DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2004/110

Greenstone belts in the central Godthåbsfjord region, southern West Greenland

Preliminary results from field work in 2004

Julie A. Hollis, Jeroen A. M. van Gool,
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(1 DVD included)

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Contents

Abstract

The distinct, kilometre-thick units of supracrustal rocks in the central Godthåbsfjord region are here termed the Qussuk, Bjørneøen, and Storø greenstone belts. Parts were the subject of detailed geological mapping and sampling in 2004. The Qussuk and Bjørneøen belts lie in the mid-Archaean Akia terrane, and the Storø belt in the Tre Brødre terrane.

The Qussuk and Bjørneøen greenstone belts may be contiguous, however differences in their original depositional setting are indicated by lithological variation and preliminary geochemical results. Large tracts of amphibolite of intermediate composition on the Qussuk peninsula preserve primary volcanic clasts, and show LREE enrichment, consistent with an island arc setting. Lesser mafic amphibolites show flat REE patterns indicative of a second magmatic source. The Bjørneøen belt is dominated by similar mafic amphibolites with a lesser component of intermediate schist. These mafic amphibolites are interpreted as original ocean floor basalts based on rare pillow structures, and an interpreted, tectonically disrupted stratigraphic sequence with ultrabasic rocks at the base, overlain by mafic amphibolites and minor metasedimentary rocks. Tourmaline- and garnet-quartz-rich metasedimentary rocks are characteristic of the Bjørneøen, and to a lesser extent Qussuk, belts and interpreted as volcanic-exhalative in origin. For the Storø greenstone belt, two volcanic sources are indicated. Abundant mafic amphibolites preserve rare pillow structures, indicative of an ocean floor setting, consistent with the occurrence of ultrabasic rocks interpreted as original dykes, and with the close association with a large gabbro-anorthosite complex at the tectonic base of the sequence. Layered intermediate amphibolite and clastic metasedimentary rocks point to a shallower depositional environment closer to a continental source.

Late Archaean kilometre- to 10s of kilometre-length shear zones may be associated with large-scale fold structures. The oldest is the Ivinnguit fault, a high-grade shear zone forming the tectonic boundary between the Akia and Tre Brødre terranes, and which cuts Storø, Bjørneøen, Sermitsiaq, and Store Malene. The Storø shear zone is a 300 m wide, NNE-trending, steeply E-dipping ductile shear zone on north-west Storø and Kangersuaq. It has a NW-directed thrust-sense and associated kilometre-scale antiforms in the hanging wall and a synform in the footwall. The Kobbefjord and Ataneq faults are presumed Proterozoic structures characterised by silicification and retrogression to chlorite-epidote-muscovite.

Mineral assemblages indicate maximum lower amphibolite facies metamorphism in the Qussuk and Bjørneøen greenstone belts, in contrast with upper amphibolite facies early in the tectonometamorphic history for the Storø greenstone belt. Alteration and mineralisation have occurred in all of the greenstone belts studied. Gold occurrences are known on central Storø, Bjørneøen, and the Qussuk peninsula. The gold occurrences and anomalies along a NE-trending belt appear to be associated primarily with the NE-trending distribution of the greenstone belts themselves, rather than any specific structural elements. In the Storø and Qussuk greenstone belts high gold values are associated with garnet-quartz rocks interpreted as hydrothermal in origin. Stratiform horizons of disseminated iron-sulphide occurrences in amphibolites in each of the belts, may be continuous for more than 1 km. Calc-silicate alteration of amphibolites is widespread and locally documented to be associated with the early tectono-metamorphic history.

Introduction

This study was funded by the Bureau of Minerals and Petroleum (BMP) in Nuuk and carried out by personnel from the Department of Geological Mapping and the Department of Ore Geology at the Geological Survey of Denmark and Greenland (GEUS), and by invited collaborators from several international research institutions including the University of Edinburgh (Scotland), Windsor University and Memorial University (Canada), and Lund University (Sweden).

The aim of the study was to investigate the geological setting and evolution of important greenstone belts around central Godthåbsfjord. The mapping and sampling was focussed on the primary depositional settings of the greenstone belts and evidence for hydrothermal alteration within them, and characterisation of the tectonostratigraphy and tectono-metamorphic evolution including investigation of regionally important structures. The main instigation for the present work was the presence of known mineral occurrences of potential economic interest in this region (e.g. Appel et al. 2003). In particular, regional gold anomalies and gold occurrences within greenstones on Storø (Qeqertarsuaq) are promising and justify a further examination of the regional geological setting of supracrustal belts. Furthermore, the Nuuk region is of particular interest for our understanding of Archaean mid-crustal processes. It contains some of the largest segments of Early Archaean crust in the world and is also a target of international research into the tectonic assembly of Archaean continental crust and greenstone belts.

Mapping and sampling was carried out in the period June 29th to August 10th 2004 with work in the following main areas: Store Malene (Ukkusissat), the region between Serfarsuit and Kobbefjord (Kangerluarsunnguaq), Sermitsiaq (Sadelø), Bjørneøen (Qoornup Qeqertarsua), Storø (Qeqertarsuaq), Kangaarsuk, Qussuk, and Ivisaartoq (Fig. 1). Field maps from most areas were compiled at 1:20 000 scale on to a new topographic base, also produced in 2004.

This report is structured on the basis of our subdivision of the studied greenstone belts into the Qussuk belts, the Bjørneøen belt (Store Malene-Sermitsiaq-Bjørneøen), and the Storø belt (Kobbefjord-Storø-Kangaarsuk). This subdivision was based on lithological and tectonostratigraphic correlations and the distribution of major bounding structural elements. Important features of the regional setting, tectonostratigraphy, lithologies, metamorphism, alteration and mineral occurrences, and structural geology are outlined and discussed in each section.

The field maps compiled as part of this project are presented both in the body of this report and as 1:20 000 scale maps in PDF format in the DVD. These maps cover several specific areas in detail and may serve as a basis for further regional mapping and sampling of important lithologies and structures. An overview geological map incorporating the study areas in 2004 is shown in Fig. 2. The central part of the Nuuk region has previously been mapped at 1:100 000 scale by the Survey: Qôrqut 64 V.1. Syd (McGregor 1983), Ivisârtoq 64 V.2 Nord (Chadwick & Coe 1988), and Fiskefjord 64 V.1. Nord (Garde 1989). These maps and original field maps used in their construction served as a basis for the 2004 mapping. Other map sources include Smith (1998) and unpublished map data from 2000-2003 by S. Grimes.

A large number of rock, stream sediment, and soil samples were collected for analytical work. In addition to some petrographical observations the first preliminary geochemical results are reported, and all analytical data received before the deadline of the report are included in Appendix A. Limited additional sample preparation has been carried out in view of further geochemical and geochronological studies. Treatment of samples collected in 2004 for analytical work is covered in Appendix B.

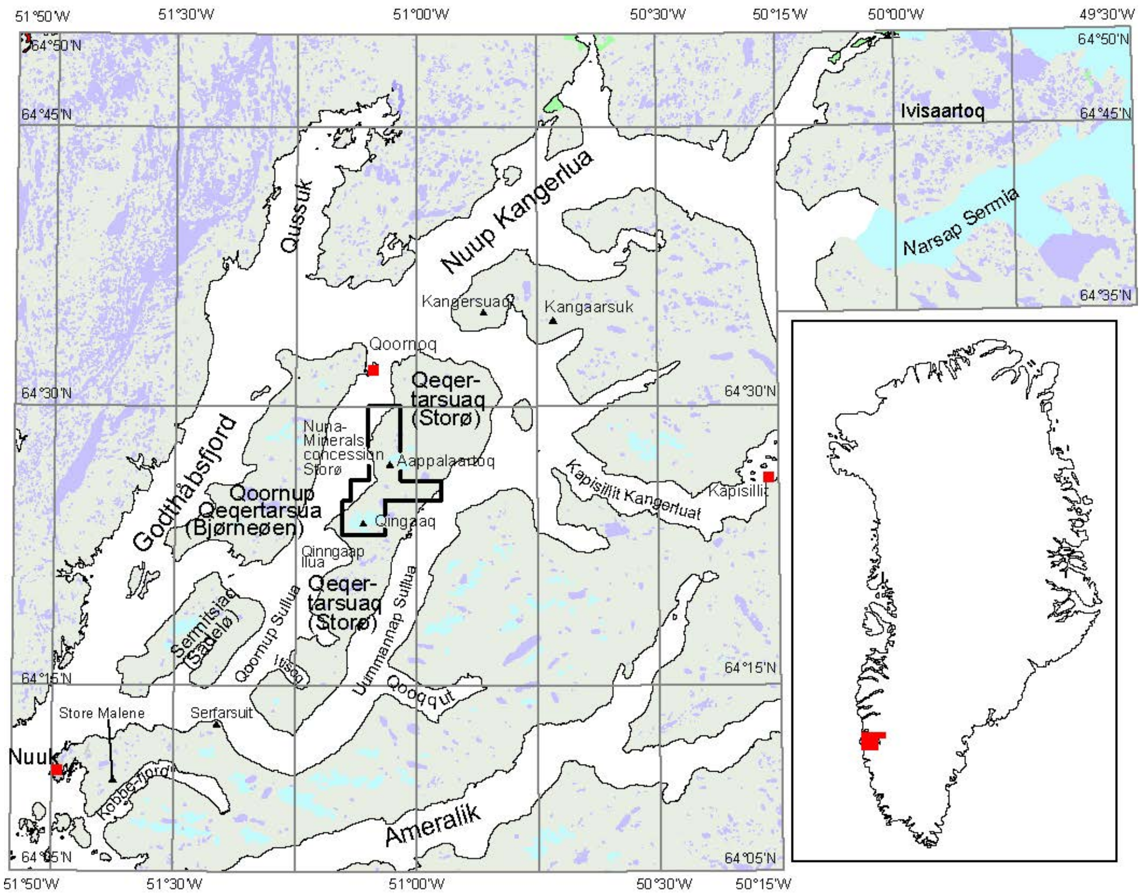

Figure 1. *Overview map covering areas mapped in 2004, with important place names used in the text. The tagged black rectangle on Storø shows the NunaMinerals A/S concession area.*

Enclosed in this report is a DVD containing:

1. The full report, compiled field maps in PDF format and an ArcView© project file containing geo-referenced compiled field data including localities, sample locations, structural data, and reference to digital photographs (see below).

2. Digital photographs from the 2004 fieldwork in jpeg format.

Instructions for accessing the DVD are given in Appendix C. A number of photographic figures are printed in the body of this report. These and numerous other photographs in this report are referenced in the following format: PFN xxx2004-nnn, where PFN stands for 'photograph file number', xxx gives the official initials of the photographer, and nnn gives the identifying number of the photograph. Locality numbers are also used throughout the text, given in the form: LN xxx2004-nnn, where xxx gives the official initials of the relevant geologist and nnn gives the identifying number of the locality. Localities (and all field data relating to these) may be viewed in the accompanying ArcView© project.

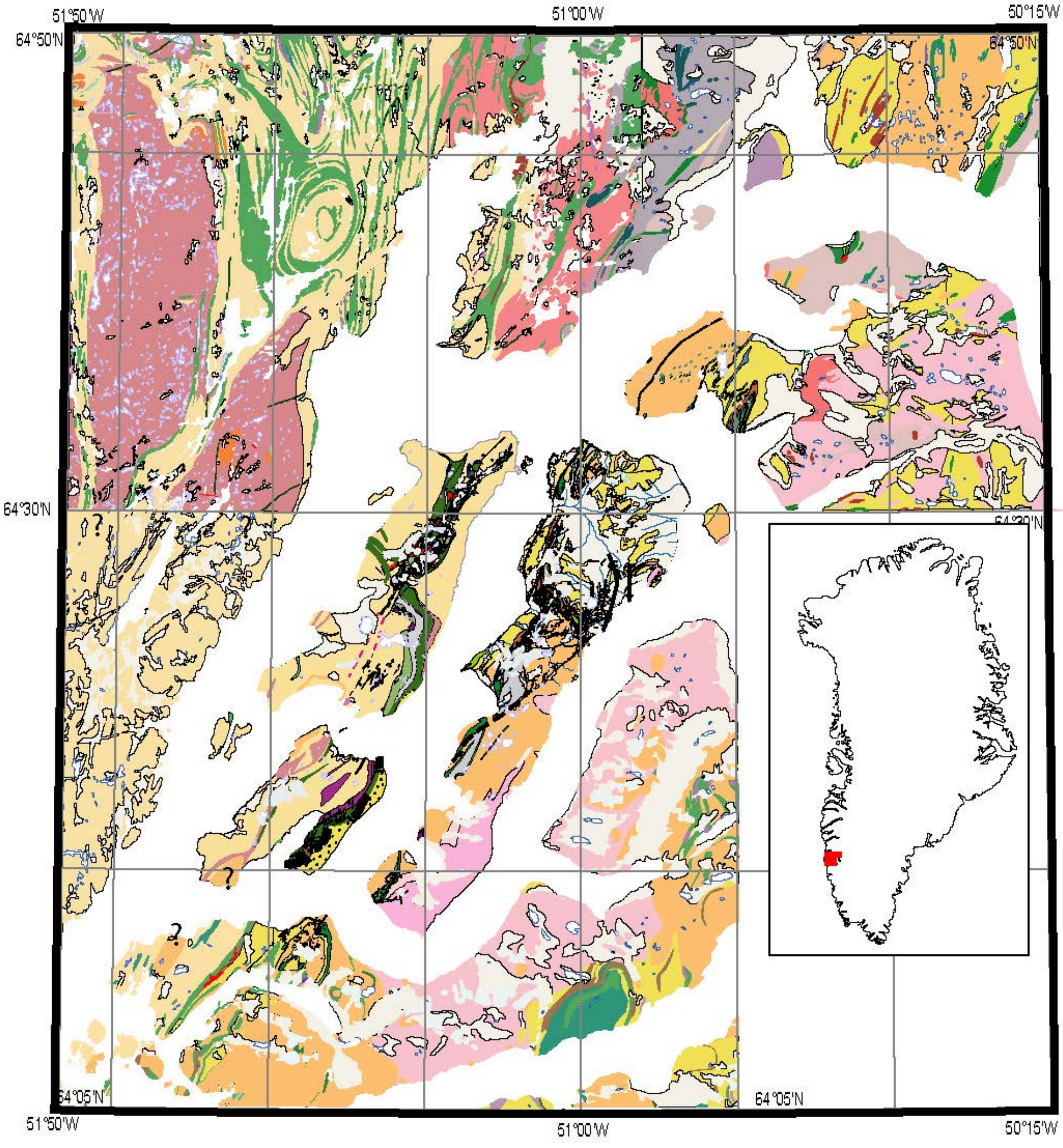

Figure 2. *Geological overview map of the central Godthåbsfjord region, compiled from published geological maps at scale 1:100 000 (McGregor 1983; Chadwick & Coe 1988; Garde 1989) and GEUS 2004 compiled field maps. The green, brown and violet lithologies are supracrustal and related intrusive rocks of the greenstone belts. See the ArcView© project in the attached DVD or the original maps for full legends.*

Regional geology of the central Godthåbsfjord region

A recent summary of the regional geology of the Nuuk region of southern West Greenland is given in Garde (2003). That study forms the basis of the short overview presented here with amendments in light of recent developments (e.g. Friend & Nutman in press). In this section we give a short regional overview with specific focus on aspects of relevance to the greenstone belts investigated in this study, whereas readers should refer to the earlier overview for a more thorough treatment of the history of development of geological ideas. Local introductions to each of the greenstone belts investigated in this study are given at the start of each chapter.

Table 1. *Overview of the geological evolution of terranes in the Godthåbsfjord region, showing timing of events in each of the terranes and common post-assembly events (after Garde 2003).*

Age (Ma)				
c. 2000-1800?	Ataneq fault			
c. 2000-1800	Kobbefjord fault system			
2400-2200	Palaeoproterozoic dolerite dyke swarm			
2530	Qôrqut granite complex			
	Akia	**Kapisillik**	**Tre Brødre**	**Færingehavn**
2720-2710	felsic dykes	felsic dykes	felsic dykes	felsic dykes
2800	metamorphic zircon growth	metamorphic zircon growth granitic sheets	Metamorphic zircon growth granitic sheets	metamorphic zircon growth granitic sheets
c. 2825			Ikkattoq gneiss	
			greenstone belts (including anorthosite)	
c. 2900	granulite facies metamorphism, TTG gneisses (incl. Nûk gneiss)	amphibolite facies metamorphism		
2970	Qugssuk granite			
c. 3000	greenstone belt/s	Ivisârtoq greenstone belt		
3200	dioritic gneiss			
c. 3300-3500				Ameralik dykes
c. 3600				metamorphic zircon growth white and Fe-rich gneiss
c. 3700-3800				Amîtsoq gneiss
c. 3850				Akilia association

The Nuuk region comprises some of the largest areas of early Archaean crust, but also includes large regions of middle to late Archaean crust. Collectively these make up part of the Archaean North Atlantic craton, which spans southern West Greenland and Labrador. Over the past three decades the Nuuk region has been the focus of intense geological interest, in the main part because a thorough understanding of the extensive Early Archaean Isua greenstone belt has significant implications for our understanding of early Earth processes and, in particular, the origins of life. However extensive work in the Nuuk region has also been fundamental to the development of our understanding of crustal processes in general and the development of the terrane model (e.g. Coney et al. 1980; Friend et al. 1987; 1988; Nutman et al. 1989; Friend et al. 1996; Friend & Nutman in press). From the mid-1980s it has been recognised that the Nuuk region can be subdivided into several continental crustal terranes of distinct ages and separated by tectonic boundaries, some of which are traceable for up to 100 km or more. Owing to the geological complexity of this region, investigations continue to reveal new and important breakthroughs in the subdivision and understanding of Archaean crustal processes. Figure 3 outlines the current state of knowledge of terrane subdivisions of the Archaean craton in the Nuuk region.

As a consequence of the volume of literature published on this region, numerous lithological and genetic classifications and terminologies have been proposed, many of which are now outdated, and which can be confusing to the reader. Here we try to use only groupings and classifications that imply genetic and/or temporal-geographic relationships (e.g. formation within a single terrane), and avoid terminologies that are not up to date. We employ the most commonly used official Danish or Greenlandic place names and use new Greenlandic spelling throughout, except for rock units originally defined using the older spelling.

To date, the Nuuk region has been subdivided into six different Archaean terranes, amalgamated in the period c. 2950 to 2700 Ma. In order of decreasing antiquity these are the Isukasia and Færingehavn (*c.* 3850 to 3300 Ma), Akia (*c.* 3200 to 2975 Ma), Kapisillik (*c.* 3075 to 2960 Ma), Tasiusarsuaq (*c.* 3000 to 2800 Ma), and Tre Brødre (*c.* 2826 to 2750 Ma) terranes. A more complete discussion of terrane geometry, history and composition can be found in Garde (2003). Those of particular relevance to this study, in central Godthåbsfjord, are the Færingehavn, Akia, Kapisillik, and Tre Brødre terranes shown in Table 1. Figure 3 illustrates the regional distribution of these terranes. In a general sense these can be regarded as a series of terranes that have been amalgamated via NW-directed thrusting during the middle to late Archaean, along tectonic boundaries that are now also deformed by later tectonism.

The Færingehavn and Tre Brødre terranes were for some time considered parts of a single terrane previously known as the Akulleq terrane. They are now known to represent terranes of different ages amalgamated in the late Archaean, though the tectonic boundaries between these are only well-defined in parts of the region (e.g. Færingehavn, Ameralik, outer Godthåbsfjord). These terranes are poorly defined in the eastern and interior parts of the region.

