlated with *D4* and *D5*.

Rapakivi and related granites on Qernertoq

Field work on Qernertoq (Fig. 8) focused on the much debated shape of the sheet of brown rapakivi granite in the eastern and south-eastern parts of the island and its relationship to the system of late arches and domes described above. Bridgwater *et al.* (1974, fig. 7), describing the rapakivi granites in general terms as mushroom-shaped intrusions with thick subvertical stems, presented a photograph of steeply inclined rapakivi granite on north-eastern Sammisoq but incorrectly labelled the locality as depicting the 1081 m peak on south-eastern

Qernertoq, where the granite is subhorizontal. Two subsequent maps (Hutton *et al.* 1990; Grocott *et al.* 1999) show the gently-dipping floor of the intrusion at the 1081 m peak steepening southward and cutting progressively downwards across host-rock fabrics. Hutton *et al.* (1990) regarded this geometry as *prima facie* evidence of emplacement in an extensional fault system. On the other hand, Grocott *et al.* (1999) argued that the contacts steepened towards a rapakivi feeder dyke. Observations in 1999 show that the orientation of the basal contact changes from vertical at sea level on the eastern shore of Kuulik to *c.* 45° on the opposite, eastern side of the mountain forming the peninsula of Ikerasakasiip Qaqqaa (Fig. 8). The high cliffs on the east coast (Fig. 5) also reveal that the sheet has an open, dome-like shape in accord with a major structure 7 km across in the underlying diatexites (see also Fig. 7). In spite of the new field data, the relative roles of emplacement-related floor depression and folding in controlling the sheet geometry on Qernertoq are uncertain (cf. Grocott *et al.* 1999).

The brown rapakivi granite is largely underlain by garnetiferous diatexites typical of the Pelite Zone. However, in south-eastern and south-western Qernertoq the brown rapakivi granite is in contact with undeformed, homogeneous grey K-feldspar megacrystic granite *sensu lato* (generally without rapakivi-textured feldspars), which Becker & Brown (1985), Hutton *et al.* (1990) and Brown *et al.* (1992) correlated with the regional diatexites. On the grounds of its homogeneity, coarse, rarely rapakivi-textured feldspars and absence of garnet, we *provisionally* regard this granite as a grey facies of the rapakivi suite (Fig. 8). A related facies of undeformed grey granite *sensu lato* with K-feldspar megacrysts, rapakivi-textured feldspar xenocrysts, abundant enclaves of grey microdiorite, and xenoliths of intensely deformed metasedimentary rock is part of the rapakivi suite on north-western Qernertoq.

The shape of the rapakivi sheet on Qernertoq is inconsistent with emplacement in an extensional regime as suggested by Hutton *et al.* (1999) and Hutton & Brown (2000). It is also at variance with the interpretation of its outcrop on south-eastern Qernertoq as a feeder dyke proposed by Grocott *et al.* (1999). Nevertheless, the undulating form of the sheet between Prins Christian Sund and Sammisoq is comparable with the shape of the bases of the two rapakivi sheets at the head of Lindenow Fjord and at Graah Fjelde still further north (Fig. 1), whose emplacement is interpreted as the result of roof uplift or floor depression (Grocott *et al.* 2000, in press).

