Proterozoic tectonic overprinting of Archaean gneisses in Nuussuaq, West Greenland

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Archaean orthogneisses and supracrustal rocks in eastern Nuussuaq in the southern part of the Rinkian orogen preserve much indirect evidence of Proterozoic reworking. In northern Nuussuaq, a marble occurrence which can be correlated with the Proterozoic Mârmorilik Formation of the Uummannaq district, is interleaved and intensely folded with Archaean orthogneisses. Dykes and sills of presumed Proterozoic age in southern Nuussuaq pre-date two major shear zones. Furthermore, published K-Ar and ^{40}Ar-^{39}Ar hornblende ages indicate that metamorphic temperatures of at least *c.* 550°C were reached in large parts of Nuussuaq during the Proterozoic.

Although available data are not sufficient to firmly establish the tectonic evolution of Nuussuaq, it can be shown that development of a regional flat-lying structure was succeeded first by upright folding and development of a major NW–SE-trending shear zone during crustal shortening, and subsequently by formation of an ENE–WSW-trending shear zone during crustal extension. A Rinkian detachment zone across Nuussuaq, similar to those known in the Uummannaq district, may link Proterozoic marble occurrences south of the peninsula with the marbles known in northern Nuussuaq and in the Uummannaq district.

Observations suggest that geological structures and lithologies can be traced from north to south across the fjord Torsukattak, into the Ataa area which is hardly affected by Proterozoic deformation. This is used to infer that a major crustal boundary structure along the fjord (previously assumed to form the northern boundary of the Burwell terrane in West Greenland) does not exist.

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The eastern, Precambrian part of Nuussuaq is conventionally considered to belong to the southernmost part of the Proterozoic Rinkian orogen (originally established by Escher & Pulvertaft 1976), just north of the region affected by contemporaneous tectonothermal activity in the Nagssugtoqidian orogen. Recent investigations (e.g. Kalsbeek & Nutman 1996; van Gool *et al.* 1996; Hanmer *et al.* 1997; Grocott & Davies 1999, this volume) indicate, however, that the traditional distinction between the Rinkian and Nagssugtoqidian orogenies in West Greenland is in need of re-evaluation.

This paper describes the Archaean basement rocks in eastern Nuussuaq which preserve evidence of strong tectonic reworking. Reconnaissance field work undertaken by the Geological Survey of Greenland in 1988–1991 during the Disko Bugt Project suggests that the reworking is early Proterozoic in age and broadly comparable in style with contemporaneous reworking of the adjacent southernmost part of the Uummannaq district (Grocott 1984; Grocott & Pulvertaft 1990). Evidence for a local NW–SE-trending Rinkian detachment zone through Nuussuaq is presented. However, it can be shown that no major crustal boundary structure occurs along the south coast of Nuussuaq – with the

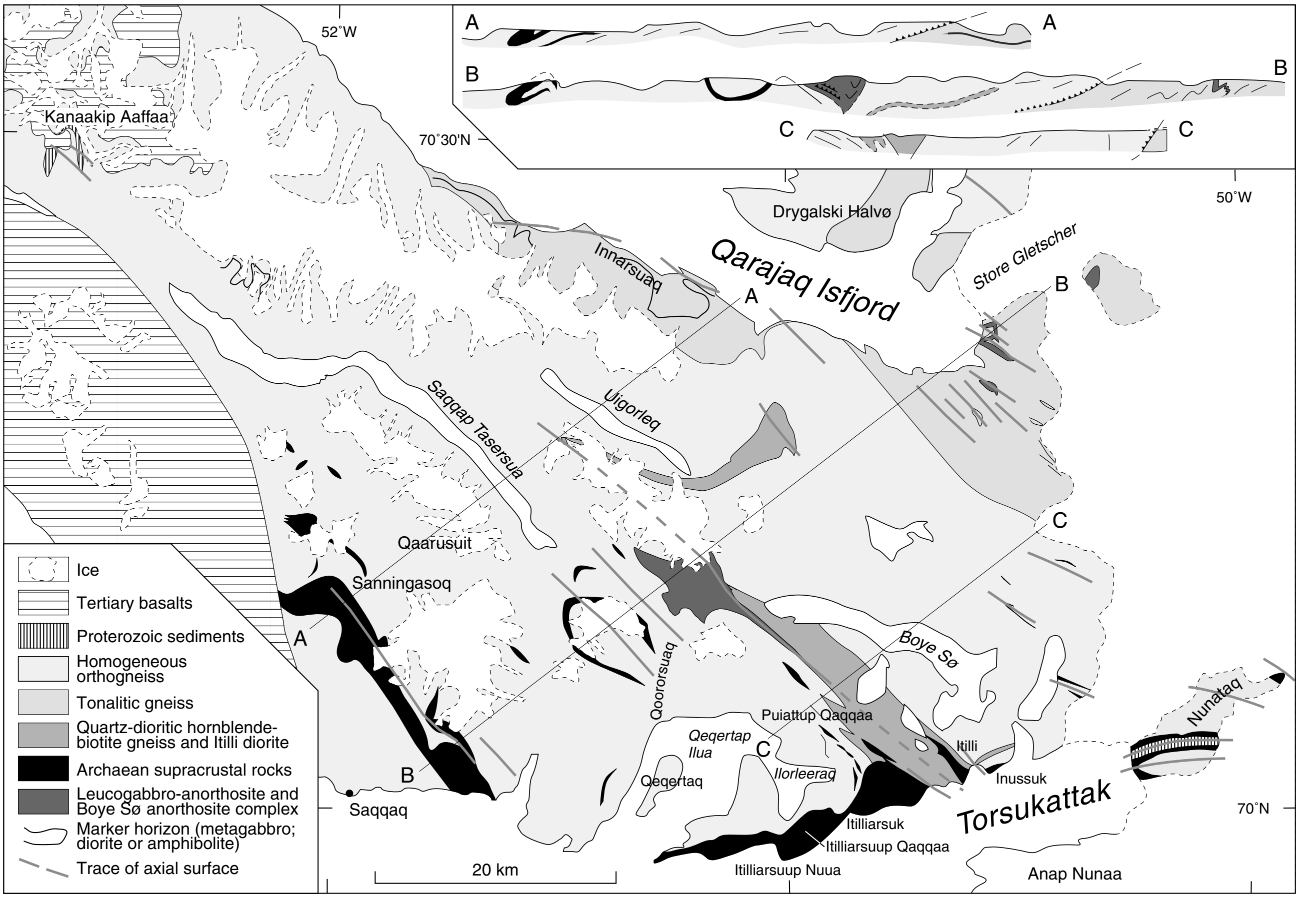

Fig. 1. Simplified geological map of eastern Nuussuaq and Nunataq (the Nuussuaq domain). Sections A–A, B–B and C–C are viewed towards NW; horizontal and vertical scales as on map. See Fig. 2 for location.

implication that the assumed Burwell terrane boundary (e.g. Hoffman 1989; van Kranendonk *et al.* 1993) cannot be substantiated in this region.