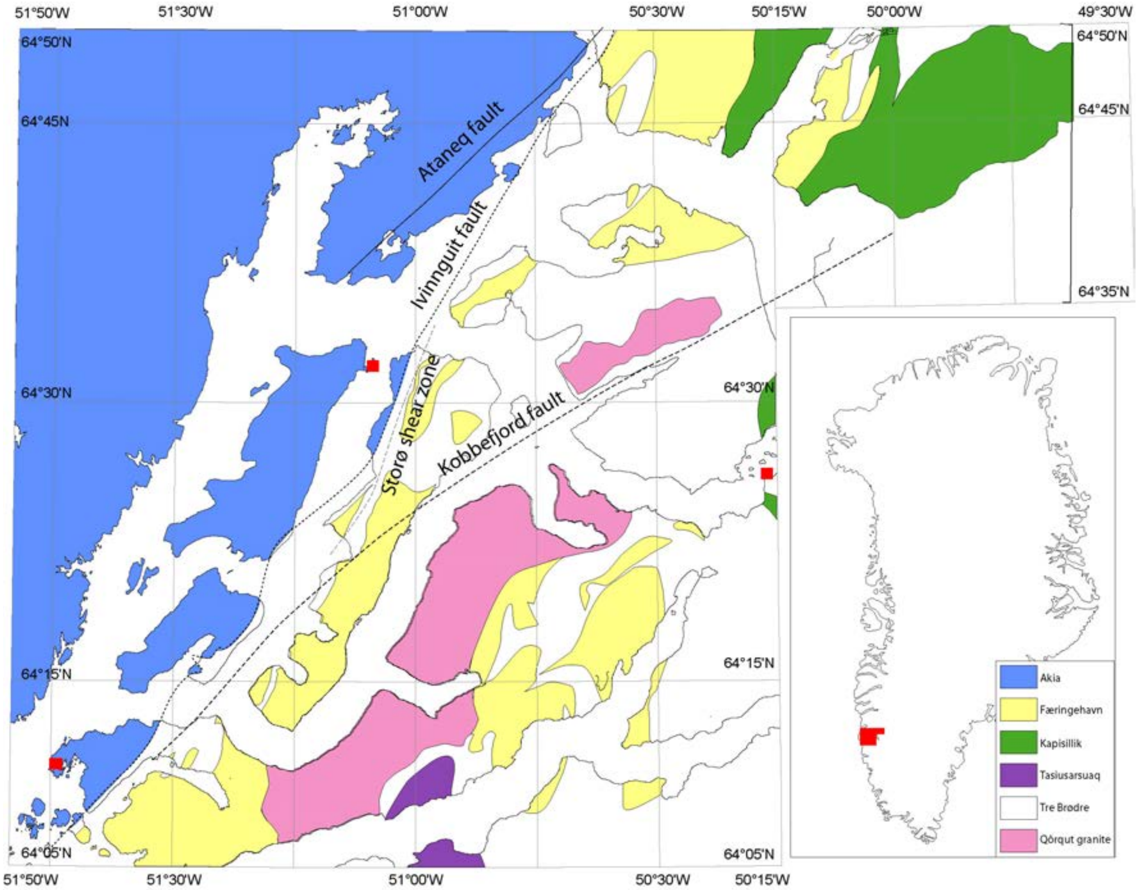

Figure 3. *Schematic map showing the approximate boundaries of the known geological terranes in the central Godthåbsfjord region, after Friend & Nutman (in press). Blue - Akia terrane, yellow - Færingehavn terrane, green - Kapisillik terrane, purple - Tasiusarsuaq terrane, all remaining land areas (white) - Tre Brødre terrane, pink - extent of Qôrqut granite outcrop.*

The Færingehavn and Isukasia terranes were also not distinguished from each other until very recently (Friend & Nutman in press) as these terranes are both comprised of similar components: *c.* 3800 to 3700 Ma tonalites (intruded by *c.* 3500 to 3300 Ma Ameralik dykes; Nutman et al. 2004), *c.* 3650 Ma granite, ultrabasic and gabbroic rocks, and Early Archaean rocks of inferred supracrustal origin. These rocks underwent granulite facies metamorphism in many areas at *c.* 3600 Ma (Friend & Nutman in press; Griffin et al. 1980; Nutman et al. 1996). In fact, these two terranes almost certainly represent dismembered parts of the same Early Archaean crust, rifted sometime in the middle Archaean. They now occupy different parts of the tectonostratigraphic sequence such that the Isukasia terrane lies structurally below the Kapisillik terrane, which in turn lies below the Færingehavn terrane. Furthermore the Isukasia terrane shows evidence for a *c.* 2950 Ma metamorphic event, which is not preserved in the Færingehavn terrane, but which is represented in the Kapisillik terrane. This indicates that the Færingehavn and Isukasia terranes were separate entities, and that the Isukasia and Kapisillik terranes had amalgamated by *c.* 2950 Ma.

Despite this common metamorphism, the Kapisillik terrane is derived from relatively much younger, middle Archaean, tonalitic and granitic orthogneiss and supracrustal rocks - the Ivisârtoq greenstone belt. In age and compositional make-up these components resemble those of the Akia terrane (*c.* 3200 to 2975 Ma). The Akia terrane preserves evidence for a *c.* 2980 Ma metamorphic event, though in the Akia terrane this reached granulite facies in many areas, whereas in the Kapisillik terrane only amphibolite facies metamorphism is preserved. Also in both terranes the depositional age of rocks of supracrustal origin has been constrained to > *c.* 3000 Ma (Garde et al. 1986, 2000; Friend & Nutman 1994; Friend & Nutman in press). Thus the Kapisillik and Akia terranes may also represent dismembered parts of a single middle Archaean terrane.

The Tre Brødre terrane, in tectonic contact with the Færingehavn terrane in many parts of the central Godthåbsfjord region, is dominated by the *c.* 2825 Ma Ikkattoq gneiss, but also includes greenstones (metasedimentary and mafic volcanic rocks) and gabbro-anorthosite. These rocks were originally considered to be part of the 'Malene supracrustal rocks' (now an abandoned unit), and thus grouped together with greenstone belts from across the region (including the Akia terrane). However, it is now known that these greenstone belts form distinct age groups and are probably unrelated. Schiøtte et al. (1988) placed a maximum depositional age of *c.* 2800 Ma on clastic metasedimentary rocks from within the Tre Brødre terrane, in contrast with the older, middle Archaean greenstones of the Akia terrane (e.g. Garde et al. 1986, 2000; Friend & Nutman 1994; Friend & Nutman in press). A further constraint is given by the assertion that the Ikkattoq gneiss intrudes the greenstones in parts of the terrane, see Nutman et al. (1989) and the chapter on the Storø greenstone belt in this report. It should be noted that although the Tre Brødre terrane is depicted covering a wide area of the Godthåbsfjord region in Fig. 3, its extent is poorly defined in the eastern, inland parts of the region and requires further investigation.

Granitic sheets and amphibolite facies metamorphism of *c.* 2720 to 2710 Ma have been noted in the Tre Brødre, Færingehavn, and Akia terranes, consistent with their amalgamation by this time. The juxtaposition of the Tre Brødre and Akia terranes occurred along the Ivinnguit fault (MacGregor et al. 1991), a tectonic structure that is thought to be continuous for tens of kilometres and which is an important structural feature within the area of this study. It is commonly referred to as a high-grade (amphibolite facies) mylonitic structure, typically only a few metres wide (e.g. Friend et al.1987, 1988), but reworking along parts of its length implies that the presently observed textures need not be related to the original assembly.

The emplacement of the sheeted Qôrqut granite complex in central Godthåbsfjord at *c.* 2530 Ma (Baadsgaard 1976; Brown et al. 1981; Moorbath et al. 1981; Friend et al. 1985; McGregor 1993) post-dates the regional deformation and terrane assembly. The Qôrqut granite cuts the Færingehavn and Tre Brødre terranes on southern Storø and further east and, on the basis of aeromagnetic data, probably extends still further east under Kangersuneq (Rasmussen & Garde 2003). The heat source for generation of Qôrqut granite is not known.

The Godthåbsfjord region was not subjected to high-grade metamorphism or penetrative deformation after the late Archaean. A thermal event in the Proterozoic resulted in emplacement of several generations of Mg-rich dolerite dykes at 2400 to 2200 Ma, with the latter age group being dominant (Bridgwater et al. 1976, 1995; Hall & Hughes 1990) and granitic dykes e.g. in the Qussuk area (Garde 1997; this report). The dolerite dykes show semi-ductile to brittle deformation and offset along the NE-trending Kobbefjord and Ataneq faults. The Kobbefjord fault resulted in localised generation of mylonitic structures and hydrous alteration under low-grade metamorphic conditions at *c.* 2000 to 1800 Ma (Smith & Dymek 1983). The Ataneq fault is though to involve, at least in-part, reworking Ivinnguit fault and similarly involved brittle deformation and pervasive local fluid-induced alteration and recrystallisation.

The Qussuk greenstone belts

Introduction: main objectives

The Qussuk area in north-western Godthåbsfjord as well as the adjacent Bjørneøen and Sermitsiaq to the south (which are described in other parts of this report), are located in the easternmost part of the Akia terrane (Figs 1, 3, 4).

The investigation at Qussuk and on the peninsula east of Qussuk (referred to as the Qussuk peninsula in the following) had three principal objectives:

1) To provide information about the primary depositional environment of the two main Archaean greenstone belts that crop out on the peninsula east of Qussuk, and locate areas of hydrothermal alteration and sulphide occurrences.

2) To investigate the late Archaean tectonic boundary (Ivinnguit fault) between the Akia and Tre Brødre terranes exposed east of the Qussuk peninsula, and the Palaeoproterozoic Ataneq fault in the south-eastern part the Qussuk peninsula, and investigate the significance of localised reworking and fluid movement along these structures.

3) to examine a small embayment on Nordlandet at the west coast of Godthåbsfjord, where the NNE-trending aeromagnetic boundary along westernmost Godthåbsfjord comes on land (Fig. 4), in order to find out whether a late Archaean or Palaeoproterozoic shear zone might exist in this area.

The field work in the Qussuk area was carried out by Adam A. Garde (GEUS) from a coastal camp in western Qussuk (LC aag2004-083, Fig. 4) with Tobias Hermansson (University of Lund, Sweden), and from three helicopter camps on the Qussuk peninsula with Mikkel Vognsen (University of Copenhagen). A few additional observations from 2004 by Henrik Stendal (GEUS) are also included here, although his work was not covered by the present contract.

Regional setting and previous work

The Akia terrane (3.2-2.97 Ga) is the oldest of several adjacent tectono-stratigraphical terranes in the Nuuk region and the one least disturbed by the late Archaean terrane assembly and reworking. The Qussuk area itself in the easternmost part of the Akia terrane has previously been covered by mapping for the Fiskefjord map sheet at scale 1:100 000 (Garde 1989) and is discussed in the monograph by Garde (1997) and several other publications cited in this paper.

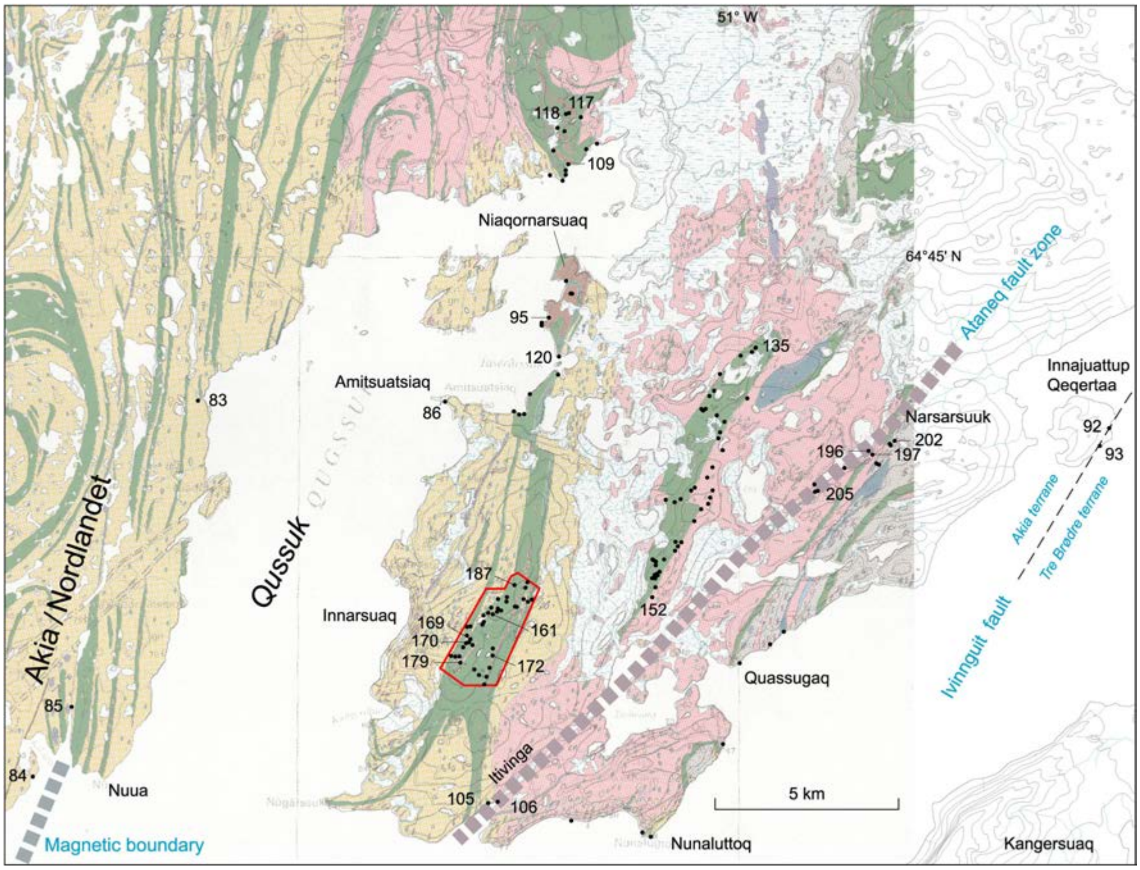

Figure 4. *Overview map of the Qussuk area with the two greenstone belts east of Qussuk (in green) and aag 2004 localities referred to in the text. The map area is shown with new topography and the published geological map Fiskefjord 1:100 000 as a dimmed underlay (see legend on the original map sheet). The position of Fig. 5 is shown by a red box.*

This area has largely escaped the 2980 Ma granulite facies event which is widespread elsewhere in the terrane (Garde et al. 2000), and has therefore preserved primary and diagenetic geological features better and probably also retained higher concentrations of mobile elements than other parts of the Akia terrane to the west. Table 2 provides a simplified overview of the components and geological evolution in the eastern part of the Akia terrane.

The field work in 2004 confirmed that the general map patterns, main lithological units, structures, and contact relationships as described by Garde (1989, 1997) are generally correct. However, we were able to significantly improve the understanding of the primary lithologies within the previously outlined amphibolite belts, and we found solid evidence of intense early hydrothermal activity in several places within the main supracrustal belts. In addition, we observed massive static hydrothermal alteration along the Palaeoproterozoic Ataneq fault in the south-eastern part of the Qussuk peninsula (Fig. 4), similar to that previously described from the adjacent western part of the Ivisaartoq map sheet area (Park 1986).

Table 2. *Overview of geological components in the Qussuk area, eastern Akia terrane, and their ages and relative positions in the geological evolution. The dominant components in the Qussuk area are marked in red and pink. Data from Garde et al. (1986), Garde (1997) and Garde et al. (2000).*

Geological setting of the Qussuk area, eastern Akia terrane

~2750 Ma?	Terrane assembly: juxtaposition of the Akia and Tre Brødre terranes
~2975 Ma	Post-kinematic diorite plugs
	End of penetrative deformation
2975 Ma	Emplacement of Qugssuk granite
2975 Ma	Emplacement of Taserssuaq tonalite complex
2980 Ma	Granulite facies metamorphism in western part
3050-2980 Ma	Four phases of regional deformation
	Emplacement of multiphase grey gneiss precursors
>3050 Ma?	formation of supracrustal rocks, mainly basaltic and gabbroic tholeiite. Minor andesite and sediment
	Ocean floor and island arc settings
3220 Ma	Dioritic core of the Akia terrane
<3220 Ma	Oldest supracrustal rocks (?)

Tectonostratigraphy, lithologies and metamorphism

General structure and age of the greenstone belts, and relationship with the Taserssuaq tonalite complex and Qugssuk granite

The previously identified amphibolite/supracrustal belts (in this report referred to as greenstone belts) at the head of Qussuk and on the Qussuk peninsula form a series of NNE-trending, isoclinally folded and steeply dipping units with thicknesses up to more than 1 km (Fig. 4; Garde 1989; Garde 1997). The belts are surrounded and variably intruded by gneissic and granitic rocks, most of which belong to the Taserssuaq tonalite complex and Qugssuk granite. These have been dated at *c.* 2975 Ma in the area north of Qussuk and thus provide a minimum age for the greenstones (Table 2; Garde et al. 1986, 2000).

In 2004 we found sporadic relict granulite facies mineral parageneses in amphibolites at the head of Qussuk (e.g. LC aag2004-120, Fig. 4), at the eastern margin of the area that has undergone granulite facies metamorphism previously dated at *c.* 2.98 Ga (Garde et al. 2000). The supracrustal rocks are therefore older than 2.98 Ga. However, their precise age is not known, and given their relatively simple structural history (see below) it is possible that the amphibolites in the Qussuk area are younger than others elsewhere in the Akia terrane.

Each of the individual greenstone belts contains upright to overturned, tight to isoclinal S-plunging folds of variable size, and a 'main' fold closure occurs at the northern end of one of the belts in the central part of the Qussuk peninsula (Fig. 4). These structures suggest that all the greenstone belts are disrupted parts of a single, large, sheet-like body that was intruded by members of the Taserssuaq tonalite complex and Qugssuk granite during a single major episode of E-W crustal shortening and folding.

Both the previous and new field observations suggest that the granitoid sheets were emplaced contemporaneously with the isoclinal folding, whereas the supracrustal rocks themselves had already previously acquired a moderate to intense planar fabric during the previous tectonic history (Table 2). The S-plunging fold system in the Qussuk area is presumed to have been formed at *c.* 2975 Ma, during and shortly after the magmatic emplacement of the Taserssuaq tonalite complex and Qugssuk granite.

Grey amphibolite and associated volcano-sedimentary rocks

Work in 2004 within the two main supracrustal belts in the Qussuk area mainly consist of unusually leucocratic amphibolite, which is rich in plagioclase and commonly contains biotite in addition to hornblende. This lithology corresponds to 'grey amphibolite' or 'leuco-amphibolite' of andesitic composition, which has previously been described by several authors from sporadic occurrences within the Archaean of southern West Greenland and which was also mentioned by Garde (1997).

Very close inspection in 2004 of numerous outcrops in the Qussuk area revealed that the grey amphibolite very commonly possesses a primary fragmental texture of pyroclastic or volcaniclastic origin, which in turn shows that part of the volcanism was explosive. A detailed map of the supracrustal belt east of Innarsuaq is shown in Fig. 5, with field localities shown as a dotted signature along traverses where the fragmental texture has been observed. The next supracrustal belt to the north-east (between LC 135 and 152, Fig. 4) comprises similar rocks but generally less well exposed and more intensely deformed. The fragmental grey amphibolites typically contain numerous, up to decimetre-sized, angular fragments composed of plagioclase, hornblende and accessory titanite, and commonly also biotite, diopsidic clinopyroxene and/or quartz, with slight variations in colour index and grain size. The clasts are set in a finer-grained and generally more leucocratic matrix consisting of the same minerals. Although large parts of the grey amphibolite are intensely deformed and the fragmental nature is therefore commonly very difficult to discern, it is locally unequivocal in low-strain rocks (Figs 6 and 7).

Occasional massive, decimetre- to metre-thick sheets of fine-grained diorite that cut the layered and fragmental rocks may either be interpreted as feeder dykes rotated towards parallelism with their hosts, or hypabyssal dykes emplaced into already deformed pyroclastic rocks.