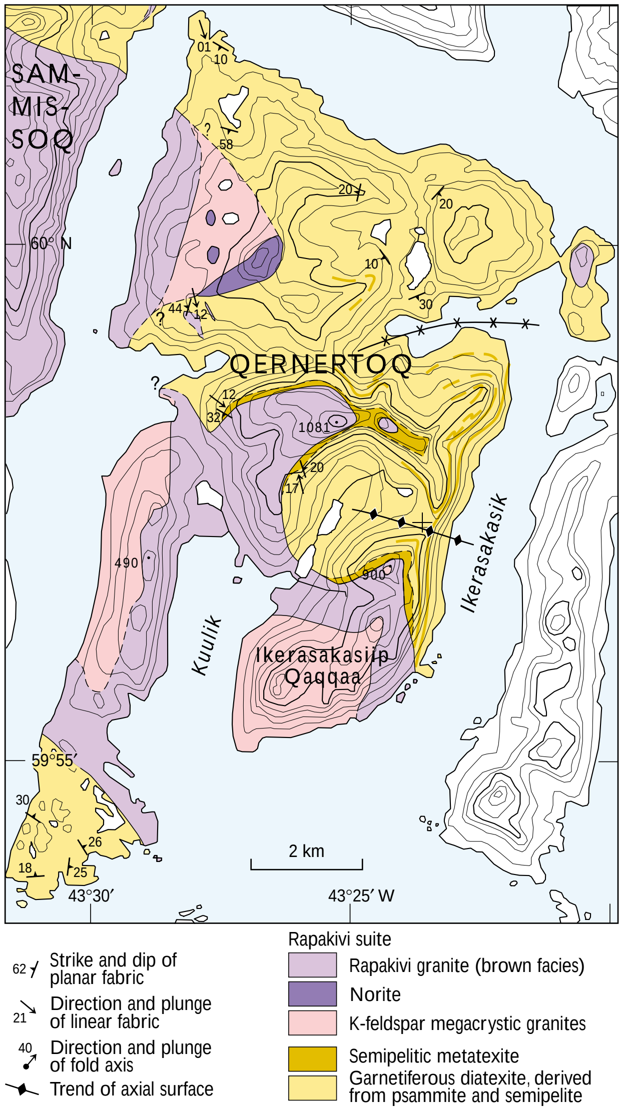

Fig. 8. Geological map of Qernertoq with 100 m contour intervals (cf. Fig. 5). For location, see Fig. 2.

Sheeted dyke complex comagmatic with rapakivi granite

Although solid-state fabrics are uncommon in the rapakivi suite, a steep to vertical, NW–SE-trending sheeted dyke complex about 200 m wide north of Prins Christian Sund shows that deformation was contemporaneous with rapakivi granite emplacement. Dykes in the south-eastern, coastal part of the exposure along Aluup Ikerasaa Tunorleq (Fig. 2) were first reported by Harrison *et al.* (1990) who interpreted them as a synplutonic complex cutting a mass of mixed magma within the rapakivi 'pluton'. The dyke complex was described as comprising composite intrusions with aphyric basalts chilled against the host rocks and micro-rapakivi gran-

Fig. 9. Mafic and composite dykes comagmatic with rapakivi granite. Sheeted dyke complex, west of Aluup Ikerasaa Tunorleq. For location, see Fig. 2. Diameter of coin is 2.8 cm. **A**: Dextral shear indicated by oblique ellipsoidal mafic pillows on the margins of a net-veined dyke. **B**: Mafic dyke comingled with brown rapakivi granite. **C**: Mafic pillows inflated by granite *sensu lato* in part of a net-veined dyke. Various stages of central and concentric inflation are seen, leading to complete disruption of the mafic pillows.

ite in the dyke interiors. Harrison and his co-workers drew attention to mafic facies in the dykes with crenulate contacts and intense dextral shear fabrics and concluded that the dykes were emplaced in a dextral shear zone.

In 1999 the synplutonic dyke complex was found to extend 5 km north-west into the high ground west of Aluup Ikerasaa Tunorleq. It comprises a swarm of dykes derived from mixed felsic and mafic magmas emplaced during dextral shear, as shown by asymmetric magmatic-state folds of dykes, magmatic-state fabrics oblique to dyke boundaries (Fig. 9A) and solid-state *S-C* fabrics. The mixed-melt dykes have mineralogical compositions identical to, but texturally different from, the host brown rapakivi granite. Xenoliths of porphyritic garnetiferous granite (diatexite) with magmatic-state flow fabrics are common in the brown rapakivi granite, some many cubic metres in size. Mafic dykes emplaced into the brown rapakivi granite before full crystallisation were variably disrupted during the comingling process (Fig. 9B). Dykes in the vertical sheeted complex show a wide range of immiscible melt structures including lobate boundaries, complex pillows and bolsters, and diffuse concentric banding in mafic facies. Concentric and radial fractures facilitated intrusion of felsic magma into basic pillows and led to progressive inflation by granite in pillow cores (Fig. 9C). Comparable net-veined mafic dykes are also known from rapakivi granites in the south-western part of the Psammite Zone (e.g. Dawes 1970). Steeply inclined brown rapakivi granite sheets which may represent feeder dykes were seen in garnetiferous diatexite north of Aluup Ikerasaa Tunorleq and in north-western Qernertoq. Dextral shearing on NW–SE-trending zones was also seen in garnetiferous diatexite in the nunatak area north-west of Aluup Ikerasaa Tunorleq and in the inlet Kanajoorartuut Kangerluat.

The sheeted dyke complex shows not only that rapakivi granite magmatism was fed by dykes as implied by the model of Grocott *et al.* (1999), but it was also closely linked with NW–SE-trending dextral shearing that is compatible with the NE–SW-trending sinistral transpressive system of the Ketilidian orogen as a whole (Chadwick *et al.* 1994; Chadwick & Garde 1996).

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Authors’ addresses

B.C., *Room 220, Laver Building, University of Exeter, Exeter EX4 4QE, UK.* E-mail: *b.chadwick@exeter.ac.uk*

A.A.G., *Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark.*

J.G. & K.J.W.McC.*, *School of Geological Sciences, Kingston University, Penrhyn Road, Kingston-upon-Thames, Surrey KT1 2EE, UK.*

* Present address*: School of Geological Sciences, University of Durham, Durham DH1 3LE, UK.*

M.A.H., *Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8, Canada.*