Geological investigations of eastern Nuussuaq

Prior to the Disko Bugt Project eastern Nuussuaq was poorly known, especially in its interior parts (see map by Escher 1971). The first modern investigations in the region by Escher & Burri (1967) included a survey of the south-eastern coast, where metamorphosed supracrustal rocks around Itilliarsuk were described (Fig. 1). These supracrustal rocks were at first believed to be part of the Proterozoic Anap nunâ Group which is exposed south of Torsukattak, but are now considered to be part of the Archaean basement. A prominent marble exposure at Kanaakip Aaffaa in northern Nuussuaq (see Fig. 1 and p. 145) was also shown on Escher's (1971) map, but no description was published at the time. In 1965 and 1980–1981 T.C.R. Pulvertaft (personal communication 1993) surveyed the north coast of Nuussuaq in connection with mapping and structural studies in the adjacent Uummannaq district (Grocott 1984; Pulvertaft 1986; Henderson & Pulvertaft 1987; Schiøtte 1988; Grocott & Pulvertaft 1990). In addition, the mining company Kryolitselskabet Øresund A/S investigated supracrustal rocks in southern Nuussuaq in the early 1980s.

The new field work carried out on Nuussuaq during the Disko Bugt Project was not comprehensive. Only a few areas in north-eastern and southern Nuussuaq, and on Nunataq, were visited on foot, whereas most of the region was surveyed by helicopter reconnaissance. Garde & Steenfelt (1999, this volume) present an overview of the Precambrian geology of the Disko Bugt region between Qarajaq Isfjord and Jakobshavn Isfjord with a description of the geological map at scale 1:250 000 (Garde 1994). They divide the region into four structural domains; the two northernmost of these, the Nuussuaq and Ataa domains, have their common boundary in Torsukattak (Fig. 1; Garde & Steenfelt 1999, this volume, fig. 1). Garde & Steenfelt (1989) reported the discovery of an anorthosite complex west of Boye Sø, and Garde (1992, 1994) presented a 56 km long structural profile along the north coast of Nuussuaq. The geology of Nunataq, at the head of Torsukattak in the transitional area between the Nuussuaq and Ataa domains, is described by Higgins & Soper (1999, this volume). Rasmussen & Pedersen (1999, this volume) and Garde *et al.* (1999, this volume) describe respectively the supracrustal rocks west of Itilliarsuk, and metavolcanic rocks with gold mineralisation near Saqqaq. A study of K-Ar and ^{40}Ar-^{39}Ar mineral ages in the Disko Bugt region, including data from Nuussuaq, is presented by Rasmussen & Holm (1999, this volume). Pulvertaft (1989) has described the boundary fault system in central Nuussuaq, which separates the Precambrian basement terrain from the Cretaceous–Tertiary volcano-sedimentary basin to the west.

Lithological units and their contact relationships

The Precambrian basement of Nuussuaq comprises almost exclusively rocks of presumed Archaean age: the Nuussuaq gneisses, the Saqqaq and Itilliarsuk supracrustal rocks of southern Nuussuaq, and the Boye Sø anorthosite complex (Figs 1, 2; Garde 1994; Garde & Steenfelt 1999, this volume). Only a few mafic dykes and sills and the marble occurrence in central Nuussuaq are known, or presumed, to be of Proterozoic age.

There is evidence locally that the supracrustal rocks rest unconformably on the gneisses, although the con-