In all parts of its outcrop areas the fragmental grey amphibolite is closely associated with fine-grained, finely laminated rocks composed of plagioclase, biotite, quartz, and sometimes hornblende. The persistent and parallel nature of the compositional layering observed in these rocks suggests they are former tuffs (with hornblende common, Fig. 8), or tuffites (dominated by plagioclase, biotite, and quartz).

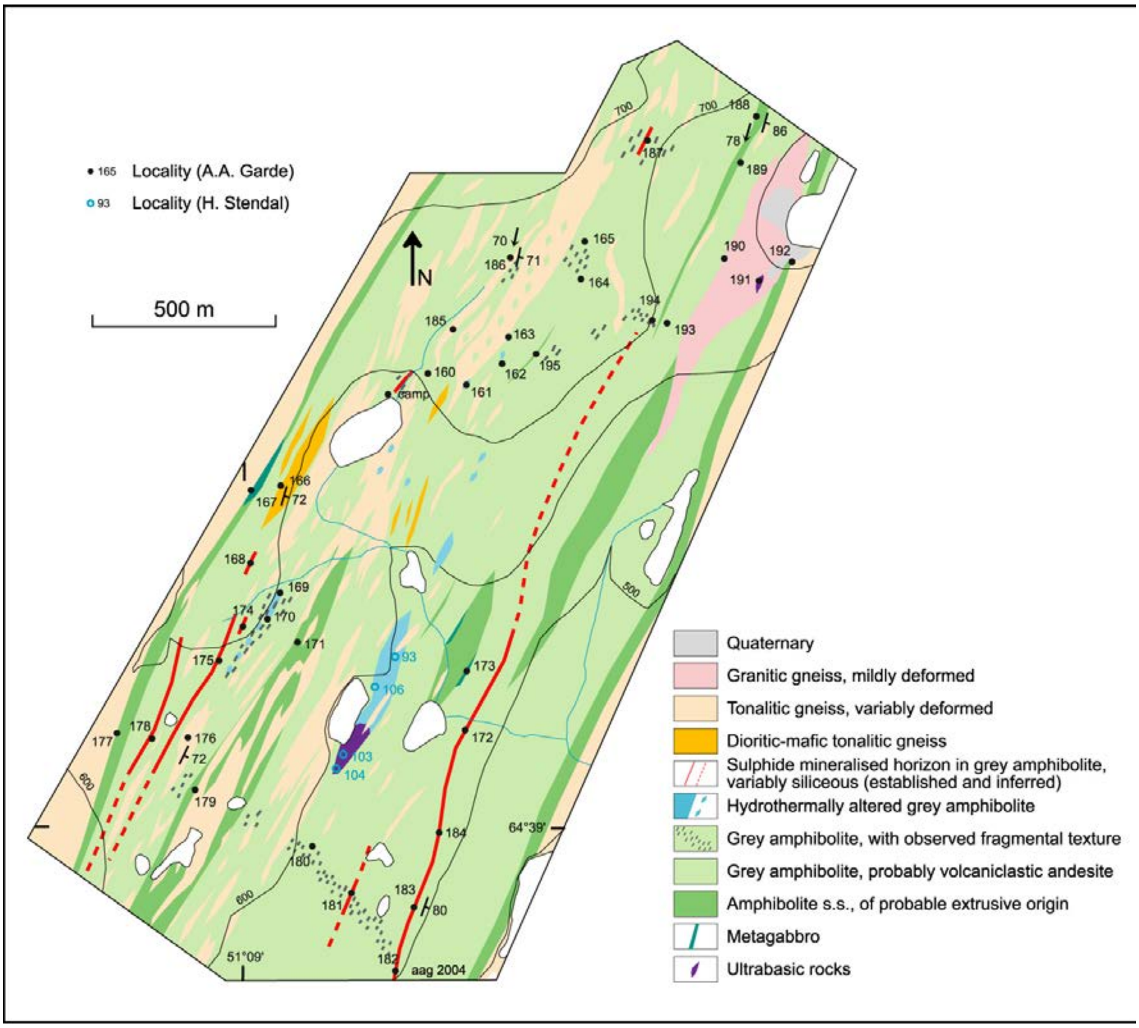

Figure 5. *Detail geological map of a supracrustal belt east of Qussuk, northern Godthåbsfjord. The central part of the map includes observations by H. Stendal and B.M. Nielsen. The location of the map area is shown on the overview map (Fig. 4).*

Figure 6. *Fragmental grey amphibolite of pyroclastic or volcaniclastic origin in the core of a S-plunging fold in the central Qussuk peninsula (LC aag2004-135). The field of view is c. 30 cm across.*

Amphibolite *s.s.* and metagabbro

Irregularly calc-silicate-banded amphibolite, possibly derived from pillow lava, and consisting of plagioclase, hornblende, and diopsidic clinopyroxene as well as common accessory titanite, was only observed rarely and in small volumes within the Qussuk area (e.g. LC aag2004-120, Fig. 4), although such rocks are generally widespread in the Archaean of southern West Greenland and indeed in other parts of the Nuuk region such as Ivisaartoq. In one or two of the least deformed localities with this lithology within the Qussuk area, we observed deformed, coherent decimetre-scale networks of thin, diopside-rich veins which may represent former pillow crust and interstices in pillow lava (e.g. LC aag2004-179).

Fine-grained, homogeneous amphibolite (*s.s.*) with equal proportions of plagioclase and hornblende is more common and may form lenses or tracts up to tens of metres thick and hundreds of metres long. These rocks occasionally contain poorly developed graded igneous layering and are interpreted as hypabyssal sill complexes. Medium-grained metagabbroic rocks, locally with much more well-developed rhythmic magmatic layering, form rare sheets up to less than 50 m thick which are most commonly associated with fine-grained, black, homogeneous amphibolite. Previously published analyses of homogeneous amphibolites s.s. from elsewhere in the Akia terrane show that they are generally of tholeiitic basaltic composition and may represent ocean floor environments.

Figure 7. *Angular volcanic clasts in grey amphibolite. LC aag2004-164.*

Ultrabasic rocks

Several tectonically disrupted lenses of ultrabasic rocks up to 50 m thick crop out around LC aag2004-152 in the southern part of the eastern main greenstone belt. Most of these are greyish brown on fresh surfaces and light brown weathering, and are composed of centimetre-sized sheaves of magnesian amphibole, phlogopite, euhedral deep green chlorite, partially altered orthopyroxene, and common accessory magnetite. Lithologies with numerous pseudomorphs after euhedral (?cumulate) orthopyroxene have also been observed (Fig. 9). The observations suggest that the ultrabasic lenses are tectonically dismembered cumulate parts of mafic intrusions.

Figure 8. *Heterogeneous, cm- to dm-scale layered grey amphibolite, interpreted as derived from former tuff. LC aag2004-120 south of Niaqornarsuaq, at the head of Qussuk.*

Figure 9. *Undeformed, hydrothermally altered ultrabasic rock with pseudomorphs of orthopyroxene. Secondary orthoamphibole, chlorite, and magnetite are common. LC aag2004-154.*

Garnet- and tourmaline-rich metasedimentary, exhalative, and/or hydrothermal rocks

Both at the head of Qussuk and in the central part of the Qussuk peninsula we have found layers up to a few metres thick of coarse-grained, garnet-, quartz-, and locally tourmaline-rich rocks (Fig. 10) associated with disseminated sulphide occurrences, and closely associated with the various types of amphibolite described above. Some of these unusual rocks may contain up to about 50 % garnet, and up to decimetre-thick, discordant quartz-garnet veins may protrude into the adjacent amphibolite. It is considered that the majority of these lithologies are similar to quartz-garnet rocks reported from the early Archaean Akilia association by McGregor & Mason (1977) and of volcanogenic-exhalative or hydrothermal origin.

These lithologies occur for example at the head of Qussuk (LC aag2004-095 and 109 south and north of Niaqornarsuaq, Fig. 4) and in the central part of the Qussuk peninsula (LC aag2004-172).

Figure 10. *Quartz-tourmaline rock of probable exhalative or hydrothermal origin in a rusty weathering zone c. 10 m thick, associated with grey amphibolite and amphibolite s.s. at the head of Qussuk (LC aag2004-109). The yellowish weathering parts are almost pure quartz, and the finely laminated dark bands consist of fine-grained tourmaline.*

Large and very prominent, rusty-weathering exposures of sillimanite-garnet-biotite-rich metasedimentary rocks occur on the S-facing hills north of the head of Qussuk (LC aag2004-117 and 118, Fig. 4). The rust stain is in part derived from local iron sulphides, but appears to be mainly related to oxidation of silicate or oxide iron, such as is commonly observed elsewhere in Greenland by weathering of sillimanite-rich rocks.

Alteration and mineralised zones

Early hydrothermal alteration, probably by CO_2-rich fluids

Evidence of early hydrothermal alteration, probably by CO_2-rich fluids, was discovered in several places within the thick greenstone body c. 3 km east of Innarsuaq (Fig. 4). The most prominent zone of massive alteration occurs in fragmental, grey amphibolite between LC aag2004-169 and 170 (Fig. 11). The largest alteration zone is about 350 m long and more than 50 m wide. The alteration zones form large tectonic lenses that are significantly less deformed than the surrounding fragmental grey amphibolite. Several other smaller zones of alteration occur in grey amphibolite within 1 km of the large lenses. They are generally boudinaged into individual dyke-like pods a few metres long (Fig. 11). The massive, hydrothermally altered grey amphibolite at LC aag2004-161 (Fig. 11) and the fragmental variety at LC aag2004-169 (Fig. 12) both contain a medium-grained, peak-metamorphic assemblage of diopside, zoisite (with yellow pleochroism, probably thulite), titanite, and fine-grained garnet. The volcanic fragments in the fragmental amphibolite (LC aag2004-169) are greyish and commonly less altered than the matrix (Fig. 12). It is considered likely that the alteration is due infiltration of CO_2-rich fluids and carbonate formation, with subsequent metamorphic decarbonation reactions producing diopside, zoisite and garnet.

Two sets of observations show unequivocally that the alteration took place prior to deformation and metamorphism, and it is therefore likely that it occurred during early diagenesis. First, In unaltered rocks the volcanic fragments and their matrix are generally mineralogically very similar, and the alteration therefore seems to have taken place before the onset of metamorphism, at a time when the matrix was more porous and permeable than the volcanic fragments themselves. Secondly, the facts that the hydrothermally altered zones are boudinaged, and that the altered lithologies are much less deformed than their unaltered counterparts, imply that the alteration took place prior to the relatively simple deformation history.

Figure 11. *Two dark green boudins of altered grey amphibolite in the foreground and middle distance with granular, peak metamorphic diopside and zoisite. Main supracrustal belt east of Innarsuaq, see Figs 4 and 5 (LC aag2004-161).*

Sulphide mineralised zones

The grey, commonly fragmental amphibolite contains several thin layers of disseminated iron sulphides, which appear to follow certain stratigraphic levels, although the latter are now difficult to discern (Figs 4 and 13). The sulphide-mineralised zones are commonly more siliceous and more coarse-grained than their surroundings. In some places the sulphide-mineralised layers are associated with garnet-quartz rocks such as already described, whereas they are not related to late shear zones. Viewed in thin section the opaque grains are elongate, typically up to 1 mm large, and evenly distributed. They appear to be in textural equilibrium with the high-grade equilibrium assemblage formed by the silicate minerals. It is therefore tentatively suggested that the disseminated iron sulphide occurrence is volcanogenic-exhalative or early diagenetic-hydrothermal in origin. However, it remains uncertain if host rocks themselves have been influenced by volcanogenic or hydrothermal alteration, or if some of them represent tuffites with a significant clastic sedimentary component.

Figure 12. *Variably altered fragmental grey amphibolite with diopside and zoisite at LC aag2004-169 in the main supracrustal belt east of Innarsuaq (Fig. 4). The alteration appears to have affected the matrix more intensely than the volcanic clasts and is interpreted as of diagenetic origin. Younger, rusty-weathering quartz veins cut the altered rocks in the central and right parts of the outcrop.*

Gold mineralised zones

Analysis of 57 rock samples collected in the Qussuk area in 2004 (see the ArcView© project attached to this report) shows that anomalous gold is present in several lithologies that were interpreted in the field as volcanic-exhalative or related to early hydrothermal activity. A quartz-tourmaline rock collected at the head of Qussuk yielded 2.2 ppm Au (477326, LC aag2004-109, Figs 4, 10), and an iron sulphide-impregnated layer in grey amphibolite from the central part of the Qussuk peninsula yielded 1.4 ppm Au (477384, LC aag2004-187, Fig. 5). This locality is cut by a narrow Palaeoproterozoic fracture zone, which however seems unrelated to the visible sulphide occurrence. A coarse-grained garnet-quartz rock, likewise sampled at the head of Qussuk, yielded 0.2 ppm Au (477313, LC aag2004-095). Several other samples from these or geologically similar localities within the grey amphibolite units contain gold in the low ppb range. Fifteen soil and stream sediment samples have also been collected and analysed. One of these, a rusty soil sample next to the above mentioned iron sulphide-impregnated layer at LC aag2004-187, yielded 14 ppm Au. Several other samples of rusty soil from sulphide-mineralised zones in the grey amphibolite yielded Au in the range 10-30 ppb Au.

No anomalous gold has been found in hydrothermally altered rocks along the Ataneq fault. A second batch of a few additional samples from the Qussuk area is being analysed at the time of writing.

Figure 13. *Narrow zone of quartz- and hornblende-rich rock with weak, disseminated sulphide occurrence in grey amphibolite at LC aag2004-178 in the main supracrustal belt east of Innarsuaq. This type of mineral occurrence, which is not related to late shear zones, is relatively common in the grey amphibolite (see Fig. 5).*

The possibility is opened as a preliminary and very tentative interpretation that the anomalous gold in the Qussuk area is of volcanogenic-exhalative origin and thus related to volcanic processes in a former island arc environment (see below). Conversely, it is concluded that the Palaeoproterozoic hydrothermal system associated with the Ataneq fault was not auriferous.

Depositional environment of the grey amphibolites and associated metasedimentary rocks

We have not yet obtained complete geochemical analyses of the grey amphibolites collected in 2004, and moreover, a thorough treatment of the new geochemical data is outside the scope of this report. However, previous major and trace element analyses of a handful of grey amphibolites and associated metasedimentary rocks from the eastern Akia terrane (Garde 1997) show that some of these rocks are andesitic in composition and have trace element characteristics that are compatible with an island-arc setting, despite evidence of variable element mobility.

The grey amphibolites studied in the field in 2004 contain recognisable fragmental textures of volcanic origin. However, most are strongly deformed, and they are all metamorphosed to upper amphibolite facies. It is therefore impossible to identify such criteria as the former presence or absence of volcanic glass, or distinguish with certainty between autoclastic rocks generated by in situ autobrecciation, pyroclastic rocks generated by explosive volcanic eruptions, or reworked volcaniclastic rocks.

Nevertheless, a few general comments can be made. First of all, the generally heterogeneous nature of the fragmental grey amphibolites suggest to the present authors that most of the rocks are pyroclastic or volcaniclastic, because autobrecciation would result in rocks in which the clasts are essentially of uniform composition. Furthermore, if the rocks are indeed of pyroclastic or volcaniclastic origin (or both), this points to subaerial or shallow subaqueous conditions of eruption, which are typically found in island arcs but not on the ocean floor, whether in mid-ocean or in a back-arc basin.

Notwithstanding the incomplete nature of the presently available geochemical data, we conclude that the Qussuk area represents a hitherto unrecognised island arc environment, strongly deformed, but lithologically complete. The area contains subaerial or shallow subaqueous pyroclastic and volcaniclastic components of andesitic composition (to be further confirmed by full geochemical analysis), large amounts of reworked sedimentary rocks retaining a general andesitic affinity, abundant local evidence of syn-volcanic or early diagenetic hydrothermal activity, and intrusive dioritic to granitic rocks that were emplaced from below into the volcanic pile during crustal shortening.

The absolute age of the andesitic metavolcanic rocks and their relationship with the likely ocean floor volcanic complexes that predominate in other parts of the Akia terrane are not known. It may be speculated that an island arc now represented by the Qussuk area was stitched to an older ocean floor in the west in connection with the intrusion of the Taserssuaq tonalite complex, in which case the grey amphibolite might be almost contemporaneous with the plutonic rocks that intrude it.

Late Archaean and Palaeoproterozoic linear structures and associated hydrothermal alteration

The Ivinnguit fault

The Ivinnguit fault is a tectonic boundary structure (terrane boundary) between the Akia terrane and several other, smaller terranes to the east (MacGregor et al. 1991). East of Qussuk the Ivinnguit fault separates the Akia terrane from the Tre Brødre terrane (Fig. 4), which consists of *c.* 2825 Ma Ikkattoq orthogneisses with abundant enclaves and massive sheets of anorthosite and leucogabbro. The Ivinnguit fault is older than *c.* 2.7 Ga, as it is cut by granitic dykes on southern Bjørneøen dated at this age (Friend et al. 1996).

The Ivinnguit fault was visited where exposed on the south-eastern side of the island Innajuattup Qeqertaa to the east of the Qussuk peninsula (LC aag2004-092 and 93, Fig. 4). The new observations fully confirmed the previously established interpretation in several publications by C.R.L. Friend, V.R. McGregor and A.P. Nutman, that the Ivinnguit fault is a steep, well defined tectonic boundary of late Archaean age that separates two different tectono-stratigraphic terranes.

There is a marked increase in the ductile strain as one approaches the Ivinnguit fault from either side. The increasing strain is noticeable already hundreds of metres away from the actual boundary, both in the homogeneous, otherwise low-strain components of the Taserssuaq tonalite complex exposed to the north-west of the boundary, and in the Ikkattoq gneiss exposed to the south-east.

At LC aag2004-092 and 93 the Ivinnguit fault itself is a well defined, *c.* 10 m thick mylonite zone which does not appear to have been significantly affected by metamorphic recrystallisation after the terrane assembly, contrary to other outcrops of terrane boundaries in the Nuuk region. Original ultramylonitic textures can thus readily be seen. However, we did not observe any extensive vein systems or any massive hydrothermal alteration, except for local, up to 10 cm thick quartz veins in the fault itself. Furthermore, we noted an undeformed dolerite dyke of presumed Palaeoproterozoic age close to LC aag2004-093, which cuts straight across the Ivinnguit fault without visible offset (Fig. 14). The undisturbed dyke and the lack of massive alteration demonstrate that the Ivinnguit fault has not been reactivated by Palaeoproterozoic movement or fluid transport along this part of its extent.

A comment on Park's (1986) interpretation of structures now related to the Ivinnguit fault

Park (1986) made a detailed survey of the structural evolution in the south-western corner of the Ivisaartoq map sheet area and in particular around the Ataneq fault. Her work was carried out before it was recognised that the Godthåbsfjord region consists of several different tectono-stratigraphic terranes with different pre-assembly magmatic and tectonic histories. However, Park (1986) did recognise intense late Archaean ductile tectonic fabrics in the westernmost part of her study area, i.e., the westernmost boundary area of what is presently known as the Tre Brødre terrane, and she was also able to distinguish these fabrics from evidence of younger brittle deformation, which she correctly related to the Ataneq fault.

The somewhat elaborate structural model established by Park (1986) for the late Archaean deformation, which she interpreted as being related to the western, tectonically thickened limb of an overturned fold, is no longer necessary. The late Archaean ductile fabrics can now be interpreted more simply as increasing planar strain development with proximity to the Ivinnguit fault. The fabrics imposed by the terrane assembly coincide with, and variably reinforce, older fabrics along the western limb of the overturned fold.

Figure 14. *Dolerite dyke of presumed Palaeoproterozoic age cutting the Ivinnguit fault at a right angle, without apparent offset. View direction NW, parallel to the dyke and perpendicular to the trend of the intensely deformed host rocks. LC. aag2004-093, Innajuattup Qeqertaa.*

The Ataneq fault

The NE-trending Ataneq fault in the south-eastern part of the Qussuk peninsula is a member of a conjugate Palaeoproterozoic fault system which also includes, for instance, the similarly NE-trending Fiskefjord fault and a WNW-ESE-trending fault across Qussuk (Fig. 4). The faulting was presumably related to Palaeoproterozoic (Nagssugtoqidian and Ketilidian) orogenesis to the north and south of the Archaean craton.