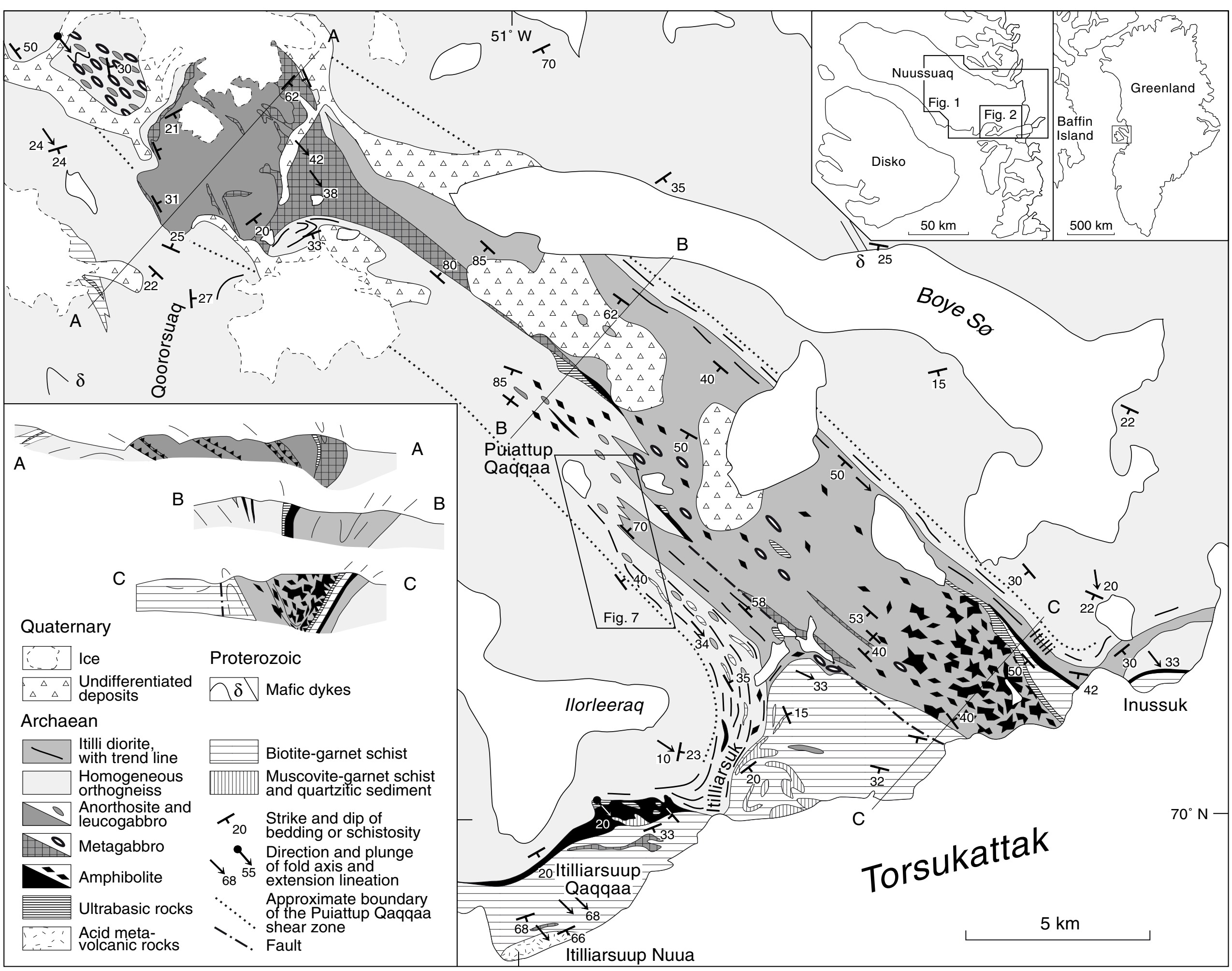

Fig. 2. Geological map of south-eastern Nuussuaq. Sections A–A, B–B and C–C are viewed towards the north-west; horizontal and vertical scales as on map.

tacts between the Itilliarsuk supracrustal rocks and Nuussuaq gneisses are too tectonised to allow a conclusion; a polymict conglomerate close to the base of the Itilliarsuk supracrustal succession contains clasts of granitoid rocks which were most likely derived from undeformed precursors of nearby orthogneisses. The contacts between the Boye Sø anorthosite complex and the Nuussuaq gneisses are also tectonic, and no primary relationships have been observed between the Saqqaq supracrustal rocks and Nuussuaq gneisses.

The Nuussuaq gneisses consist of two major lithological and tectonic units (Fig. 1; Garde & Steenfelt 1999, this volume): a predominant pale, uniform, leucocratic orthogneiss (homogeneous orthogneiss), and a darker grey, more mafic orthogneiss found in north-eastern Nuussuaq (tonalitic gneiss; commonly with layers and lenses of anorthosite, leucogabbro and gabbro). In addition, a mafic tonalitic to quartz-dioritic hornblende-biotite gneiss forms a 20 km long sheet at Uigorleq in north-eastern Nuussuaq (Fig. 1), and augen gneiss occurs in southern Nuussuaq close to Saqqaq (Garde 1994). The Itilli diorite, which extends from the Boye Sø anorthosite complex to the south coast of Nuussuaq (Fig. 2), appears to be younger than the supracrustal rocks and most of the Nuussuaq gneisses.

On Nunataq at the head of Torsukattak fjord two superimposed successions of Archaean and Proterozoic supracrustal rocks outline overturned tight to isoclinal folds (Fig. 1; Higgins & Soper 1999, this volume). The Archaean succession consists of amphibolite and garnet-mica schist. The Proterozoic succession comprises a basal quartzitic sandstone, a few metres thick marble horizon and a sequence of fine-grained semipelitic rocks; this succession is an attenuated lateral continuation of the lowermost part of the Anap nunâ Group, which is more widely exposed on Anap Nunaa south of Nunataq (Fig. 1).

Structural elements in the Nuussuaq domain

Field observations by the authors in the Nuussuaq domain suggest, as noted above, that its present structure was largely developed during Palaeoproterozoic reworking of Archaean basement rocks during the Rinkian orogeny; this view is supported by new K-Ar hornblende ages in the range of *c.* 1770–1880 Ma from various parts of the Nuussuaq domain (Rasmussen & Holm 1999, this volume). Resetting of hornblende K-Ar isotope systematics shows that a minimum temperature of *c.* 550°C was reached in the Nuussuaq domain during Rinkian metamorphism, sufficient to allow regional ductile deformation. In the Ataa domain south of Torsukattak, however, only limited resetting of Archaean mineral ages has occurred, and the metamorphic grade of Proterozoic metasediments at the present level of exposure is lower greenschist facies.

Large parts of eastern Nuussuaq are characterised by an overall flat-lying structure, which is deformed by a series of NW–SE-trending, mostly upright to overturned folds, and in the north-west recumbent isoclinal folds; interference patterns between two sets of coaxial folds with ESE–WNW-trending axes are common at the head of Qarajaq Isfjord. Asymmetric shear fabrics observed in southern Nuussuaq suggest later hanging-wall displacements in a northerly direction. A major NW–SE-trending, steeply dipping, 7 km wide shear zone, the Puiattup Qaqqaa shear zone, occurs in southern Nuussuaq near Boye Sø. Another shear zone, trending E–W, is inferred to occur along Torsukattak (Figs 2, 10) associated with strong schistosity and extension lineation fabrics which are preserved in the coastal areas on the north side of Torsukattak. The different structural elements are described below, and a tentative chronological scheme is given in Table 1.

Flat-lying structure

Large areas in the interior of Nuussuaq are covered by boulder fields and local ice caps, but a general flat-lying structure can be discerned from exposures along the north coast and at the lakes Saqqap Tasersua and Uigorleq (Fig. 1). On the north coast the flat-lying structure is marked by layers of anorthosite, leucogabbro and gabbro intercalated with tonalitic gneiss, and by a subhorizontal to shallow south-dipping tectonic boundary between homogeneous orthogneiss in the hanging wall and tonalitic gneiss in the footwall (see long profile in Garde 1992 and Garde 1994). North of Qarajaq Isfjord, Grocott (1984) and Pulvertaft (1986) reported flat-lying to south-dipping tectonic boundaries on Drygalski Halvø (shown on Fig. 1) and on Ikerasak (not shown) west of Drygalski Halvø, between grey gneiss in the hanging wall (equivalent to tonalitic gneiss on Nuussuaq) and a homogeneous, more leucocratic biotite gneiss in the footwall. These observations collectively indicate that the tonalitic gneiss makes up a major subhorizontal sheet tectonically intercalated between layers of homogeneous orthogneiss.

Almost horizontal layers of amphibolite or dioritic

Table 1. Tentative chronology of Proterozoic tectonic events and structural elements in Nuussuaq

Phase A.	Tectonic intercalation of major rock units	Intercalation of tonalitic gneiss and homogeneous orthogneiss
		Intercalation of orthogneisses with anorthosite-leucogabbro-gabbro
		Intercalation of homogeneous amphibolite with Itilliarsuk supracrustal rocks?
		Intercalation of Proterozoic marble with Archaean basement
		Emplacement of Ilorleeraq dykes?
Phase B.	N–S or NE–SW shortening	Formation of NW–SE trending folds and Puiattup Qaqqaa shear zone
		SE-plunging lineation
		Northerly hanging-wall movement in southern Nuussuaq
		Rotation of Ilorleeraq dykes (escape structure?)
Phase C.	NNW–SSE extension	Formation of Torsukattak shear zone
		Steep SE-plunging lineation and flattening along Torsukattak

gneiss are exposed over long distances at the tops of south-facing cliffs along Saqqap Tasersua and Uigorleq. Viewed from a helicopter these mafic marker horizons appear to have a very strong schistosity which suggests that intense ductile deformation has been focused along the mafic layers. In the lower parts of the same cliffs occurs a distinct subhorizontal, few metres thick pyrite and quartz-rich horizon, which may have been deposited from fluids migrating along a shear zone.

NW–SE-trending recumbent isoclinal folds in northern Nuussuaq

Recumbent isoclinal folds have been observed both in northern Nuussuaq and locally in southern Nuussuaq. Mafic marker horizons similar to those occurring along Saqqap Tasersua and Uigorleq crop out in several places north-west of these lakes, where they outline recumbent isoclinal fold closures. The most prominent isoclinal fold is located at the mountain Kanaakip Aaffaa in northern Nuussuaq (Fig. 1; Garde & Steenfelt 1999, this volume, fig. 26) and is outlined by an up to *c.* 500 m thick sheet of cream-coloured marble with zinc mineralisation (King 1983; Garde & Thomassen 1990; Della Valle & Denton 1991), intercalated with Archaean orthogneiss. The orientations of minor fold axes and associated extension lineations are south-easterly with subhorizontal to moderate plunges (Garde & Thomassen 1990), suggesting extension in a NW–SE direction. The marble can be correlated with the lower Proterozoic Mârmorilik Formation of the adjacent Uummannaq district described by Garde (1978) and Pulvertaft (1986), which also hosts zinc mineralisation; the isoclinal folding demonstrates that intense Proterozoic deformation has occurred in northern Nuussuaq.

A number of thin, flat-lying marble horizons also occur in the orthogneisses west and north of the main marble outcrop (Fig. 3; see also Rosenkrantz *et al.* 1974; Pulvertaft 1987; Garde & Thomassen 1990). They are interpreted as tectonic remnants of the same marble

Fig. 3. Sheets of light coloured lower Proterozoic marble (near and middle distance) with shallow northerly dips, intercalated with Archaean orthogneiss. Northern Nuussuaq, looking north towards Qarajaq Isfjord and Uummannaq. Marble layer is 10–50 m thick.

unit, repeated by (Proterozoic) isoclinal folding or thrust stacking.

NW–SE-trending upright to overturned folds

Open to tight, generally NW–SE-trending folds with amplitudes from a few hundred metres to *c.* 2–3 km disturb the general flat-lying structure of central and northern Nuussuaq, and some can be traced for up to 20 km. In northern Nuussuaq the fold axes have subhorizontal plunges. One such fold occurs in steep cliffs north-west of Innarsuaq on the north coast of Nuussuaq (Garde 1992, fig. 3); it has a subhorizontal, WNW–ESE-trending fold axis and is overturned towards the south-south-west. Farther towards the south-east the plunge of the fold axes increases, and steepens to about 70° near Torsukattak (probably due to reorientation by the Torsukattak shear zone, see p. 150).

Refolded folds

Refolded folds, some of which may be of Archaean age, have been recognised in several parts of Nuussuaq. South of Store Gletscher at the head of Qarajaq Isfjord (Fig. 1), a tightly folded anorthosite layer is refolded by small-scale inclined folds. In this area outcrops displaying two superimposed sets of folds are common; the folds are approximately coaxial, with subhorizontal ESE–WNW-trending axes. Superimposed folding on a scale of 1–5 km was inferred from structural trends visible on aerial photographs of this area, an interpretation supported by structural readings obtained during helicopter reconnaissance.

Observations north-east of Saqqaq suggest the presence of one (or several) early (Archaean?) recumbent folds within the Saqqaq supracrustal rocks, refolded by upright to overturned NW–SE-trending folds with subhorizontal to SE-plunging axes.

Subhorizontal ductile shear fabrics

Shear fabrics which appear to be younger than the latest phase of folding have been observed in central and, notably, south-western Nuussuaq, for example in the area south of Qaarusuit and within the Puiattup Qaqqaa shear zone (see below). South of Qaarusuit, thin subhorizontal to south-dipping zones of intense foliation with a spacing of 10–20 cm transect minor

Fig. 4. δ-shaped porphyroclast in orthogneiss, viewed southwestwards on a steep SE–NW-striking surface, suggesting northwest-directed displacement of the hanging wall. Locality 5 km south-south-west of southern end of Saqqap Tasersua.

folds, or may be axial planar to such folds; south-east-plunging mineral lineations are common within the zones of intense foliation. Feldspar porphyroclasts of centimetre size, presumably relicts of earlier migmatite veins, locally display σ- and δ-porphyroclast structures which consistently indicate northwards or north-westwards hanging-wall movement (Fig. 4). Asymmetric boudins of amphibolite or anorthosite-leucogabbro have been observed in the orthogneiss in several parts of southern Nuussuaq, and provide further evidence of northward hanging-wall displacement.

South-east-plunging extension lineations in central and southern Nuussuaq

A late south-east-plunging extension lineation is prominent in southern Nuussuaq in the vicinity of Itilliarsuk and Itilli. The lineation steepens and becomes more intense towards the coast, where it totally overprints earlier fabrics and is accompanied by strong flattening. These observations are part of the evidence for the presence of the Torsukattak shear zone (see p. 150).

The Puiattup Qaqqaa shear zone and structure of the Boye Sø anorthosite complex

The Puiattup Qaqqaa shear zone is a prominent NW–SE-trending, synformal zone of strongly deformed rocks up to *c.* 7 km wide that extends from the south coast of Nuussuaq west of Itilli, through the Boye Sø anorthosite complex in central Nuussuaq. The structure may continue north-westwards to Saqqap Tasersua and beyond (Figs 1, 2). The Puiattup Qaqqaa shear zone comprises a tectonic mélange of Archaean supracrustal and infracrustal rocks which appear to have been interleaved during N–S or NE–SW compression and NW–SE extension; it may also incorporate Proterozoic sediments. The system of NW–SE-trending folds on both sides of the shear zone may have formed in response to the same phase of deformation; evidence for this is presented below.