The Ataneq fault was investigated by boat where it meets the south coast of the peninsula at Itivinga (LC aag2004-105 and 106) and from a short field camp near Narsarsuuk (LC aag2004-196 to 205). In both areas the Ataneq fault is characterised by extensive hydrothermal alteration of the host rocks in a very wide (<1 km) zone. Most rocks within this zone of intense alteration are pale, massive and thoroughly recrystallised, with a fine-grained sugary texture dominated by milky quartz, albitic plagioclase with very intense alteration to sericite, and in places red-stained K-feldspar. The impregnation is less complete in the outermost 50 to 100 m of the alteration zone, where the original lithologies are commonly recognisable. Late brittle crushing in already altered rocks is partly overprinted by fronts of more complete alteration and recrystallisation, behind which all brittle fractures are annealed (Fig. 15). At around LC aag2004-202 (Fig. 4), a gabbroic member of the Taserssuaq tonalite complex is cut by the fault zone. Along the contact between the outer fault zone and the unaltered metagabbro we observed considerable impregnation of disseminated iron sulphides as well as silica, which locally extends for up to *c.* 50 m into the metagabbro.

Due to the pervasive late alteration it was impossible to find any localities where genuine pre-alteration fabrics related to the preceding faulting itself could be studied. The overall dextral sense of shear of the Ataneq fault could thus only be deducted from the general map pattern.

An ENE-trending granitic dyke and sinistral fault at Amitsuatsiaq, eastern Qussuk

Garde (1997) described a narrow, NW-trending microgranite dyke exposed along a fault on both sides of Qussuk; the dyke has been dated at 2085 +55 -65 Ma (zircon U-Pb discordia, lower intercept), and was assumed by Garde (1997) to be conjugate with the Palaeoproterozoic, NE-SW trending Fiskefjord and Ataneq faults. The geological map pattern suggests a sinistral offset of around 800 m along the microgranite dyke (Fig. 4).

Figure 15. *Hydrothermally altered quartzo-feldspathic gneiss in the Ataneq fault zone with cm-scale brecciation, variably overprinted by further alteration. Still younger fractures with cm-scale offsets are also visible. LC aag2004-197.*

Figure 16. *The northern contact between the microgranite dyke (right) and the Archaean host rocks (left), where the contact itself is not disturbed by movement after the dyke emplacement. LC aag2004-086, Amitsuatsiaq.*

The dyke was visited at LC aag2004-086 near the point Amitsuatsiaq (Fig. 4). Here the microgranite dyke is 11 m wide and very fine grained, with phenocrysts of quartz (and feldspar?) up to few millimetres large. Where protected by later strain, the dyke cuts cleanly across a steep, intense N-S-trending tectonic fabric in the Archaean host rock (Fig. 16). Elsewhere, both the dyke and its host rocks show evidence of sinistral, transitional ductile-brittle movement, with development of decimetre-scale kink folds. These observations confirm the previous interpretation that the dyke is related to the regional conjugate Palaeoproterozoic fault system, and they may furthermore suggest that the dyke itself was injected prior to faulting. No significant hydrothermal alteration was observed along the dyke margin or wall rock.

Tectonic structure west of Nuua, where the magnetic boundary between Nordlandet and western Godthåbsfjord is exposed on land

A NNE-trending aeromagnetic boundary along the west side of Godthåbsfjord separates a region of high susceptibility at Nordlandet in the west from the Godthåbsfjord region itself with lower susceptibility in the east. This prominent magnetic structure was discussed by Rasmussen & Garde (2003) in a previous study of existing geological and geophysical data from the Godthåbsfjord region. The aeromagnetic boundary appears to 'run ashore' onto Nordlandet in the embayment west of Nuua (Fig. 4; Rasmussen & Garde 2003, fig. 29). The western branch of Godthåbsfjord is also the locus of an inferred major fault with downthrow to the east. A fault of this nature is required to account for the jump from the granulite facies rocks exposed on Nordlandet to the amphibolite facies rocks exposed around Nuuk and on Bjørneøen.

In order to test whether the magnetic boundary is related to a major fault where it appears to run ashore on Nordlandet, two localities west of Nuua were visited, where the geological map shows a prominent N-S structural grain (LC aag2004-084 and 85, Fig. 4). Both these recorded localities and the exposures between them consist of mixtures of supracrustal rocks and orthogneisses in granulite facies or partially retrogressed from granulite facies. No signs of tectonic movement subsequent to the granulite facies metamorphism were identified. These findings are in accord with an older study of the N-S trending rocks at the head of Fiskefjord on strike to the north, where the intense, steep N-S trending fabric was likewise found to be syn-granulite facies or not younger than syn- high-grade partial retrogression. The retrogression took place at *c.* 2.97 Ga ago (Garde et al. 2000).

It can be concluded that no Palaeoproterozoic fault exists in the vicinity of Nuua in eastern Nordlandet, which might account for the magnetic boundary structure. It is proposed as an alternative interpretation that the N-S orientation and variation of the magnetic susceptibility in this area is related to the alternate, N-S trending belts of supracrustal rocks and orthogneisses, coupled with the incomplete retrogression at amphibolite facies condition described by Garde (1997). Furthermore, the magnetic boundary structure may also be related to the above-mentioned hidden fault in western Godthåbsfjord. This hypothetic fault might link with the Ataneq fault on the Qussuk peninsula, although there is no indication of a large vertical displacement in the latter area.

The Bjørneøen greenstone belt

Introduction and regional setting

The Bjørneøen greenstone belt is defined here as the mafic, ultrabasic, and metavolcanic and metasedimentary rocks forming a largely continuous belt stretching from Store Malene (and further south-west of the Nuuk peninsula) north-east through Sermitsiaq and Bjørneøen. This belt lies within the mid-Archaean Akia terrane (*c.* 3.2 to 3.0 Ga; Taylor et al. 1980; Baadsgaard & McGregor 1981; Garde 1997; Friend et al. 1996). Detrital zircon age data from the Bjørneøen greenstone belt are presently not available. However Friend & Nutman (1994) reported 3050 to 3000 Ma detrital zircon from one sample from Nordlandet, indicating that these rocks probably have an older depositional age than the greenstones in the outer Godthåbsfjord region (*c.* 2.8 Ga; Schiøtte et al. 1988). A minimum age constraint may be given by the 2712 ± 12 Ma Qârusuk felsic dykes, which cut earlier fabrics in the Nûk gneiss on southern Bjørneøen (MacGregor et al. 1983). Similar felsic dykes cutting the greenstone belt on south-east Bjørneøen may be of the same age. Samples have been collected for geochronological work.

The main focus of work in this area was to characterise the Bjørneøen greenstone belt in terms of its lithological constituents and tectono-metamorphic history and also to collect appropriate samples for placing geochemical and geochronological constraints on its tectonometamorphic evolution. Mapping was focussed along the belt itself, and the contact relationships with the regional orthogneiss units investigated. The field work was carried out by Dirk Frei (GEUS), Steven Grimes (Memorial University of Newfoundland, Canada), Julie Hollis (GEUS), Mark Hutchison, Nigel Kelly (University of Edinburgh, U.K.), and Mikkel Vognsen (University of Copenhagen). Field geological data and maps are presented for relevant regions on Sermitsiaq (Fig. 17), south Bjørneøen (Fig. 18) and north Bjørneøen (Fig. 19). Additional observations were made and samples collected on Store Malene (where a detailed map already exists, reproduced here in Fig. 20) and from a coastal section through the belt north of Store Malene. The map of Sermitsiaq (Fig. 17) builds on previous mapping work on this island by Olsen (1986, 1988) and MacGregor (1979-80). The western arm of the island is shown as a simplified version of the GEUS series geological map sheet Qôrqut (MacGregor, 1983). The eastern arm of the island, with the Bjørneøen greenstone belt, is of more significance to this study and was the main focus of mapping and sampling on the island (Fig. 17). The Bjørneøen maps (Figs 18 and 19) build on previous work by MacGregor (1983; 1993; 1960s to 1990s mapping), P. James (unpublished data), A.A. Garde (unpublished data), and Smith (1998).

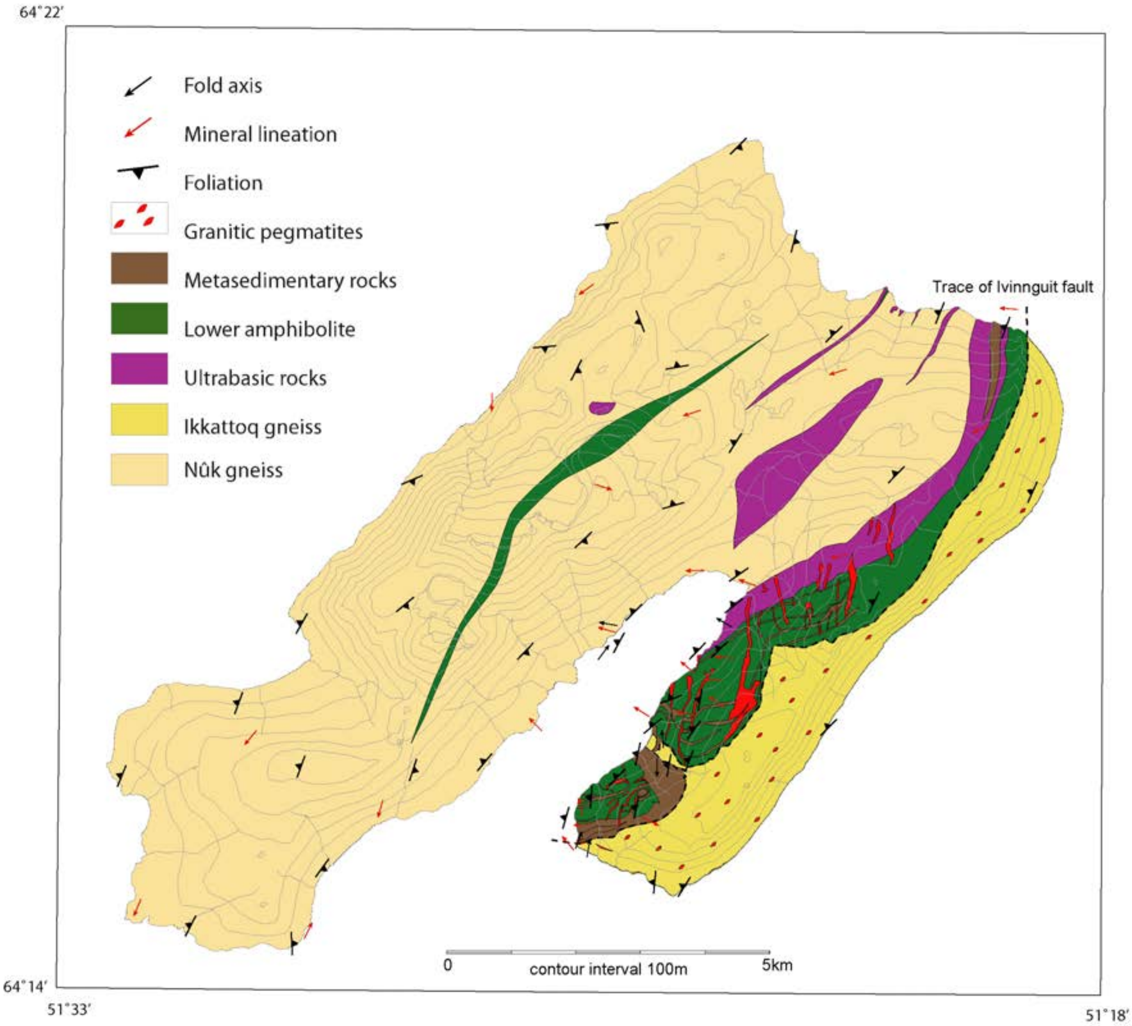

Figure 17. *Geological interpretation map of Sermitsiaq by J. Hollis & N. Kelly, based on 2004 GEUS mapping, Olsen (1988), and the Survey Qôrqut 64 V.1. Syd 1:100 000 geological map sheet (McGregor 1983).*

Lithologies, tectonostratigraphy and metamorphism

The Bjørneøen greenstone belt

The Bjørneøen greenstone belt, like others in the region, is dominated by metamorphosed mafic volcanic or intrusive rocks, referred to as amphibolites. These account for *c.* 80% of the volume of the belt and have been subdivided into three distinct units (characterised below) including components such as homogeneous dark amphibolite, calc-silicate banded amphibolite, and heterogeneous, layered and/or fragmental amphibolite of intermediate composition. Ultrabasic rocks comprise *c.* 15%. These rarely preserve relict igneous orthopyroxene but are more commonly heavily retrogressed to tremolite-, anthophyllite-, and chloritic schists. The remaining few per cent are made up by heterogeneous metasedimentary and metavolcanic rocks including banded quartzo-feldspathic rocks interpreted as metatuffs, biotite ± garnet schist, quartzite, banded garnet-tourmaline-bearing quartzo-feldspathic rocks with interleaved tourmalinite layers, and rare quartz-cordierite rocks that are thought to be hydrothermal in origin (e.g. Dymek & Smith 1990; Smith et al. 1992). The entire belt is multiply deformed and metamorphosed at amphibolite facies with variable development of a lower grade retrogressive overprint. It is also locally intruded by felsic dykes (possibly related to the *c.* 3.0 Ga Nûk gneiss) and by voluminous granitic pegmatites that may be related to the Qôrqut granite. Pegmatites are more prolific toward the eastern margin of the belt (i.e. with proximity to the Qôrqut granite body) which is consistent with a genetic relationship between the two.

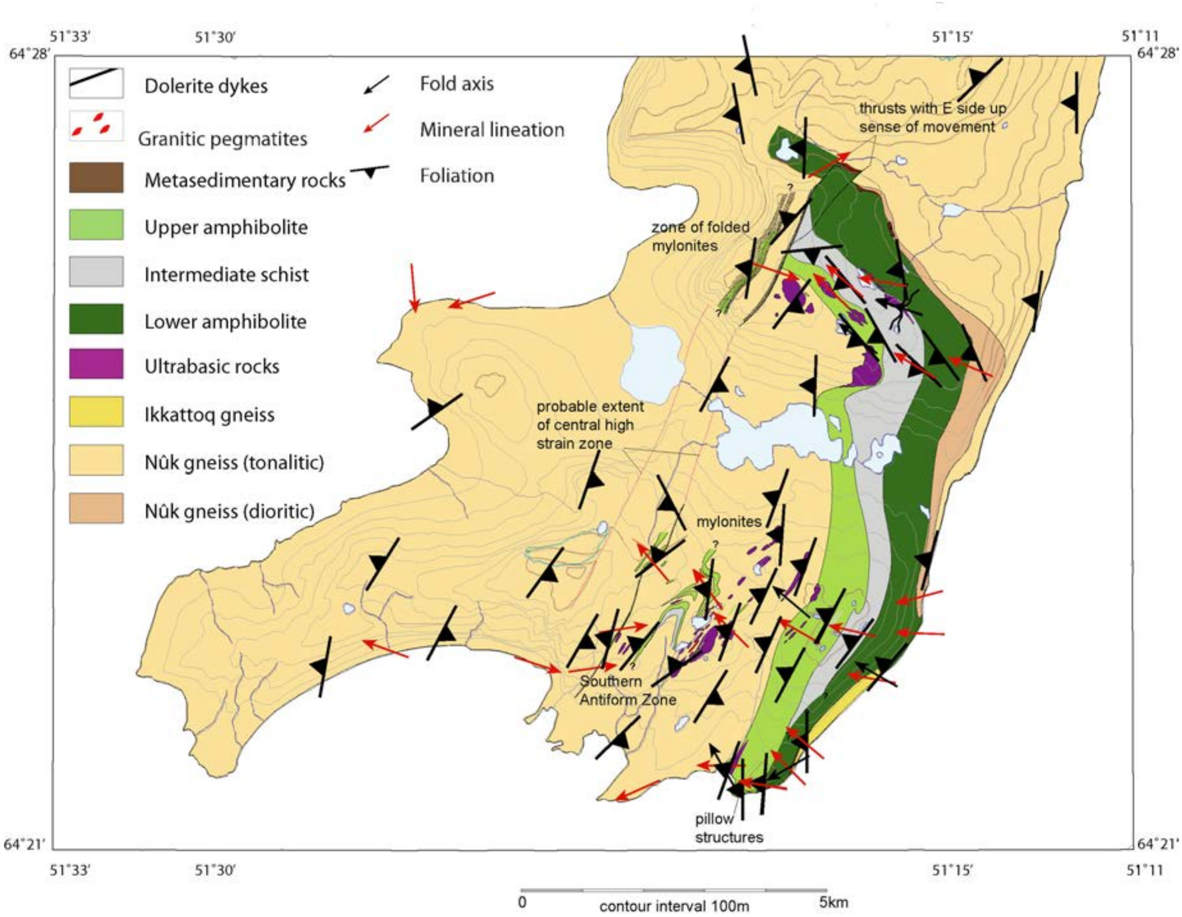

Figure 18. *Geological interpretation map of southern Bjørneøen by N. Kelly, based on GEUS 2004 mapping, Smith (1998), and the Survey Qôrqut 64 V.1. Syd 1:100 000 geological map sheet (McGregor 1983).*

Only in rare cases do low-strain zones preserve evidence of early structures or primary magmatic or sedimentary features. The only example of primary structures in which a younging direction could be ascertained is an amphibolite locality on south-east Bjørneøen in which pillow structures area easily observable (Bridgwater et al. 1976). Here the sequence youngs toward the east. Given the dominantly west dipping foliation throughout eastern Bjørneøen and Sermitsiaq this implies that the sequence is overturned in this region. This interpretation is consistent with the inferred stratigraphic sequence and origin of formation of the belt (see below), but should be treated with caution in view of the intensity of deformation and recrystallisation of these rocks, generally obscuring primary features.

For the purpose of approaching discussion of the tectonostratigraphic sequence and characterising the lithologies, the Bjørneøen greenstone belt is described below from an inferred base in the west toward the east. Subsequently the associated orthogneiss units present on Store Malene, Sermitsiaq, and Bjørneøen are described.

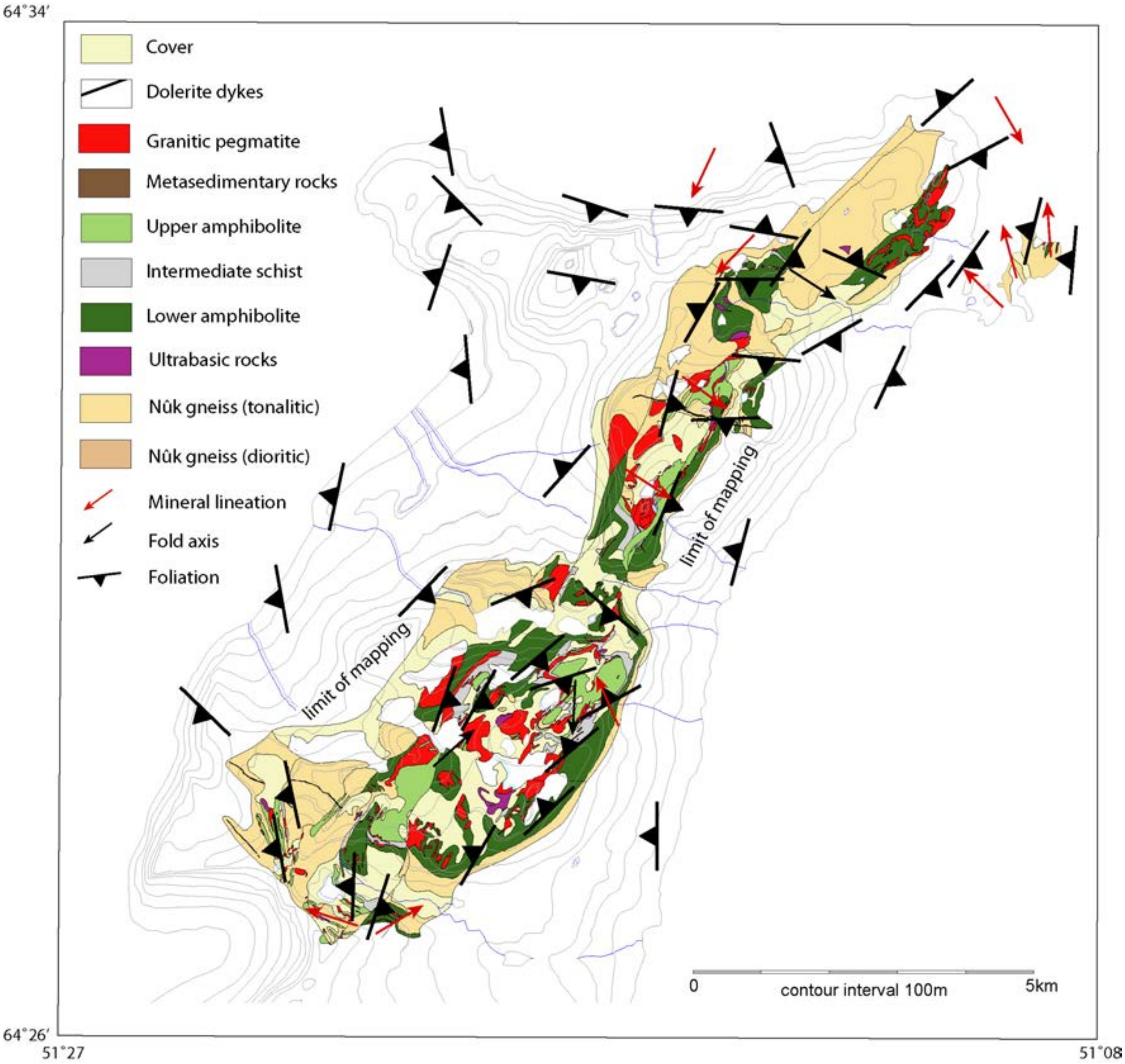

Figure 19. *Geological interpretation map of northern Bjørneøen by S.W. Grimes, based on 2004 GEUS mapping, Smith (1998), the Survey Qôrqut 64 V.1. Syd 1:100 000 geological map sheet (McGregor 1983), and the Survey Fiskefjord 64 V.1. Nord 1:100 000 geological map sheet (Garde 1989).*

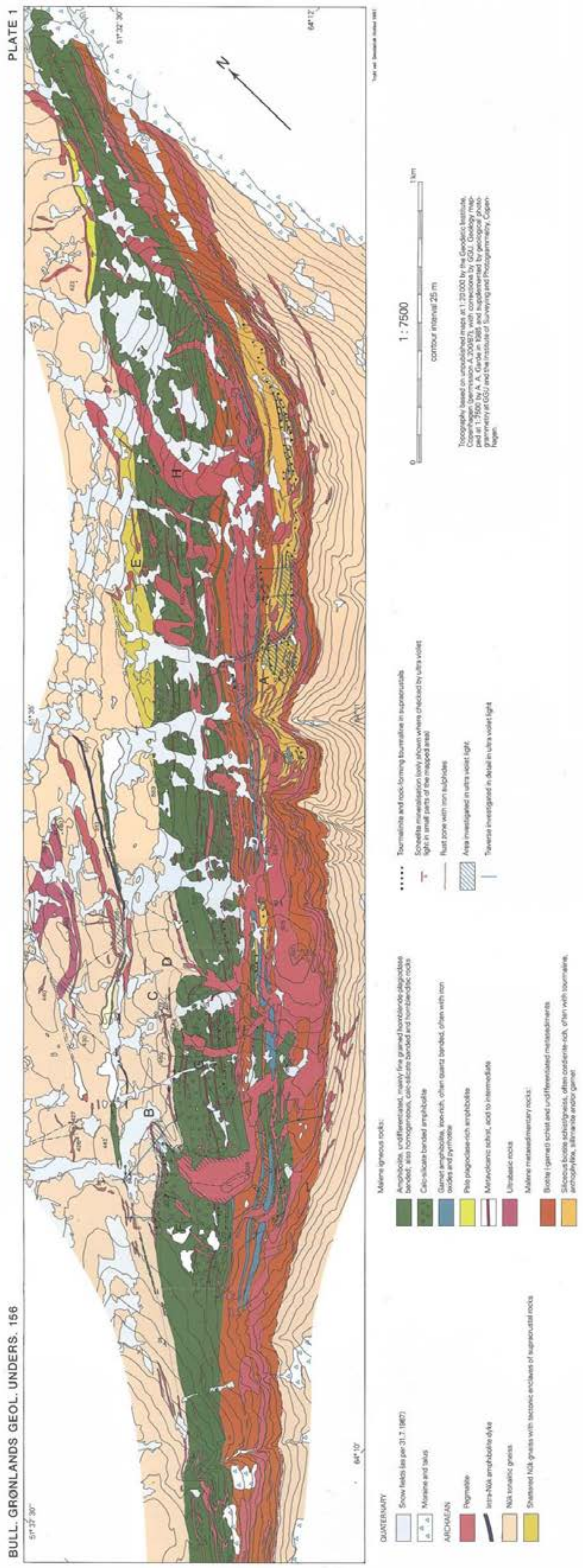

Figure 20. *Geological map of Store Malene by A.A. Garde, reproduced from Plate 1 of Appel & Garde (1987).*

Ultrabasic rocks

Layers, lenses and pods of ultrabasic rocks, varying in size from a few metres to hundreds of metres, occur predominantly in the upper structural level of the Bjørneøen greenstone belt and as large bodies within the Nûk gneiss. Smaller lenses and pods also occur interleaved with the amphibolites. Pods are particularly common along boundaries between units. The ultrabasic lenses and pods are parallel to, and are commonly enveloped by, layering in the host rocks. The most extensive unit of ultrabasic schists forms a thick continuous body from the head of the bay (LC nmk2004-011) to the north-east coast of Sermitsiaq, structurally overlying the amphibolites and underlying the Nûk gneiss. In general, ultrabasic rocks in the Bjørneøen belt are massive or weakly foliated. However, in zones of higher strain, they typically have a pronounced schistosity developed on their boundaries, or as discrete cross-cutting zones.

There is considerable diversity in the appearance and composition of the ultrabasic rocks. They occur typically as green schists comprised of tremolite, chlorite, and anthophyllite (Fig. 21), but with considerable variation in mineralogy and texture. In some cases orthopyroxene and olivine (interpreted as relict igneous grains) have been observed, giving the rock a spotted appearance. However in many cases no evidence for relict early assemblages or structures is preserved. Rare hornblendite layers are also associated with the ultrabasic rocks. The ultrabasic rocks can be subdivided into four main types:

- massive or weakly foliated, homogeneous, fine- to medium grained serpentinite. Mineralogically this type is dominated by antigorite and lizardite, whereas fibrous chrysotile only occurs rarely. This type is often characterised by a distinctive orange-grey coloured weathering surface formed by a network-forming crust of isomorphous siderite + talc.

- heterogeneous serpentinite with a very distinctive ‘leopard skin’ weathering surface formed by centimetre-sized orange-grey weathering grains with a green, schistose matrix enveloping these. This ‘leopard skin’ appearance may represent a relict texture of orthopyroxene and/or olivine.

- blackwall" rocks typical of metasomatism during low-grade metamorphism of ultrabasic lithologies. These comprise chlorite-, talc-, actinolite-, and antophyllite-bearing schists (± biotite and plagioclase) that occur as discrete layers or as rinds at the contact of ultrabasic lenses, pods, and bodies to their host rocks or along (often folded) country-rock veins. This schist preserves a folded foliation in some cases,

- coarse-grained, dark-green coloured rocks typically composed of > 90 % clinopyroxene, possibly derived from pyroxenite cumulates, or alternatively the products of hydrothermal alteration. Where more intensely deformed, this type is composed of medium-grained, dark green clinopyroxene in a matrix of lighter-green chlorite ± serpentine ± talc.

The preferential development of chlorite-anthophyllite in zones of higher strain (post-dating primary olivine-orthopyroxene-clinopyroxene) indicates amphibolite facies metamorphism associated with deformation. Recrystallisation is particularly prevalent along contacts with the Nûk gneiss and amphibolites. In some cases foliation-transgressive tremolite-anthophyllite-chlorite-rich zones suggest fluid-assisted alteration of the primary magmatic host. The timing of this fluid alteration is unknown. The occurrence of chloritic zones defining upright closed to tight fold structures (see below) suggests that either some recrystallisation occurred early in the tectonometamorphic history of these rocks, or that fluid-assisted alteration allowed selective replacement of compositional layering.

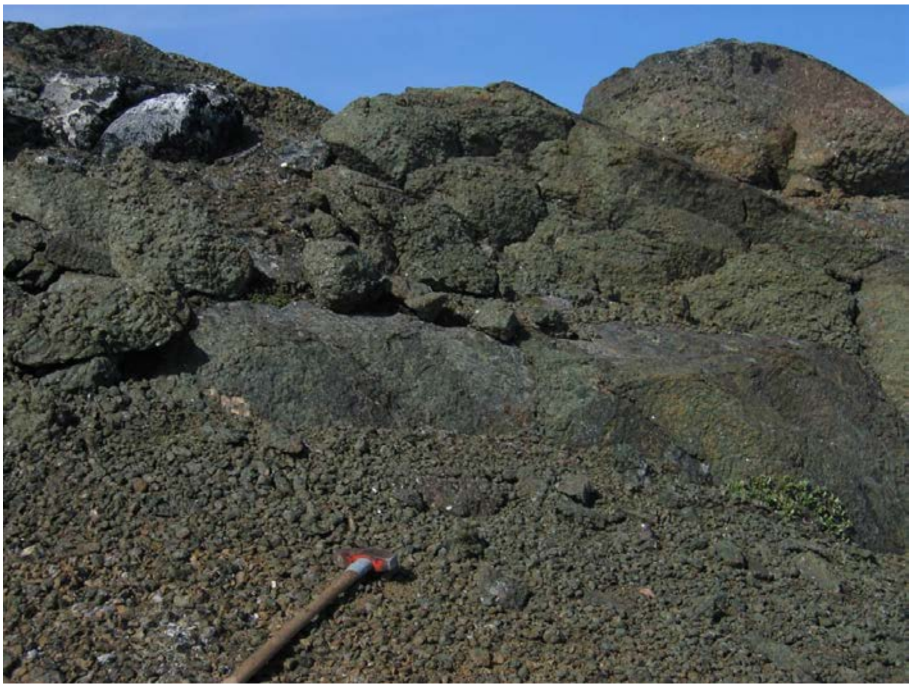

Figure 21. *'Leopard skin' weathering pattern of massive ultrabasic pods, owing to relict centimetre-sized orange-grey weathering orthopyroxene (PFN nmk2004-308).*

Amphibolite

Amphibolites form the largest component of the Bjørneøen greenstone belt. They have previously been mapped as a single unit (James 1975; MacGregor 1983) or as several units including amphibolite and intermediate metavolcanic rocks on Bjørneøen (Smith 1998). The 2004 GEUS mapping confirmed most of the main lithologies mapped by Smith, however, the broad zone of amphibolite that extends through southern Bjørneøen as indicated on the field map of James (1975; coincident with the central high strain zone on Fig. 18 and on the Survey 1:100,000 geological map sheet) has been amended (Fig. 18).

The amphibolites have been subdivided into three broad units. They are, from west and structurally highest: 1) upper amphibolite, 2) intermediate schist (metavolcanic), and 3) lower amphibolite. Further sub-divisions proposed by Smith (1998) were considered to be unwarranted.

1) Upper amphibolite

The upper amphibolite is a relatively heterogeneous unit. It is dominantly comprised of a dark hornblende with minor plagioclase rock that is variably banded (PFN nmk2004-192-198) or homogeneous in appearance (Fig. 22, PFN nmk2004-192). It contains a high abundance of ultrabasic, calc-silicate amphibolite, and intermediate schist (see below, PFN nmk2004-093) layers and pods. Locally the unit may contain near-mylonitic fabrics. The banded amphibolite is dominantly comprised of hornblende with minor plagioclase, with millimetre- to ten centimetre-scale layering defined by variations in plagioclase content (± clinopyroxene ± epidote) and by attenuated leucocratic layers (< 2 mm width) that are rarely continuous over > 30 cm. As the boundary between the upper amphibolite and the Nûk gneiss is approached, there is a higher abundance of pegmatite dykes, which are folded, sheared, and boudinaged.

Figure 22. *Heterogeneous upper amphibolite with pods of ultrabasic material and calc-silicate (PFN nmk2004-192).*

2) Intermediate schist

The intermediate schist is a very heterogeneous layered unit, and in comparison with the upper and lower amphibolite units, contains biotite, rather than hornblende, as the main ferromagnesian mineral phase. It shows some similarities in composition and primary structures with the grey amphibolite in the Qussuk area, however hornblende is relatively uncommon in the lithology on Bjørneøen. The unit commonly contains lenses and pods of mafic and ultrabasic material, which are usually intensely sheared within layering. In particular ultrabasic schist lenses and pods are abundant near the contact between this unit and the upper amphibolite. This unit crops out only on Bjørneøen and does not extend all the way to the southern coast. It is not recognised on Sermitsiaq, though a thin band of pale plagioclase-rich biotite-bearing gneiss mapped by Appel & Garde (1987) on Store

Malene may represent a dismembered continuation of this lithology. Intermediate schist forms a major component of the two greenstone belts on the Qussuk peninsula (see previous chapter).

The intermediate schist is predominantly composed of fine to medium-grained plagioclase, biotite, and quartz with local garnet and more rarely hornblende. Layering in most localities is defined by variations in biotite and plagioclase content (Fig. 23, PFN swg2004-287). In northern Bjørneøen more leucocratic layers within this unit are common and the unit locally grades into quartz-rich lenses. Rare anastomosing layers may reflect relict primary features (e.g. flow bands or highly deformed volcanic clasts; Fig. 23), although interpretation of these is hampered by the high degree of deformation.

Figure 23. *Deformed intermediate biotite-bearing schist of supposed volcanic origin with anastomosing layering (PFN swg2004-287).*

The character of the intermediate schist varies along strike, which is apparently associated with the degree of strain experienced during development of regional high strain zones (see below). In a broad high strain zone on along the eastern margin of Bjørneøen (see Structure section below), interlayered, centimetre-scale biotite-rich and plagioclase-rich schist form wispy, discontinuous layers (PFN nmk2004-144 to 146, & 161) that are commonly folded and swept into narrow shear zones (5 to 10 cm; top of PFN nmk2004-146 & 162). In some zones, the rock is fine grained and mylonitic in appearance (PFN nmk2004-163). Discontinuous coarse-grained leucocratic lenses or boudins are enveloped by layering (PFN nmk2004-145 to 146). Boudins also include rotated blocks of clinopyroxenite and mafic amphibolite (PFN nmk2004-143 & 147). Variably deformed quartz veins and felsic layers either transgress or are sub-parallel to and attenuated in foliation (PFN nmk2004-157).

Between two NE-trending high strain zones on eastern and central Bjørneøen (see Structures section below) is a transition zone of lower strain, which has allowed the preservation of more lithological complexity. This unit is more heterogeneous compared with rocks in the eastern high strain zone, with a more well defined layering and abundant attenuated lenses and boudins of felsic, intermediate and mafic material (PFN nmk2004-174, 180, 348, & 357). In this zone a characteristic feature of the rocks is the frequent occurrence of coarse-grained, leucocratic lenses and boudins, commonly centimetre- to tens of centimetres wide and comprised of hornblende, garnet, and plagioclase ± clinopyroxene. They are variably rotated and brittley deformed. Boudin trains define traceable layers over tens of metres, and may have formed more continuous lithological layers prior to deformation. Partially (tectonically) truncated and boudinaged fragments of layered intermediate schist (PFN nmk2004-336, 337, 338, 378, 379) are also commonly preserved closer to the central high strain zone.

Given the complexity of internal structure part of which is probably primary in origin and its intermediate composition, this unit is interpreted as volcanic in origin.

3) Lower banded amphibolite

In comparison to the upper amphibolite unit, the lower amphibolite unit is predominantly homogeneous, with fine-grained plagioclase ± hornblende ± biotite, commonly fine enough to have a slaty appearance. It also contains a lower proportion of ultrabasic, calc-silicate amphibolite, and layers and pods of intermediate schist. These rocks are correlated with the bulk of the amphibolite unit on Sermitsiaq (which is typically is a relatively homogeneous dark, slaty rock, with lesser calc-silicate layering) and with the main body of the amphibolite on Store Malene (structurally underlying a sliver of biotite-bearing intermediate schist). A well-developed foliation is in most cases layer-parallel and defined by aligned hornblende and plagioclase (± biotite). In zones of higher strain, the foliation is defined by elongate hornblende and plagioclase-rich ribbons or trails, and in some cases appears mylonitic. The amphibolite also contains leucocratic layers (dominantly plagioclase) that vary from transgressive to layering to attenuated into the foliation. The amphibolite is locally garnet-bearing and these garnets are, in some cases, elongate parallel to foliation and enveloped by laminations of hornblende and plagioclase.

In this unit primary features were only observed in one locality. On the south-east coast of Bjørneøen well-developed decimetre-wide pillow structures are preserved (Fig. 24, PFN mth2004-073 to 075; first reported in Bridgwater et al. 1976) in local, several metre-scale low-strain zones. These are bounded by decimetre-wide high strain zones, into which the pillow structures are progressively deformed, showing a dextral shear sense. Sag-structures at the base of the pillows in low strain zones show a consistent eastward younging direction.

The lower amphibolite includes layers of metagabbro, intermediate schist, and calc-silicate rocks. Metagabbro forms a discontinuous (over hundreds of metres) layer along the boundary between the lower amphibolite and intermediate schist in central Bjørneøen. It is massive and comprised of weakly foliated, coarse-grained (> 1 cm in places) hornblende and plagioclase ± clinopyroxene and garnet. Intermediate schist occurs as rare layers interleaved within the lower amphibolite. The lower amphibolite also contains rare lenses of calc-silicate (clinopyroxene, epidote, plagioclase), which may be an alteration product of the amphibolite.

The metamorphic grade varies largely in response to the degree of deformation. Where early medium to coarse-grained diopside + epidote + plagioclase ± calcite assemblages have been observed these are commonly partially replaced by epidote-hornblende-bearing assemblages (± biotite ± garnet) defining the regional foliation. In some cases early plagioclase and hornblende are observed breaking down to epidote. Similarly symplectic hornblende and epidote occur as partial replacement products of medium to coarse-grained diopside. These observations suggest that early calc-silicate assemblages were recrystallised during lower amphibolite-facies conditions during the main fabric-forming deformation event. Local occurrence of actinolite-bearing assemblages in amphibolites and garnet-bearing amphibolites support the inference of lower amphibolite facies conditions. The origin of the early calc-silicate assemblages is unknown. These may be early hydrothermal alteration products within the volcanic pile.

Figure 24. *Deformed pillow lavas with moderate W-plunging lineation and eastward younging direction (looking toward 090, PFN mth2004-073).*

Metasedimentary rocks

Metasedimentary rocks on Bjørneøen, Sermitsiaq, and Store Malene have previously been described in several sources (James 1975; Olsen 1986; 1988; Appel & Garde 1987; McGregor 1993). These rocks comprise only a small proportion of the greenstone belt. The most extensive thickness of these rocks occurs on Store Malene, thinning to the north. The 2004 GEUS mapping identified a thin layer on the south-east coast of Bjørneøen (only tens of metres wide), which represents the northernmost extension of these rocks. They are lithologically diverse and unusual in their mineralogical make-up. Correlation along the Bjørneøen belt is supported by the consistent occurrence of unusual tourmaline-rich rocks and heterogeneous banded rocks containing layers and pods of tourmalinite. The metasedimentary rocks form the structurally lowest level of the Bjørneøen greenstone belt, everywhere sitting within a high strain zone along their contact with the Ikkattoq gneiss.