Along the length of the shear zone both its internal structure and lithologies show considerable variation. In the north-western part, the Boye Sø anorthosite complex forms an elongate, *c.* 5 km wide lens of imbricated and locally folded tectonic slices of anorthosite and related rocks (Fig. 2, section A–A; Garde & Steenfelt 1999, this volume, fig. 15). Although the bulk of the anorthosite complex is almost undeformed, a number of thin ductile shear zones display very high strain (as is common in very competent rocks, e.g. Myers 1978). Most of these high strain zones are localised along partially disrupted layers of metagabbro (Garde & Steenfelt 1999, this volume, fig. 15). The thrust slices which make up the south-western and central portions of the complex dip north-eastwards, whereas the much thinner north-eastern part dips steeply towards the south-west. The two parts of the complex thus form the limbs of a major, highly asymmetric synformal fold, which appears to post-date the tectonic interleaving and thrusting. The hinge zone is outlined by a tight south-east-plunging fold closure in metagabbroic and ultrabasic rocks in the northern part of the complex (Fig. 2, section A–A). Towards the north-west the Boye Sø anorthosite complex breaks up into a *c.* 4 km long tail of jumbled, commonly folded enclaves of anorthosite, leucogabbro and gabbro in a matrix of orthogneiss. Farther north-west a *c.* 100 m thick composite layer of schistose and strongly folded biotite-garnet schist and amphibolite suggests that the Puiattup Qaqqaa shear zone may continue in this direction (Fig. 1).

The south-eastern part of the Puiattup Qaqqaa shear zone is developed in granitic, tonalitic and dioritic orthogneiss, metavolcanic and metasedimentary supracrustal rocks, ultrabasic rocks, and a large area of Itilli diorite and homogeneous amphibolite. Near the south-western margin of the shear zone these lithologies are tectonically interleaved, strongly foliated, and locally tightly folded. Thin lenses of supracrustal rocks and lensoid fragments of mafic dykes occur along second-order shear zones in the orthogneisses, and towards the south-western margin of the main shear zone the polyphase gneisses themselves have a very distinct small-scale layered to lensoid tectonic fabric (Fig. 5). Rootless isoclinal folds are common, and migmatitic neosome veins in the orthogneisses are deformed into thin streaks which wrap around K-feldspar porphyroclasts.

Fig. 5. Strongly deformed orthogneiss with tectonic layers and lenses of supracrustal rocks and (?)mafic dykes. Near the south-western margin of the Puiattup Qaqqaa shear zone, *c.* 4 km north of the coast of Torsukattak. Hammer shaft is 45 cm in length.

Several tectonic lenses of anorthosite-leucogabbro occur in the south-eastern part of the shear zone, ranging from a few metres to *c.* 1 km in length, and mostly located within larger enclaves of supracrustal rocks. The largest lens occurs at a minor summit 480 m high, 3 km east of Itilliarsuk (Fig. 2) and exhibits an isoclinal

Fig. 6. Upper margin of a 1 km long anorthosite lens at the 480 m top 3 km east of Itilliarsuk. The anorthosite (left), which is little deformed internally, has a thin envelope of intensely sheared leucogabbro and gabbro (right). Width of outcrop in foreground is *c.* 5 m.

fold. It comprises a core of closely packed, up to football-sized aggregates of calcic plagioclase, and a thin envelope of intensely sheared metagabbro (Fig. 6) in tectonic contact with schistose, micaceous metasediment. The disrupted anorthosite-leucogabbro lenses imply considerable lateral movement along the shear zone, although the sense of displacement is not known. These lenses may once have been contiguous with the Boye Sø anorthosite complex and transported to the south-east, or related to a body of anorthosite south of Nuussuaq (small occurrences of anorthosite-leucogabbro are known on Arveprinsen Ejland; Knudsen *et al.* 1988; Garde & Steenfelt 1999, this volume) and thus transported in a northerly direction.

At the south coast of Nuussuaq the two margins of the Puiattup Qaqqaa shear zone diverge in opposite directions, respectively towards Itilliarsuk and Inussuk until they have a common ENE–WSW trend along Torsukattak (Fig. 2). This peculiar geometry is interpreted as a result of intersection between the Puiattup Qaqqaa shear zone and a second, largely unexposed, ENE–WSW-trending shear zone along Torsukattak with downthrow of the southern side towards the south-east (see p. 150 and Fig. 10).

There are further structural complications in the south-eastern part of the Puiattup Qaqqaa shear zone. The supracrustal rocks at Itilli consists of an extensive unit of homogeneous amphibolite which has agmatitic relationships with the Itilli diorite (Fig. 2). To the north-east this amphibolite is bounded by an intensely deformed ultrabasic horizon near the north-eastern boundary of the shear zone (Fig. 2, sections B–B and C–C). To the south-west at the opposite margin of the shear zone the homogeneous amphibolite is bounded by a screen of mixed, intensely foliated metasediments and metavolcanic rocks, in which a tight, *c.* 500 m wide south-east-plunging antiform occurs (Fig. 2, section C–C); a vertical fault is located along the south-western flank of this antiform. No lithologies elsewhere within the Itilliarsuk supracrustal sequence resemble the homogeneous amphibolite at Itilli. However, it might be equivalent to the massive greenstones in the northern part of Arveprinsen Ejland opposite Torsukattak (Marshall & Schønwandt 1999, this volume). We therefore tentatively interpret the homogeneous amphibolite as a lithological and structural element which was not originally a member of the Itilliarsuk supracrustal sequence, and which became juxtaposed against the local metasediments and metavolcanic rocks as a consequence of thrusting along the underlying ultrabasic layer. The juxtaposition may have been contemporaneous with the development of the flat-lying structure elsewhere in Nuussuaq, and must have taken place prior to intrusion of the Itilli diorite and the subsequent intense deformation along the north-eastern margin of the Puiattup Qaqqaa shear zone, and before the latter acquired its present geometry.

Folds in southern Nuussuaq

Tight to isoclinal, NW–SE-trending recumbent folds of possible Proterozoic age occur in the Itilliarsuk supracrustal rocks, in the vicinity of and possibly related to the Puiattup Qaqqaa shear zone. Intense minor folding on a scale of decimetres to metres was observed during short helicopter landings in orthogneisses on the island Qeqertaq and along the coast of Qeqertap Ilua. These folds are generally tight with upright, E–W- to NNE–SSW-trending axial surfaces; hinge lines with NW–SE trends and south-east plunges are most common. Local undeformed pegmatites (up to *c.* 10 cm thick) cut the folds. The folding in this area clearly post-dates a regional, possibly Archaean, migmatisation event in the orthogneiss and may also be related to development of the Puiattup Qaqqaa shear zone.