These rocks are heterogeneous both up-section and also along strike throughout the belt. Also, both thrusting and folding of the sequence have been observed locally and therefore it is likely that the preserved sequence in any one section does not reflect (or reflects only in-part) an original depositional sequence. They comprise a range of lithologies including heterogeneous layered quartzo-feldspathic rocks (± garnet ± tourmaline), quartzite (± garnet), biotite schist (± garnet), anthophyllite-cordierite-bearing magnesian schists, and cordierite-bearing quartzitic rocks. Some of these lithologies are discussed in more detail below.

At their structural upper contact with the amphibolite, metasedimentary rocks are commonly interleaved with the overlying amphibolites on a scale of tens of metres. Owing to relatively high strain it is difficult to establish the original nature of the contact between these interleaved units.

Quartzo-feldspathic metasedimentary rocks are dominantly comprised of quartz and plagioclase with lesser zoisite, muscovite, and garnet. In some cases these are homogeneous pale yellow-grey rocks with common muscovite and rare garnet. They exhibit a gneissic compositional layering rather than a schistose fabric (see also Appel & Garde, 1987). Tourmaline is present in varying proportions disseminated throughout the rock and defines a weak to moderate lineation in some cases but in many outcrops is randomly oriented. Locally this lithology grades into quartzite (± garnet).

Heterogeneously layered quartzo-feldspathic rocks are also common. These are typically pale yellow-grey, garnet-poor, and commonly contain zoisite. They have centimetre to decimetre thickness, laterally continuous laminations. They typically contain foliation-parallel pods and layers of micaceous schist (± garnet) and tourmalinite (> 90% tourmaline ± garnet) layers and lenses that often define isoclinal folds, boudins, and other pull-apart structures (Fig. 25 & 26). Tourmaline lenses are often rimmed by plagioclase. The layered quartzo-feldspathic host commonly contains porphyroblastic pink garnet (typically 2 to 5 cm diameter), some with inclusion trails visible in hand specimen. Thin, interleaved biotite-rich layers are cordierite-bearing on some cases, and some associated quartz-rich pods contain large smoky-grey cordierite porphyroblasts. Anthophyllite-cordierite-bearing magnesian schists and cordierite-quartz metasedimentary rocks have also been reported in association with biotite schists from Store Malene, Kangaarsuk, and elsewhere in the Godthåbsfjord region (e.g. Appel & Garde 1987; Dymek & Smith 1990). Quartz veins are common and are typically intensely deformed, isoclinally folded, and boudinaged. In some cases fold asymmetries and boudins indicate a top to the south-east movement sense, though kinematic indicators are inconsistent throughout the belt.

The structurally lowermost boundary of the metasedimentary rocks is typically heavily intruded by granitic pegmatites that are moderately to strongly folded within the dominant gneissosity. No direct contact was observed between the metasedimentary rocks and the underlying Ikkattoq gneiss.

Figure 25. *Biotite schist with large porphyroblastic garnets (PFN jho2004-207).*

Figure 26. *Garnet-bearing tourmaline-rich layer in heterogeneous layered quartzo-feldspathic rocks. (PFN jho2004-193).*

Orthogneiss units

Nûk gneiss

The Nûk gneiss has been dated by various methods at 3.07 to 2.94 Ga (Taylor et al. 1980; Baadsgaard & McGregor 1981; Garde et al. 1986; Friend et al. 1996). This lithology dominates the western arm of Sermitsiaq, western and eastern Bjørneøen, and the Nuuk peninsula west of Store Malene. It is a medium to coarse-grained felsic orthogneiss. Relict megacrysts of plagioclase (variably deformed and recrystallised) preserve an early magmatic texture in areas of relatively low strain. Compositional variations on the outcrop scale, as well as grain size variations may reflect partially preserved of magmatic features. When intensely deformed, the orthogneiss becomes platy in outcrop, with both a well-developed S and L tectonic fabric. The Nûk gneiss as mapped during the 2004 field season, may be subdivided into two broad types: 1) tonalitic orthogneiss and 2) interlayered tonalitic and dioritic orthogneiss.

1) The tonalitic orthogneiss (Fig. 27, PFN jho2004-263) is medium to coarse-grained, dominantly comprised of plagioclase and quartz, with lesser biotite, and locally garnet-bearing. When intensely deformed, felsic orthogneiss preserves elongate or ribbon-like plagioclase grains (PFN nmk2004-459) that locally define an L-tectonite fabric. Biotite also defines foliation-parallel ribbons. It contains minor layers of dioritic gneiss (see below), which along with its host commonly contains variable abundances of leucosome. It is weakly to well-layered (PFN nmk2004-269). Tonalitic Nûk gneiss is by far dominant.

2) The second type is interlayered tonalitic and dioritic orthogneiss (Fig. 28, PFN nmk2004-237) in which dioritic orthogneiss forms more than 25% of the rock by volume (PFN nmk2004-237). The dioritic layers are predominantly comprised of plagioclase and biotite, but may be locally garnet- and hornblende-bearing. In areas of low strain, dioritic gneiss is typically intruded by, or occurs as rafts in tonalitic orthogneiss, suggesting it is relatively older. However the relationships between the two orthogneisses are commonly obscured by intense shearing.

The interlayered felsic-dioritic Nûk gneiss is most commonly found along the western boundary zone of the greenstone belt at the south-east end of Bjørneøen; within the central high strain zone on Bjørneøen; as a relatively continuous layer on the eastern contact of the greenstone belt on Bjørneøen (Fig. 18); and on north-west Sermitsiaq (Fig. 17). On the eastern contact of the greenstone belt on Bjørneøen the gneisses are layered on a metre to ten metre scale, and preserve rare intrusive features; tonalitic and dioritic gneiss are in places mutually cross-cutting, although tonalitic gneiss cutting diorite is common (PFN nmk2004-130, 132, & 131). Most contacts are tectonised in this zone.

Figure 27. *Well-developed S and L fabric in coarse-grained Nûk gneiss (PFN jho2004-263).*

Figure 28. *Layering in tonalitic-dioritic Nûk gneiss (PFN nmk2004-237).*

Where proximal to amphibolite or ultrabasic rocks (either inclusions in the Nûk gneiss, or near boundaries with the main greenstone belt) both tonalitic and dioritic components of the Nûk gneiss can contain large garnet porphyroblasts (> 2cm) or aggregates, enveloped by the foliation (PFN nmk2004-137). This is probably a contamination effect. Mafic (amphibolite) and ultrabasic layers, lenses and pods are common in various parts of the Nûk gneiss. Minor occurrences of amphibolite are found as discontinuous layers and pods and as extensive, more continuous layers within a large antiformal structure on southern Bjørneøen (Fig. 18). These are similar to rocks in the upper and lower amphibolite units (described above), although the main antiform structure also preserves a wide lens of grey biotite-bearing amphibolite. On the basis of all these inclusions, the Nûk gneiss is interpreted to be intrusive into the greenstone belt. However, clear intrusive contact relationships have not been observed, probably as a consequence of tectonic reworking. In much of the mapped area, gneiss-supracrustal rock contacts are planar, with parallel foliation, and some of these contacts are thrusted. On Sermitsiaq, decimetre- to metre-wide tonalitic sheets cut ultrabasic rocks and amphibolites close to their upper structural contact with the main body of the Nûk gneiss. These may represent sheets of Nûk gneiss, though dating of appropriate samples is required to establish this.

Ikkattoq gneiss

The *c.* 2825 Ma Ikkattoq gneiss forms the main component of the late Archaean Tre Brødre terrane (Friend et al. 1988; Nutman et al. 1989) and crops out along the eastern margin of the Bjørneøen greenstone belt on Store Malene and Sermitsiaq, and on the SE corner of Bjørneøen. It is a pale grey, medium-grained, granodioritic to tonalitic gneiss with sub-metre scale spaced gneissic layering. It commonly has a sugary texture in areas of relatively low strain. The occurrence of millimetre- to centimetre-thick granitic leucocratic layers is relatively common, though these form a minor component of the rock, which is dominated by the grey granodioritic to tonalitic phase. The leucocratic layers are commonly trangressive to a moderately developed gneissosity, though in some cases they are completely transposed into gneissosity. They may represent remnants of deformed pegmatites.

The Ikkattoq gneiss often has metre-scale enclaves of leucogabbroic (and less commonly gabbroic) gneiss and anorthosite, observed along the south coast of Sermitsiaq (Fig. 29). As the high strain zone along the lower contact of the Sermitsiaq supracrustal belt is approached from the east, the Ikkattoq gneiss shows progressive development of higher strain fabrics. These features include progressive transposition of granitic layers, increasing intensity of gneissic fabric, development of isoclinal folds and rootless folds. Granitic pegmatites that cross-cut gneissosity in the Ikkattoq gneiss also show progressive deformation and transposition into gneissosity as the contact with the supracrustal rocks is approached.

Alteration and mineralised zones

Abundant tourmalinite lenses and layers occur in the metasedimentary and metavolcanic rocks on Store Malene (Appel & Garde 1987), Sermitsiaq (Olsen 1986), and Bjørneøen. Tourmalinites are typically aligned within foliation and commonly define early isoclines and refolded isoclinal folds, indicating that they formed early in the tectonometamorphic history.

A close association of tourmaline with scheelite has also been established in this region (e.g. Appel 1983, 1985, 1986; Appel & Garde 1987). Scheelite has been reported from throughout the Godthåbsfjord region. Scheelite occurrences were mapped on Store Malene and Sermitsiaq by Olsen (1988) and Appel & Garde (1987) with the aid of ultra-violet light. The association of tourmaline and scheelite occurring within early structures supports hypotheses that these are the products of early hydrothermal alteration of metasedimentary and metavolcanic rocks in a submarine exhalative setting (e.g. Appel & Garde, 1987).

Figure 29. *Boudin of gabbroic gneiss within the Ikkattoq gneiss. (PFN jho2004-182).*

The occurrence of calc-silicate layers (diopside-epidote-bearing) in some of the amphibolites may be consistent with early alteration by circulating fluids. Within the upper amphibolite on Bjørneøen stratabound and cross-cutting calc-silicate layers occur in relatively low-strain domains. These are transposed into foliation in high-strain domains. On Sermitsiaq pyrite is locally developed within outcrop-scale occurrences of yellow-orange rusty weathered layers, concordant with foliation within the amphibolite.

Localised sulphide occurrences on Bjørneøen, previously investigated by NunaOil A/S, were investigated further in 2004 in a parallel GEUS project. Within the NunaOil A/S southern grid (Smith 1998) thin lenses of quartz-garnet rock occur, pinching in and out along strike in association with semi-massive sphalerite, galena and magnetite. Within the northern grid two mineralised bands, parallel to foliation in the amphibolites, comprise siliceous, garnetiferous, and pyritic mica schist. Disseminated pyrite, pyrrhotite, minor chalcopyrite, and trace native copper occur in these zones. The mineralised bands do not continue to the north (B. Thomassen, pers comm: 2004).

Structure

In this section we outline some of the major deformation events in the Bjørneøen greenstone belt and correlate major structures. Table 3 gives an overview of the sequence of major fabric-forming deformation episodes in this belt. Structural evidence for at least three deformation events is present in the Bjørneøen greenstone belt. Early structures are inferred to relate to Akia terrane events that occurred prior to terrane amalgamation. Subsequent NE-trending amphibolite facies high strain zones and associated closed to isoclinal upright folding may be related to deformation resulting from terrane amalgamation (along the Ivinnguit Fault), owing to the intensity of strain preserved along this tectonic boundary, and which affects both terranes. Later, lower-grade reworking of the higher grade structures is evident locally.

Table 2. *Chronology of important regional structures within the Bjørneøen greenstone belt.*

Chronology of structural types	Association	Timing	Grade
NNE-striking, steeply E-dipping, semi-brittle mylonite zones. Down dip L (min). East side up thrust sense.		Possibly Proterozoic?	Greenschist
Broad NE-striking high strain zones, mod to strong S (some mylonitic), NW-plunging L & tight folds, NW-directed thrusts.	Syn- to post - terrane assembly	< 2825 Ma (post-Ikkattoq gneiss)	Amphibolite
Locally preserved layer parallel S, min L, early isoclines	Akia terrane, pre-assembly	c. 2.97 Ma?	Amphibolite

Early structures

Due to the similarity in metamorphic grade between assemblages preserved in early fabrics and mineral assemblages defining the main regional foliation, and the degree of dynamic recrystallisation of rocks during development of the regional foliation, the positive identification of early structures is difficult. However, previous studies (e.g. Nutman et al. 1989) have established that the Akia terrane was affected by an amphibolite (Godthåbsfjord) to granulite (Nordlandet) facies metamorphic event at *c.* 2.97 Ga, which is probably correlative with at least some of these early structures.

In northern Bjørneøen, where the intensity of strain was lower than in the eastern parts of southern Bjørneøen, a typically early planar tectonic fabric (S), is preserved in both greenstones and Nûk gneiss. In amphibolite this fabric is defined by hornblende + plagioclase ± biotite, which locally also define a mineral lineation (L). In southern Bjørneøen and Sermitsiaq, the intensity of later strain is such that caution must be employed when interpreting early structures. In a low-strain zone on south-east Bjørneøen, where well-developed pillow lavas are preserved, weakly deformed dioritic and felsic Nûk gneiss preserve coarse-grained biotite-bearing fabrics that are progressively recrystallised to medium-grained S fabrics in later high-strain zones. These coarse-grained fabrics are inferred to be relics of an early foliation. Further possible evidence for early structures is observed in the form of refolded isoclines that occur on limbs of the large upright antiform in southern Bjørneøen (PFN nmk2004-307).

NE-striking high strain zones, large-scale upright folding, and NW-directed thrusts

NE-striking high strain zones, large-scale upright folding, and NW-directed thrusts observed throughout the Bjørneøen greenstone belt are interpreted as showing a genetic relationship to each other, although correlation of these structures throughout the belt is tenuous based on limited data and the complexity of the terrane. These structures are presented together in this section, although they may in fact represent several phases of deformation post-dating the early structures described above, or alternatively represent a long-lived progressive deformation event. The dominant features within this group of structures include NE-striking upright tight folds and the development of amphibolite facies high strain zones. Strain partitioning is evident both on kilometre-scale and on outcrop scale.

The important large-scale fold structures include upright to easterly-overturned tight folds on Store Malene, the 'Southern Antiform Zone' on southern Bjørneøen (Fig. 18), and abundant development of moderately N or S-plunging (Store Malene, northern Bjørneøen) and moderately north-west plunging (Sermitsiaq, southern Bjørneøen) tight to isoclinal folds and mineral lineations. On Bjørneøen asymmetric folds are commonly overturned with a top to the north-westerly sense of movement. On northern Bjørneøen fold hinges show some scatter, whereas in southern Bjørneøen both mineral stretching lineations and folds are parallel, plunging moderately to the NW to WNW. On Sermitsiaq folds and mineral lineations show a dominant NW plunge, though with significant scatter and some preservation of an earlier N and S plunging lineation. This may be indicative of progressive rotation of earlier structures during a prolonged episode of deformation. Early tight to isoclinal SE to NW plunging folds are also preserved on Store Malene, associated with abundant listric imbricate thrust faults with a north-west movement sense. Similarly, a duplex structure, with NW-directed transport thrust fault features is also preserved in northern Bjørneøen (Fig. 19). These features may represent an early phase, or a lower strain phase, of a long-lived deformation event in which folding and thrusting dominated over fabric development. On Store Malene these thrusts are re-oriented by the larger-scale characteristic upright tight folds, in this case plunging NNE or SSW.

A common moderately to strongly developed foliation, typically defined by amphibolite facies mineral assemblages, occurs throughout the belt. In some areas this is variably intensified and/or transposed into high strain zones. A high strain zone forms the contact between the Akia and Tre Brødre terranes at the structural base of the greenstones on Bjørneøen and Sermitsiaq, where they are in tectonic contact with the Ikkattoq Gneiss along the Ivinnguit fault. This high strain affects both the Bjørneøen greenstone belt and the adjacent Ikkattoq gneiss.

The terrane boundary is best defined on the island of Sermitsiaq where it occurs within a ductile, high strain zone 2 to 3 kilometres wide. The highest strain is focussed on this boundary, with the intensity of associated deformation decreasing with distance from the greenstone belt-Ikkattoq gneiss contact. The extension of this ductile boundary has been traced to the south-east corner of Bjørneøen, and from there continues offshore to the east of this island. Previously the Ivinnguit fault has been inferred to run through the greenstone belt on Store Malene, thus dividing greenstones belonging to the Akia and Tre Brødre terranes respectively. The basis for this interpretation has been the difference in ages of orthogneiss on the west (Nûk gneiss) and east (Ikkattoq gneiss) of the greenstone belt and on the observation of a major mylonitic structure running through the centre of the belt. However, there are several lines of evidence to suggest that the Ivinnguit fault contact may actually occur at the base of the Bjørneøen Belt on Store Malene, with the consequence that the entire Bjørneøen greenstone belt lies within the Akia terrane:

1) an amphibolite facies mylonitic contact between the Bjørneøen Belt and the Ikkattoq gneiss has been observed by us in 2004 on the steep eastern slope of the mountain,

2) the tourmaline-rich rocks characteristic of the Bjørneøen greenstone belt within the Akia terrane continue up to the eastern contact of the greenstone belt with the Ikkattoq gneiss,

3) many ductile thrust faults have been observed within the greenstone belt on Store Malene, which complicate the identification of any specific mylonitic structure as the terrane boundary.

The Bjørneøen Belt swings away from the high strain zone moving toward central Bjørneøen. A second zone of high strain cuts through the central part of Bjørneøen, and trends approximately parallel to high strain zone to the east. This central zone is characterised by medium-coarse grained mylonitic fabrics in the Nûk gneiss, which are deformed by open to tight NE plunging folds. This fold orientation is consistent with the plunge of the large antiforms in southern Bjørneøen. The similarity in trend between this central and eastern high strain zones suggests a common origin.

Low-grade reworking of ductile structures

The eastern edge of the central high strain zone on Bjørneøen is reworked by a NNE-striking and steeply E-dipping, semi-brittle mylonite-ultramylonite zone. Mineral stretching lineations in this mylonite are typically steeply down-dip, and consistently rotated and recrystallised sigma- and delta-shaped clasts indicate an east-side-up thrust sense, supported also by offset of lithological boundaries. Localised chloritisation of lithologies, suggests greenschist facies conditions. A similar semi-brittle structure is observed to offset the ductile high strain boundary between greenstones and Ikkattoq gneiss on the NE coast of Sermitsiaq with an east-side-up sense of movement.

Depositional and tectonic environment of the Bjørneøen belt

In discussing the tectonic evolution of the Bjørneøen (and other) belts, it is important to keep in mind that these rocks are multiply deformed and metamorphosed to amphibolite facies conditions. Thrust and fold repetition and tectonic removal of some parts of the sequence are also likely to be important. Low strain domains in which primary features can be observed are rare, but in the absence of extensive geochemical data (in progress) these are important features that we rely on for our present interpretations of primary depositional and tectonic settings. The lithologies and (tectono) stratigraphy, rare primary structures, and inferred primary alteration features all point toward an ocean floor extensional setting with submarine exhalative volcanism and associated hydrothermal alteration of metasedimentary and metavolcanic rocks. This has been proposed by previous workers (e.g. Appel & Garde 1987), and our 2004 field observations support this general model.