Ilorleeraq dykes and their relationships with the Puiattup Qaqqaa shear zone

The Ilorleeraq dykes (Garde & Steenfelt 1999, this volume) are a group of mostly 2–5 m thick mafic dykes which occur in south-eastern Nuussuaq. These dykes are considered to be of early Proterozoic age, and the observation that some are affected by the Puiattup Qaqqaa shear zone or folded by the NW–SE-trending fold system implies that these structures are Proterozoic.

Two vertical, 5–10 m thick mafic dykes with 150° trend occur in an area of homogeneous orthogneiss with uniform easterly structural grain north of Boye Sø (Fig. 2). These dykes appear to be unaffected by deformation or metamorphism. No dykes have been observed along the north-eastern flank of the Puiattup Qaqqaa shear zone, but several occur in the central part. The latter dykes are also vertical, but trend at 135° parallel to the shear zone, and are variably recrystallised. Additional dykes occur north of the embayment Ilorleeraq, north of the area where the west flank of the Puiattup Qaqqaa shear zone swings into parallelism with Torsukattak. From north-east to

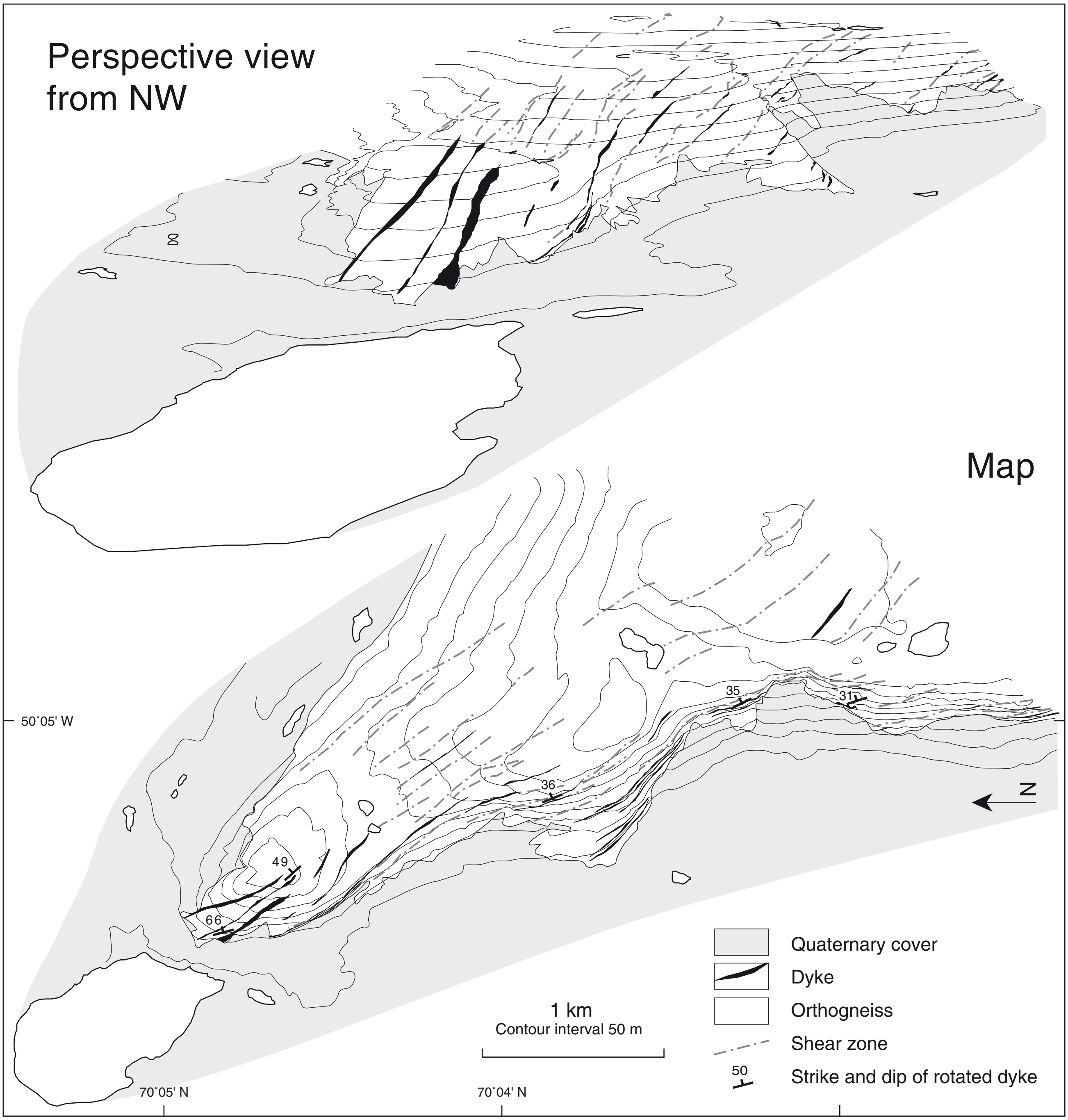

Fig. 7. Map and perspective view of Ilorleeraq dykes in the south-western part of the Puiattup Qaqqaa shear zone (location see Fig. 2), rotated from steep to flat-lying ENE-dipping orientations. The figure was constructed from seven 35-mm colour slides taken from a helicopter, using multi-model photogrammetry (Dueholm 1992; Dueholm *et al.* 1993). Modified from Dueholm *et al.* (1993, fig. 1).

south-west these dykes become progressively more intensely foliated and recrystallised as they are gradually rotated from nearly vertical to shallow NE-dipping orientations (Fig. 7). Close to Ilorleeraq the dykes have been transformed into flat-lying, discontinuous, 10–50 cm thick (rarely up to 10 m thick) layers conformable with their strongly foliated hosts (Fig. 8), and are completely recrystallised with new metamorphic hornblende.

The rotated dykes demonstrate that the north-easterly dip of the shear zone margin in this area was acquired by rotation from an earlier vertical, not flat-

Fig. 8. Intensely sheared subhorizontal Ilorleeraq dykes and dyke fragments in orthogneiss 2.5 km north-east of Ilorleeraq. The cliff face behind the lake is *c.* 100 m high.

lying orientation (see Fig. 2, section B–B), and implies that the upper part of the margin was transported towards the south-west. This observation appears to be in conflict with evidence from elsewhere in southern Nuussuaq of late hanging-wall movement in a northerly direction. However, it may be explained as a localised escape structure, which was formed in response to NE–SW compression during evolution of the Puiattup Qaqqaa shear zone.