The Bjørneøen belt, although deformed and metamorphosed, retains a broadly consistent stratigraphy throughout, though with considerably variation in thickness and pinching out of some lithologies along strike. Broadly, the structural uppermost section, against the Nûk gneiss, is dominated by ultrabasic rocks that may represent mantle-derived magmas emplaced into a contemporaneous oceanic crust (i.e. the structurally lower thick amphibolite units). Alternatively they may represent cumulate-derived rocks. The Intermediate schist on Bjørneøen, possibly correlative with the pale biotite-gneiss reported from Store Malene (Appel & Garde 1987) in an appropriate position in the tectonostratigraphy, may be derived from intermediate volcanism, as the complexity of internal structure in these rocks is consistent with a metavolcanic origin. On south-east Bjørneøen the only way-up criteria for the belt is preserved in well-defined pillow lavas with a consistent easterly younging direction. These confirm a sub-aqueous origin for at least part of the belt and indicate that the belt is overturned in this area. This is consistent with the proposed general lithostratigraphy, which would have ultrabasic rocks at the original base (mantle-derived magmas), overlain by amphibolite (a basaltic volcanic pile), in turn overlain by a thin sequence of heterogeneous metavolcanic and metasedimentary rocks. These metasedimentary and metavolcanic rocks show several features that also support this model. Previous workers have also suggested that the tourmaline-rich rocks on Store Malene (Appel & Garde 1987) were formed via hydrothermal alteration of volcanic rocks. Similarly the origin of regionally important quartz-cordierite rocks have been interpreted as the hydrothermal alteration products of felsic volcanoclastic sediments (Dymek & Smith 1990). These interpretations are consistent with our observations. In particular laminated quartzo-feldspathic rocks may represent ash fall deposits, stratigraphically overlying the amphibolites. However, the occurrence of significant volumes of biotite and biotite-garnet schist suggests that at least some of the lithologies present in this section were originally clastic deposits.

The Storø greenstone belt

Introduction and regional setting

Storø, or Qeqertarsuaq in Greenlandic, is the largest island in Godthåbsfjord and contains the most promising gold occurrences in the region, hosted by rocks of the Storø greenstone belt. This NNE-trending belt has most extensive exposures on central and northern Storø, but it continues along strike northwards on the peninsula containing Kangersuaq and Kangaarsuk mountains, and southwards to southern Storø and the area north and west of Kobbefjord (Figs 1-3). Most of the greenstone belt of northern Storø is covered by a mineral exploration license (licence number 2002/07 – NunaMinerals A/S, hereafter referred to as “the concession area”; see Fig. 1), and any discussion of this area is based on company reports and previously published material. Fieldwork was carried out in 2004 outside the concession area, along the north shore and on the southern half of Storø, as well as to the north and south of the island (see the ArcView project on the DVD for an overview of all visited locations). Digital copies of the 2004 field maps of these areas are included on the DVD. The geology of the concession area will be discussed in more detail, based on field work carried out in 2004, in a GEUS report by Appel and co-workers, to be printed in 2005.

The Storø greenstone belt has previously been mapped at a 1:100 000 scale (McGregor 1983, 1993; Chadwick and Coe 1988; Garde 1988), but these maps were compiled before the concept of different terranes in the region took shape in the late 1980’s, and at a time that only a limited number of geochronology data were available. As a result there is no distinction in these maps between Nûk gneisses and Ikkattoq gneisses. Detailed maps of variable scale and quality exist of the concession area on Storø in company reports (Grahl-Madsen 1994; Era-Maptec 1995; Skyseth 1997; Smith 1998). An unpublished map by Grimes (pers. com. 2004) of the northern part of Storø is added to the DVD. The most complete description of the rocks of the Storø belt are in the published Qôrqut map description by McGregor (1993). The geological descriptions in company reports focus mainly on the mineralised zones, and no comprehensive description of the whole Storø greenstone belt exists.

The Storø greenstone belt is located in what previously has been referred to as the Akulleq terrane (McGregor et al. 1991; Friend et al. 1996), but which now is split into the Tre Brødre and Færingehavn terranes (Nutman et al. 1989; Friend & Nutman in press; see regional geology chapter). The green-stones form part of the former. A 1 to 2 km wide strip of Nûk gneisses of the Akia terrane occurs on the north-western-most part of Storø, bound to the east by what is interpreted as the Ivinnguit fault (Fig. 3). At present no geochronological data exist to confirm this interpretation. Rocks of the Færingehavn terrane in the Storø belt comprise Early Archaean rocks, referred to as Amîtsoq gneisses, which dominate the central and southern part of Storø, as well as the areas south-west of the island and west of Kangaarsuk. The Tre Brødre terrane in the Storø belt comprises TTG rocks of the Ikkattoq gneisses and similar unnamed grey gneisses, which occur predominantly on northern Storø and on Kangaarsuk, and rocks of the anorthosite complex and supracrustal greenstone belt, which are most abundant on central Storø, in the concession area. Along the south-eastern margin of the island occur late granite intrusions of the Qôrqut granite, which forms a large intrusive body further east (Fig. 2).

Four major shear zones - and branches thereof - occur on Storø and the along strike areas. The Ivinnguit fault separates the Akia terrane from the Tre-Brødre terrane in north-western Storø and west of Kobbefjord (Fig. 3). The Tre-Brødre and Færingehavn terranes are separated by a poorly known detachment, exposed on northern Storø, west of Kangaarsuk, and north of Kobbefjord. Both terrane boundaries are intensely folded. The Storø shear zone forms a third ductile shear zone, running virtually parallel with, and in the hanging wall of, the Ivinnguit fault and traces the western edge of Storø, spectacularly exposed in the mountain slopes on central Storø. Branches, or equivalents of this structure continue northwards on Kangersuaq. A fourth large structural discontinuity is the Palaeoproterozoic Kobbefjord fault, which trends NE–SW on central Storø and continues to Kobbefjord to the south-west.

The descriptions here are predominantly restricted to the rocks of the greenstone belt. The associated rocks of the Tre-Brødre terrane and those in the Færingehavn terrane are referred to less extensively. The Nûk gneisses of the Akia terrane are described in more detail from Bjørneøen and Sermitsiaq in the previous chapter, and they are dealt with only briefly here. Finally, the Qôrqut granite, which intrudes into both Færingehavn and Tre Brødre terrane after amalgamation of the two. Figures 30-33 illustrate compiled field maps for the Storø greenstone belt from our 2004 field work, from Kobbefjord through Storø to Kangaarsuk.

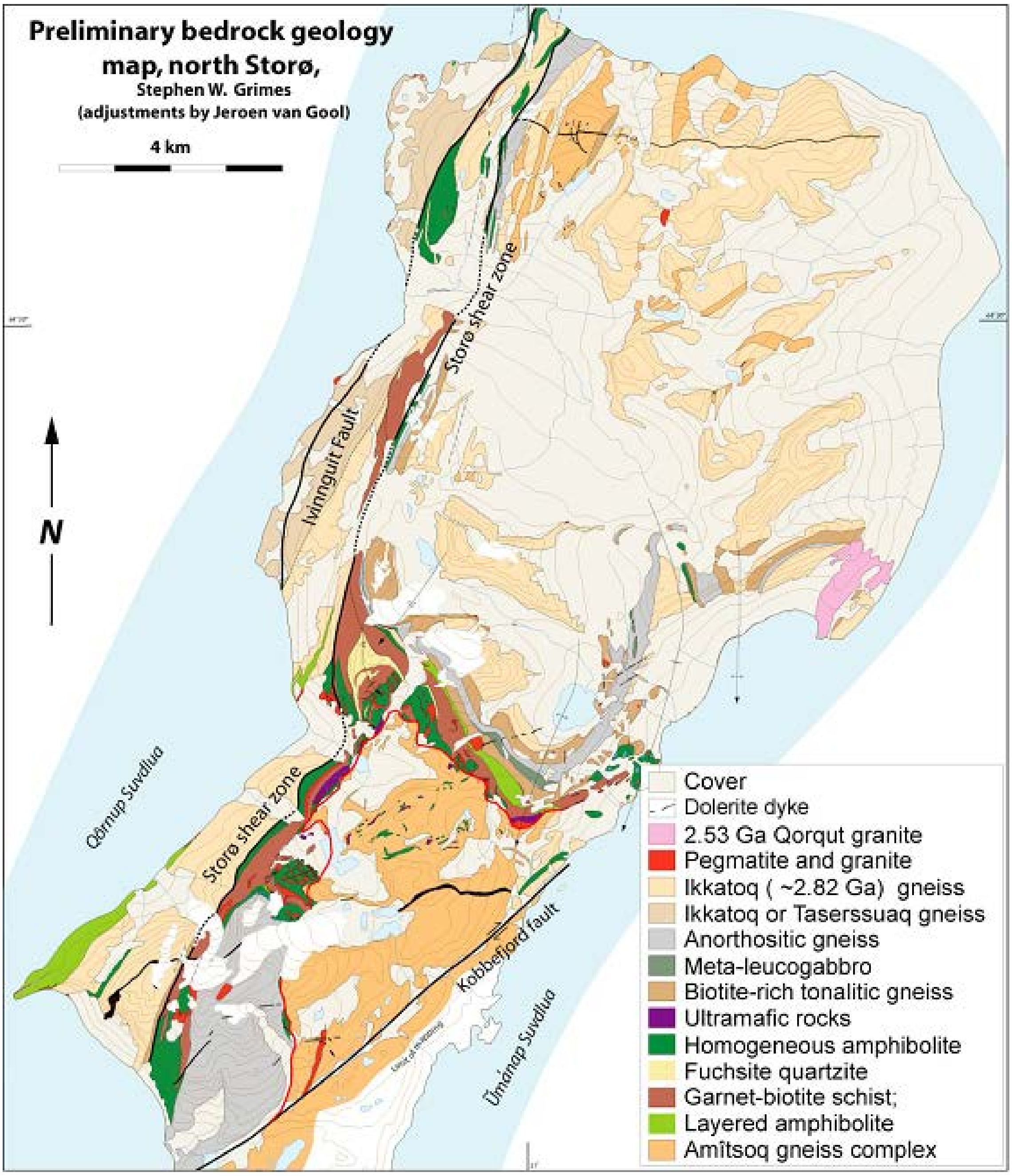

Figure 30. *Geological map by S.W. Grimes, based on fieldwork carried out in 2000 and aerial photograph interpretation, reduced from 1:20 000 scale. Additional information at Aappalaartoq from map by J.S. Petersen (in Grahl-Madsen 1994).*

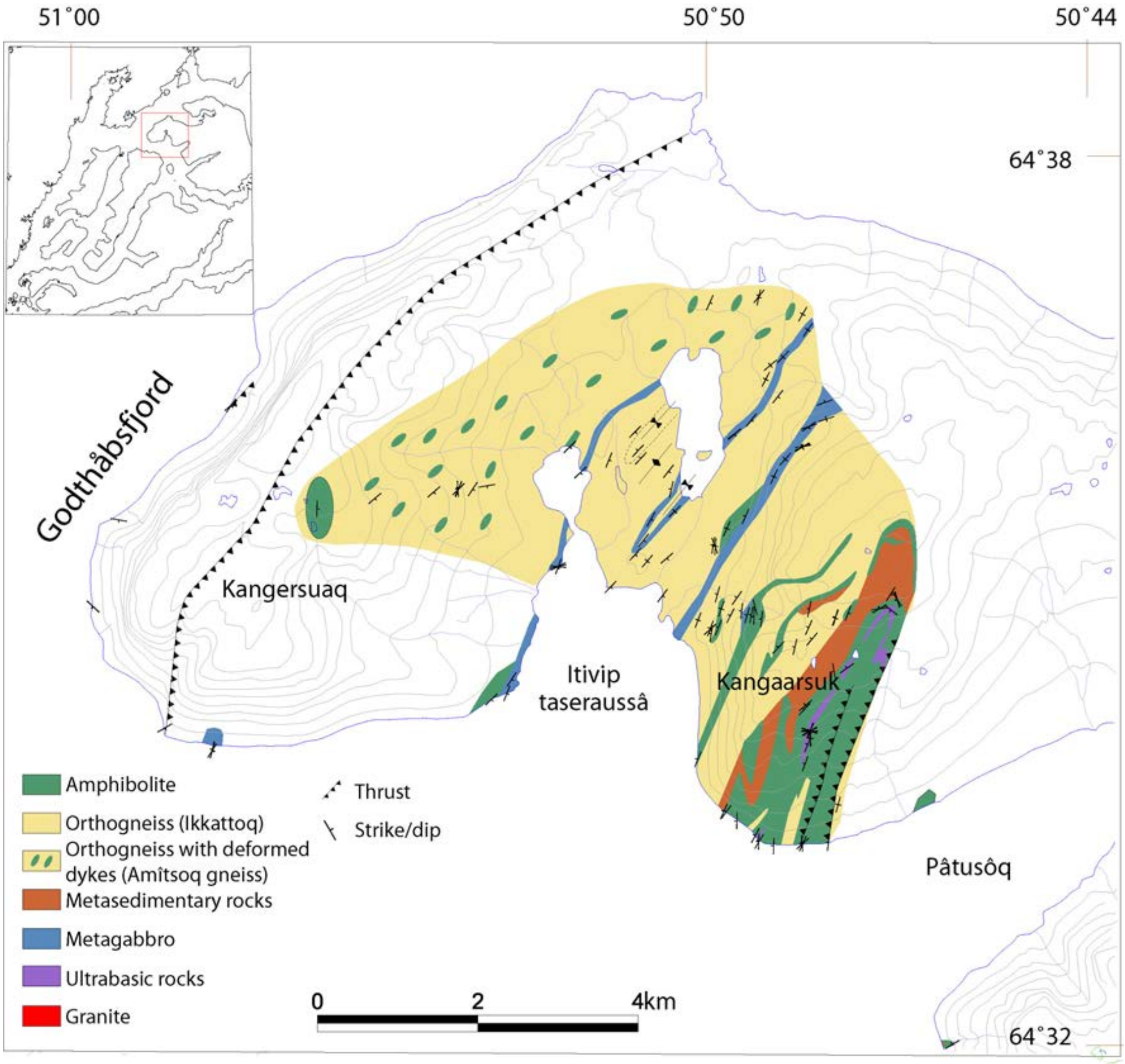

Figure 31. *Geological map of the Kangaarsuk peninsula by P.R. Jakobsen and S.A.S. Pedersen, reduced from 1:20 000 scale.*

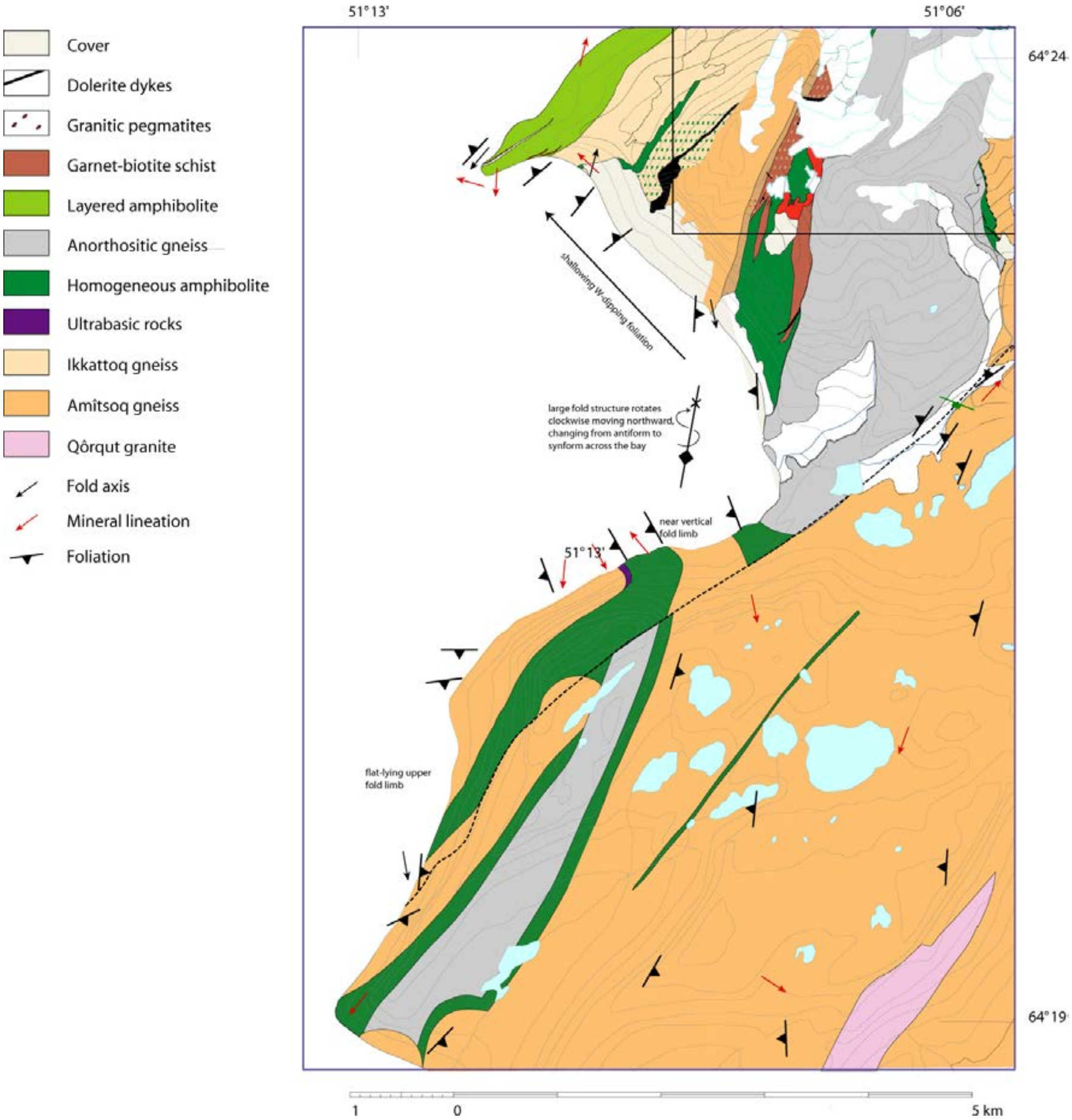

Figure 32. *Geological map of central Storø by J.A. Hollis, reduced from 1:20 000 scale.*

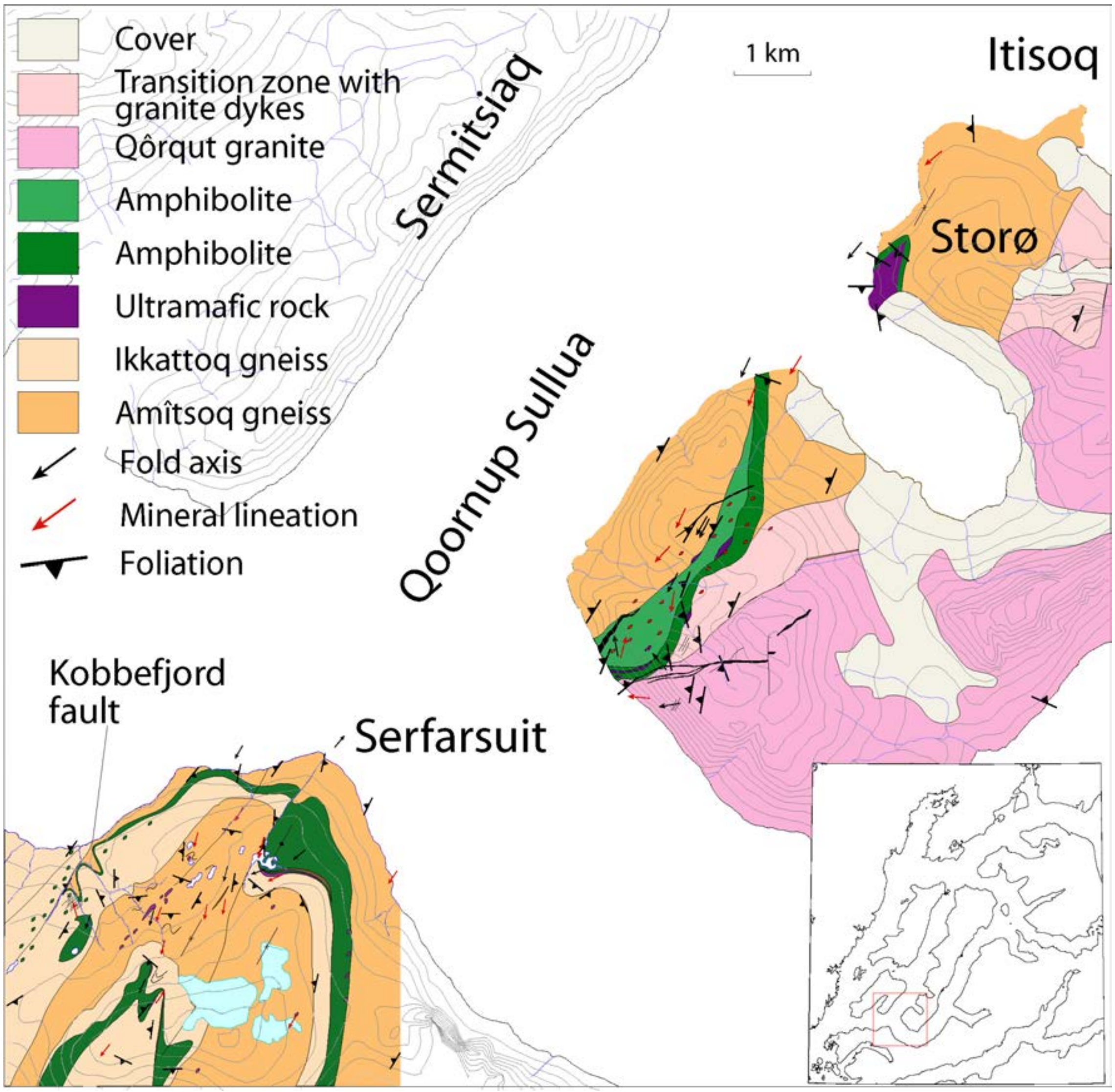

Figure 33. *Geological map of the southern part of Storø and the Kobbefjord-Serfarsuit area south-west of Storø by J.A. Hollis. Reduced from 1:20 000 scale.*

Tre Brødre terrane

Most of northern Storø, Kangaarsuk, and parts of the Kobbefjord area are within the Tre Brødre terrane, which comprise the predominantly supracrustal rocks of the Storø greenstone belt, intrusive rocks of the gabbro-anorthosite suite, the Ikkattoq gneisses and a younger unnamed grey gneiss.