A thin recrystallised dyke occurs *c.* 15 km north-west of Ilorleeraq in a side branch of the valley Qoororsuaq (Fig. 2). This dyke is folded in the hinge zone of a tight NW–SE-trending synformal fold which is part of the regional suite of NW–SE-trending folds (see Fig. 1). If this dyke is an Ilorleeraq dyke, and if these dykes are indeed Proterozoic, it follows that the synform (and probably also other NW–SE-trending folds elsewhere in Nuussuaq) is Proterozoic and possibly contemporaneous with the Puiattup Qaqqaa shear zone.

Fig. 9. Mafic sill (*c.* 25 m thick) of presumed Proterozoic age, apparently displaying an isoclinal fold, in orthogneiss with light snow cover. Southern Nuussuaq 20 km north-north-east of Saqqaq.

Other deformed dykes and sills

Other mafic dykes and sills occur along the south coast of Qarajaq Isfjord and south of Saqqap Tasersua. Some of the sills are differentiated, with olivine-rich cumulate bases (Garde & Steenfelt 1999, this volume); no direct relationship with the Ilorleeraq dykes has so far been established. A thick flat-lying differentiated sill visited at Sanningasoq, south of Saqqap Tasersua, is strongly sheared along its base, whereas its centre is almost undisturbed. Other intrusions exposed on steep cliff faces have irregular shapes which could be due to folding (Fig. 9; Garde 1992, fig. 3), but these observations could not be confirmed due to inaccessibility. Differentiated mafic sills of probable Proterozoic age have also been described from the Rodebay structural domain south of Torsukattak (Escher *et al.* 1999; Garde & Steenfelt 1999, both in this volume) and from the Uummannaq district (Schiøtte 1988).

Interpretation of structures along Torsukattak and on Nunataq: the Torsukattak shear zone

The apparent lack of direct lithological and structural correlation across Torsukattak, between the Nuussuaq domain and Ataa domain, suggests that the fjord hides an ENE–WSW-trending structural discontinuity. Small-scale structures at Oqaatsut, Arveprinsen Ejland and Anap Nunaa in the northernmost part of the Ataa domain (Garde & Steenfelt 1999, this volume, fig. 1) indicate that this structure is probably a major shear zone, here termed the Torsukattak shear zone. Observations by the authors and Higgins & Soper (1999, this volume) indicate that the shear zone is closely related to the isoclinal E–W-trending folds at Nunataq, and furthermore demonstrate that it is not a major crustal boundary.

On Oqaatsut west of Arveprinsen Ejland (Pedersen 1995; Garde & Steenfelt 1999, this volume, fig. 1; Rasmussen & Pedersen 1999, this volume), minor folds with E–W-trending axes plunging *c.* 30° eastwards have been observed in the northernmost part of the Atâ tonalite close to Torsukattak (H. Rasmussen, personal communication 1992). At the north coast of Arveprinsen Ejland the general N–S-trending Archaean structural grain of the supracrustal rocks is overprinted by a younger E–W-trending steep foliation and minor shear zones (M. Marker, personal communication 1991). Fur-

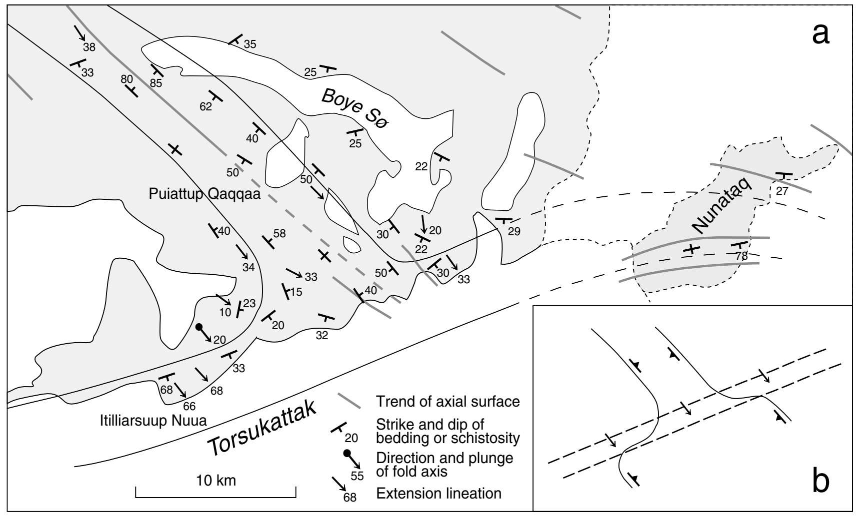

Fig. 10. **a**: Measured fabrics and extension lineations between Nunataq and Itilliarsuup Nuua, south-east Nuussuaq, where the Puiattup Qaqqaa and Torsukattak shear zones intersect.
b: Diagram showing how a SSE-dipping shear zone with downthrow to the south-east would affect the flanks of a NW–SE-trending synform fold. The peculiar geometry at the south-eastern end of the Puiattup Qaqqaa shear zone can be explained by intersection with the northern part of the Torsukattak shear zone.

thermore, the Proterozoic sediments on the island Qeqertakassak in Torsukattak and on Anap Nunaa display an east–west structural grain (Andersen 1991; Kalsbeek 1992; Escher 1995), and extensive albitisation in these areas (Kalsbeek 1992) might possibly be related to major shearing. In addition, N.J. Soper and A.K. Higgins (personal communication 1991) demonstrated that along the north coast of Anap Nunaa the intensity of Proterozoic deformation increases northwards. On the large isolated peninsula of Nunataq, at the head of Torsukattak, an overturned anticline in southern Nunataq is bordered northwards by an isoclinal syncline, which incorporates both Archaean and Proterozoic supracrustal rocks described above; the folds are therefore Proterozoic (Fig. 1; Higgins & Soper 1999, this volume).

Archaean supracrustal rocks lithologically similar to those at Nunataq reappear at Inussuk on the south coast of Nuussuaq (Figs 1, 2), on strike with the northern flank of the isoclinal syncline on Nunataq; it is therefore conceivable that the northern flank of the Proterozoic isoclinal syncline at Nunataq continues westwards along Torsukattak and gradually develops into the ENE–WSW-trending Torsukattak ductile shear zone. Farther west, at Itilli, the strike of the supracrustal rocks changes along the Puiattup Qaqqaa shear zone. To the south-west at Itilliarsuup Qaqqaa the supracrustal rocks are strongly flattened with a prominent south-east-plunging extension lineation (described above), which overprints earlier structures and becomes further intensified towards Itilliarsuup Nuua. We assume that this lineation post-dates the shallow SE-plunging lineations found to the north-east and that it reflects intense deformation in the interior part of the Torsukattak shear zone, with a large oblique shear component parallel to the lineation.

Interpretation of the Torsukattak shear zone

Both the intensification and steepening of fabric elements in the southernmost part of Nuussuaq and the geometry of the south-eastern end of the Puiattup Qaqqaa shear zone, where the two synform flanks swing in opposite directions, can be interpreted in terms of late deformation along the Torsukattak shear zone. Figure 10a shows measured fabric elements at the south coast of Nuussuaq between Nunataq and Itilliarsuup Nuua, and the common boundaries of the Puiattup Qaqqaa and Torsukattak shear zones. The diagram in Fig. 10b shows schematically how a narrow shear zone with the orientation of the Torsukattak shear zone would widen a synformal structure with the orientation of the Puiattup Qaqqaa shear zone and reorientate its margins, assuming that the main sense of displacement was parallel to the extension lineation with oblique south-east downthrow of the southern side. The resulting geometry along the schematic shear zone (Fig. 10b) matches the observed structures along the north coast of Torsukattak (Fig. 10a) and may also match the wide overall syncline outlined by the Proterozoic sediments on Anap Nunaa south of the fjord (Andersen 1991; Garde 1994). An oblique downthrow of the Ataa domain on the southern side of Torsukattak could also account for the previously discussed contrast in metamorphic grade across the fjord.

The model implies crustal extension across Torsukattak late in the Proterozoic structural evolution. It follows that the tight to isoclinal folds on Nunataq, and the Puiattup Qaqqaa shear zone (and also adjacent upright NW–SE-trending folds) must be assumed to have developed during one or several earlier compressive phases during the Proterozoic (see Table 1).

Discussion

Proterozoic reworking of Nuussuaq and relative timing of tectonic events

Substantial indirect evidence suggests that eastern Nuussuaq and Nunataq have been affected by major Proterozoic structural and metamorphic reworking, although the data available and reported here are not sufficient to establish a comprehensive Archaean and Proterozoic tectonic history of the region. The evidence for Proterozoic reworking can be summarised in three points. First, the Lower Proterozoic marbles and associated rocks are interleaved and folded with Archaean orthogneisses in both northern Nuussuaq and Nunataq. Secondly, Ilorleeraq dykes and differentiated olivine-bearing sills, both of presumed Proterozoic age, pre-date the development of the Puiattup Qaqqaa shear zone and probably also pre-date the regional system of NW–SE-trending folds in Nuussuaq. Thirdly, hornblende K-Ar age determinations (Rasmussen & Holm 1999, this volume) show that metamorphic temperatures of about 550°C were reached in the early Proterozoic over large parts of Nuussuaq.

The present structure of the Precambrian region of Nuussuaq can be presumed to reflect several successive tectonic events, but these are not fully documented or understood, and the relative chronology can only be established for some of the structural elements described above (Table 1). The intercalation of sheets and enclaves of anorthosite-leucogabbro-gabbro with the tonalitic gneiss, and the interleaving of a major sheet of tonalitic gneiss within two sheets of homogeneous orthogneiss in northern Nuussuaq, both pre-date the NW–SE-trending upright to overturned folds, but may have been contemporaneous with at least some of the isoclinal folds. The Puiattup Qaqqaa shear zone is either contemporaneous with, or post-dates, the latter folds. The Torsukattak shear zone is interpreted as post-dating the Puiattup Qaqqaa shear zone, and it is suggested that oblique slip in the Torsukattak shear zone parallel to the extension lineation resulted in major downthrow of the Ataa domain relative to the Nuussuaq domain during crustal extension. Asymmetric flat-lying shear fabrics in southern Nuussuaq which indicate northward hanging-wall movement (presumably during a period of compression) are relatively late structures which post-date the latest phase of folding, but their age relative to the Puiattup Qaqqaa and Torsukattak shear zones is uncertain.

A Rinkian detachment zone through Nuussuaq?

Several Rinkian detachment zones affect Archaean gneisses and Proterozoic metasedimentary rocks in the Uummannaq district north of Nuussuaq, and commonly exploit marble horizons of the Mârmorilik Formation (Pulvertaft 1986; Henderson & Pulvertaft 1987; Grocott & Pulvertaft 1990, and references therein). Detachment zones along Proterozoic marble units have also recently been described from the northern part of the Nagssugtoqidian orogen (Kalsbeek & Nutman 1996; van Gool *et al.* 1996). We propose that a detachment zone of similar nature transects Nuussuaq from south-east to north-west, linking the Anap nunâ Group south of Nuussuaq with the Mârmorilik Formation in the Uummannaq district, and in part hosted by the Puiattup Qaqqaa and Torsukattak shear zones. The proposed detachment zone would originate in Nunataq; as noted above, the isoclinally folded quartzite, marble and semipelite sequence on Nunataq is correlated with the lowest part of the Anap nunâ Group in southern Anap Nunaa (Higgins & Soper 1999, this volume). From the overturned isocline in Nunataq the detachment zone would continue westwards along the Torsukattak shear zone, and then swing into the Puiattup Qaqqaa shear zone and follow it north-westwards towards Saqqap Tasersua. Here the general structure is flat-lying, although structural details are poorly known. North-west of Saqqap Tasersua folded Proterozoic marble is interleaved with flat-lying Archaean gneisses. Linear structures in the marble are parallel to, and on line with the Puiattup Qaqqaa shear zone. The thin tectonic enclaves of marble in northern Nuussuaq provide a structural link further northwards to the nearest marble outcrops of the Mârmorilik Formation on Storøen and Ikerasak in the Uummannaq district (see e.g. Pulvertaft 1986, fig. 3).

Absence of a suitable boundary structure south of Nuussuaq for the previously proposed Burwell terrane

In some plate-tectonic reconstructions of the Proterozoic evolution of the North Atlantic Region (e.g. Hoffman 1989), the Burwell terrane has been extended eastwards from Baffin Island into central West Greenland, with its northern boundary inferred to lie at the south coast of Nuussuaq (i.e. along Torsukattak). As shown above, we have been unable to confirm the presence of a major crustal boundary in this area. Field observations on Nunataq and along the coasts of Torsukattak show that geological units and structures can be traced from the Ataa domain to the Nuussuaq domain, although they are partially concealed by Proterozoic isoclinal folds and the Torsukattak shear zone. Therefore, there is no evidence for the presence of the Burwell terrane in this region.

Van Kranendonk *et al.* (1993) and van Kranendonk & Wardle (1996) proposed the term Disko terrane for the unreworked Archaean rocks south of Torsukattak; the observations presented here suggest that the Ataa domain may only be a local tectonic lens more or less in its original position, which has escaped Proterozoic deformation. Discussion of the plate-tectonic implications of this conclusion in eastern Canada and on Baffin Island is beyond the scope of the present paper.

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