The Storø Greenstone belt

The oldest rocks in the Tre Brødre terrane in this region are the supracrustal rocks in the greenstone belt. The belt is thickest, and most lithologically diverse on central and northern Storø (Fig. 30). To the north and south it thins and only isolated remnants are preserved. In the Kobbefjord-Serfarsuit area only discontinuous thin (up to several tens of metres) lenses and bands of greenstone occur (Fig. 33). On northern Storø, the rocks of the greenstone belt form a sequence of metavolcanic and metasedimentary rocks and include ultrabasic lenses. These rocks are closely associated with the anorthosite suite described below which forms the base of the tectono-stratigraphic sequence. No depositional basement is known for these rocks. The belt is best exposed and least deformed east of Aappalaartoq, where it was mapped in detail by J.S. Petersen (in Grahl-Madsen 1994). The age of the rocks is poorly constrained as Middle to Late Archaean, but must predate the age of the Ikkattoq gneisses (*c.* 2825 Ma) which intrude them.

Lower amphibolite

The lowest unit consists of 150 metres of banded amphibolites that are laminated to finely layered at millimetre to centimetre scale. The spacing of the layers and compositional variation is irregular, which may indicate a supracrustal nature of these rocks. They are fine grained, generally light grey and of intermediate, but variable composition, dominated by plagioclase, hornblende and epidote (retrograde), with minor quartz, and rarely clinopyroxene or garnet. Pillow structures are reported from amphibolites immediately east of the top of Aappalaartoq (Grahl-Madsen 1994).

Metasedimentary rocks

The banded amphibolite is overlain by 100 to 200 metres of compositionally layered rusty brown metasedimentary rocks, predominantly garnet-biotite schist and garnet-sillimanite-biotite schist, containing variable amounts of muscovite, sillimanite and locally cordierite, graphite, and minor staurolite. Cordierite occurs most commonly in leucosomes. On the northern slopes of Qingaaq, a garnet rich felsic unit occurs, which is interpreted as an alteration product of the original quartzo-feldspathic part of the metasedimentary sequence. Melt veins are common, all indicating fairly high temperature amphibolite facies metamorphism. These metasedimentary rocks are variable in thickness and near the top of the unit interleaved with amphibolite. Similar interleaving was observed south-west of Storø. Sillimanite and melt veins in pelitic rocks indicate that these have been exposed to relatively low pressure, upper amphibolite facies metamorphism, although staurolite and muscovite (in the assumed presence of quartz) indicate somewhat lower temperatures and might either be relicts or retrograde products.

Quartzitic gneiss

On the western and southern slopes of Aappalaartoq is a thick unit of quartz-rich gneisses, with a maximum structural thickness of 300 to 400 metres in a synformal fold hinge near the top of the mountain. Laterally the unit wedges out to both the south and south-east. Near the synformal hinge, where the unit is thickest, it is subdivided into a lower sillimanite-fuchsite-bearing member and an upper muscovite-fuchsite-bearing member. These rocks are isoclinally folded and the apparent thickness is structurally defined.

Garnet iron formation

The upper part of the metasedimentary succession locally contains several closely spaced up to 1 metre thick layers of garnet-rich iron formation, consisting predominantly of garnet, magnetite, and quartz. It forms packages of garnetite interleaved with the garnet-biotite schist, and forming individual layers of less than one metre wide and are laterally discontinuous. These are known mainly from the metasedimentary belt between Aappalaartoq and Qingaaq mountains, and were observed as lenses and pods (without magnetite) in pelitic rocks in the Serfarsuit-Kobbefjord area.

Upper amphibolite

The uppermost rocks in the tectono-stratigraphic sequence are fine to medium grained black amphibolites, which can be up to 250 m wide, but more commonly form thin sheets (10 to 50 m) interleaved with rusty garnet-biotite schist. The largest occurrences are on the southern slopes of Aappalaartoq and the northern slope of Qingaaq, but in both cases the dip slope exaggerates the thickness of the amphibolites in the map pattern. These amphibolites also contain deformed pillow structures, but in general their protoliths are more homogeneous. The top part of the greenstone belt sequence in central Storø contains numerous sulphide-mineralised zones, occurring both in metasedimentary rocks and amphibolites. These generally occur in zones of intense alteration, where sheeted quartz veins occur, as well as calcite veins, associated with alteration of the amphibolites to diopside, epidote or garnet, often occurring in more felsic, coarse-grained patches.

Ultrabasic rocks

Lenses of meta-ultrabasic rocks occur throughout the sequence, but are most common at the top, along the contact with the structurally overlying Amîtsoq gneisses, where they can form bodies of up to one hundred metres wide. They are predominantly ultrabasic schists, consisting of actinolite-tremolite-phlogopite, and are locally magnetite-rich in finer-grained parts. Larger bodies are often preserved fold hinges (e.g. in the main amphibolite near Kangaarsuk and in the Serfarsuit-Kobbefjord area), and the internal foliation is typically at a high angle to the regional foliation. On the fold limbs, the ultrabasic schists are sheared out to thin stringers or altogether absent. In places, these rocks preserve relict, coarse-grained igneous textures consisting of orthopyroxene-olivine ± clinopyroxene (Fig. 34, PFN jho2004-387). However, commonly these rocks are typically variably deformed and recrystallised. The presence of the ultrabasic rocks throughout the tectono-stratigraphic sequence is in accordance with an interpretation as ultrabasic dykes.

Figure 34. *Very coarse-grained ultrabasic rock with a preserved igneous texture. The rock contains orthopyroxene-olivine ± clinopyroxene. (PFN jho2004-387)*

Greenstone belt rocks outside the concession area

The overview map (Fig. 2) shows that supracrustal rocks of the greenstone belt extend outside the concession area, but nowhere else is the same complete section exposed. The amphibolite body at Kangaarsuk is banded, dark-green to black, hornblende-rich and contains abundant garnet. Epidote-rich calc-silicate bands, 10 to 20cm wide, occur on the highest ridge of the mountain and are spaced 0.5 to 1 metre. These might be the result of later alteration. The amphibolite contains both a layer of ultrabasic rocks, with large lenses forming remnants of fold closures, and near the western margin garnet-sillimanite-mica schist occurs at the highest tectono-stratigraphic level. These metasedimentary rocks also comprise quartz-muscovite schist.

Coarsely banded amphibolite consisting of dark green, amphibole-rich bands alternating with intermediate and felsic layers, occurs at the Ivinnguit fault on the north shore of Storø and on the narrow peninsula north of Qinngaap Ilua (central Storø; Figs 30, 35, PFN jvg2004-0267, see also PFN jvg2004-0179 and jho2004-435). They comprise layered biotite-bearing quartzo-feldspathic rocks, amphibolite layers, garnet-hornblende, and garnet-biotite layers. On the thin peninsula on western Storø also layered garnet-bearing dioritic rocks are present. These rocks are interpreted as metavolcanic in origin, supported by their close association with thicker amphibolite units and, in the case of the a similar amphibolite unit near Serfarsuit, with thin heterogeneous biotite- and garnet-bearing metasedimentary rocks.

Figure 35. *Coarsely banded amphibolite consisting of dark green, amphibole-rich bands alternating with intermediate and felsic layers. (PFN jvg2004-0267)*

On southern Storø, the structurally lowest amphibolite is a medium-grained, dark homogeneous amphibolite containing hornblende-plagioclase ± clinopyroxene, and rare garnet. This is overlain by a thin, discontinuous unit of heterogeneous metasedimentary rocks which dominantly consist of medium-grained garnet-sillimanite-cordierite-biotite gneiss and garnet-biotite gneiss. On a decimetre to metre-scale they show compositional layering from more felsic to more mafic (biotite-rich) varieties. In the uppermost part of the amphibolite sequence in southern Storø the amphibolites become very heterogeneous on a metre to ten-metre scale. Here banded mafic rocks are interleaved with ultrabasic units and to some degree also with the metasedimentary rocks. The amphibolites include layers of hornblendite, biotite-rich schist, and garnet amphibolite. In some cases the latter shows well-developed felsic rims on garnet, which show no evidence of deformation.

The greenstone belt rocks outside the concession area are all slightly distinct from the ones on central Storø. However, it is likely that the differences in lithologies and sequences represent lateral variations of one single, disrupted supracrustal belt.

Gabbro anorthosite suite

The base of the tectono-stratigraphic sequence in northern Storø is characterised by a medium to coarse-grained gabbro-anorthosite complex, occurring in the core of anti-formal structures. The largest anorthosite body, at Qingaaq Mountain, is two kilometres wide. It extends also to south Storø and occurs as up to 100m wide bands and trails of inclusions of meta-gabbro on the peninsula north of Storø (Fig. 2). East of Aappalaartoq mountain is the best preserved succession of meta-anorthosite and meta-gabbros, but here the more massive anorthosite is lacking. The anorthosite at Qingaaq is a homogeneous gneiss dominated by very calcic plagioclase, with minor stringers of hornblende. Near the margins of the anorthosite, the rocks grade, with increasing mafic content, into heterogeneous leuco-gabbro and gabbro. Contacts with the overlying layered amphibolites are generally poorly defined. This suite of rocks tends to be strongly deformed and the meta-gabbros are commonly altered to amphibolite, often mapped together with the overlying supracrustal amphibolites.

Ikkattoq gneisses and younger unnamed gneiss

The *c.* 2825 Ma Ikkattoq gneisses (Friend et al. 1988) dominate the Tre-Brødre terrane. They occur as fine to medium-grained, rather homogeneous, tonalitic, pale grey biotite gneisses with a simple structure (Fig. 36, PFN jvg2004-0195). In northern Storø they occupy the core of the large antiform, structurally underneath the level of the anorthosite and interleaved with panels of Amîtsoq gneiss (Fig. 30). From here they extend northwards to Kangaarsuk (Fig. 31). They also occur north of Kobbefjord, in the southern extension of the rocks on eastern Sermitsiaq. The Ikkattoq gneisses contain isolated, mafic stringers, and minor amounts of garnet in isolated locations. Leucosomes are less common in the Ikkattoq gneisses, compared to the Nûk gneisses, and form a minor component of the rocks. Inclusions of mafic rocks are not common and they vary from true amphibolites to dioritic phases. They Ikkattoq gneisses on northern Storø and Kangaarsuk intrude in the gabbro-anorthosite rocks, and trains of gabbroic lenses commonly occur here in the gneisses (Fig. 37, PFN prj2004-003). Where they are not affected by the strain of the shear zones, the homogeneous parts of the gneisses have a linear or L>S fabric.

A younger set of grey gneisses, often occurring as dykes intruding both supracrustal rocks and Amîtsoq gneisses, has previously been mapped as Ikkattoq gneiss, but has given SHRIMP zircon ages of *c.* 2710 Ma (McGregor 1993; Friend et al. 1996). These are tentatively correlated with Qârusuk dykes that intrude into the Akia terrane and the Tasiusarsuaq terrane (McGregor et al. 1983, McGregor 1993) and thus give a minimum age for terrane assembly. It is likely that some of the gneisses in the Storø belt mapped as Ikkattoq gneiss are actually the younger unnamed *c.* 2.7 Ga gneiss. For example, this could well be the case for gneisses on north Storø that are mapped as Ikkattoq, but contain enclaves of Amîtsoq gneiss. Similar intrusive relationships of Ikkattoq gneiss into Amîtsoq gneiss in Ameralik fjord to the south were explained in such a way by McGregor (1993). Intrusion of Ikkattoq gneiss into Amîtsoq gneiss would otherwise violate the terrane model, which proposes that the Tre-Brødre and Færingehavn terranes were juxtaposed shortly after 2.8 Ma, the intrusive age of the Ikkattoq gneisses. Grey gneisses, relatively rich in biotite and locally garnet bearing, intrude in the lower amphibolites in the greenstone belt and in the gabbro-anorthosite complex and are thought to be members of this younger suite of gneisses (S. Grimes, pers. com. 2004). Geochronological analyses are required to resolve this issue. Although the relatively mafic nature of these intrusions locally make it possible to distinguish them from true Ikkattoq gneiss, it is in general difficult to separate the two.

Figure 36. *High strain tonalitic Ikkattoq gneiss, near the Ivinnguit fault, northern Storø. (PFN jvg2004-0195)*

Figure 37. *Contact between leucogabbro to the left, and grey tonalitic Ikkattoq gneiss to the right. The grey gneiss intrudes into the gabbro. Near Kangaarsuk. (PFN prj2004-003)*

Akia terrane

Nûk gneisses

Nûk gneisses form a strip of rocks in the north-western corner of Storø, and are more widespread on Bjørneøen, Sermitsiaq and west of the Ivinnguit fault west of Kobbefjord. They form grey biotite-bearing granodioritic to tonalitic gneisses, commonly consisting of several intrusive phases of slightly different compositions or grain sizes, each in itself rather homogeneous (PFN jvg2004-0159). They are commonly medium grained, and younger phases are slightly finer grained (fine to medium grained). The grey gneisses can have a spotted character, resulting from the static recrystallisation of a porphyritic igneous texture (PFN jvg2004-0155). Similar rocks derived from a porphyritic protolith on Eastern Bjørneøen and east of the Qussuk peninsula were distinguished as belonging to the Taserssuaq tonalite by Garde (1989). The rocks have a coarse gneissic fabric and contain abundant leucosome, which tends to be discordant and irregularly shaped or folded. Inclusions of commonly homogeneous amphibolite as well as dioritic phases are seen throughout, but tend to be rather small. Agmatites occur, but are uncommon. The occurrence of leucosome (inferred to represent former melt veins) and the biotite stability in the rocks places them in the upper amphibolite facies, but the mineralogy does not allow a precise estimate of metamorphic grade.

Færingehavn terrane

Amîtsoq gneisses

Complex, heterogeneous Amîtsoq gneisses are the only component of the Færingehavn terrane in the area. They are dominated by very heterogeneous, multi-phase migmatitic gneisses, consisting predominantly of a grey tonalitic biotite gneiss that contains abundant small tabular amphibolite lenses (possibly remnants of Ameralik dykes) and abundant melt veins, which occur locally in centimetre-spaced rhythmic pattern (Fig. 38, PFN jho2004-461; PFN jvg2004-204 to 206 and PFN jvg2004-209 and 210). Larger inclusions (tens to hundreds of metres wide) of amphibolite and ultrabasic rocks occur on central Storø. Locally the gneisses contain a large component of white granitic melt. The Amîtsoq gneisses are commonly complexly folded and show several phases of deformation, as well as a series of intrusive phases. Their main occurrence is on central and southern Storø, and south-west of Storø. Minor volumes of complex grey gneisses with amphibolite inclusions are mapped as Amîtsoq gneiss on northern Storø and Kangersuaq. However, these gneisses occur at a lower structural level than the remainder of the rocks of the Færingehavn terrane, and are interleaved with rocks of the Tre Brødre terrane. This requires either a complex thrust interleaving of the two terranes, or a re-interpretation of these grey gneisses.

Figure 38. *Multi-component Amîtsoq gneiss with relict Ameralik dykes. (PFN jho2004-461)*

Lithologies that post-date terrane assembly

Pegmatites

Three or more generations of coarse-grained, quartz-plagioclase- dominated pegmatite occur throughout the greenstone belt and to a minor extent in the orthogneisses. They occur throughout the Storø greenstone belt and in the associated grey gneisses. Particularly on southern Storø, close to the main body of the Qôrqut granite, they heavily disrupt structures in the greenstone belt. The pegmatites intrude predominantly into amphibolites and late, upright fold hinges, and they are abundant in the Storø shear zone. They are between 5 centimetres and 5 metres wide, with the oldest phase being concordant, intensely deformed, boudinaged and foliated. The youngest are coarse-grained, undeformed, and discordant, truncating the regional fabric. Some of the youngest pegmatites are tentatively correlated with the Qôrqut granite, also at larger distances from the main granite body.

Qôrqut granite complex

The *c.* 2530 Ma Qôrqut granite complex dominates the south-eastern part of Storø. In the main body this is a medium-grained, non-porphyritic, biotite granite, consisting of a polyphase complex of hundreds of 10–50 m wide, cross-cutting granitic sheets. The cliff section along the SW coast of Storø illustrates some of the important intrusive contact relationships of the Qôrqut granite within in the amphibolite and Amîtsoq gneiss. Within *c.* 50m of the margin of the granite fragments of the wall rock occur as enclaves. The rather weakly deformed granite truncates the foliation in both amphibolite and Amîtsoq gneiss. In a *c.* 100m wide contact zone the granite shows weak development of a foliation defined by biotite alignment, but otherwise the granite is undeformed.

Meta-dolerite dykes

Massive, black dolerite dykes occur throughout the region, intruding all terranes. The majority belongs to the Palaeoproterozoic MD (meta-dolerite) suite at 2.4 to 2.2 Ga (Hall & Hughes 1990; Bridgwater et al. 1995). Potentially Tertiary dykes are also represented, but have not been identified as such. The metadolerites are fine-grained, black, homogeneous, and generally preserve an igneous texture, locally with chilled margins. They consist of plagioclase, orthopyroxene, olivine, and opaque minerals, but are slightly retrogressed with minor growth of amphibole (actinolite) on contacts between plagioclase and pyroxene. In the Kobbefjord shear zone, dykes are deformed and retrogressed to biotite-actinolite-epidote schists and highly silicified. They vary in width from few centimetres to several tens of metres, the most commonly observed are in the order of two metres wide. They trend predominantly E and NE. A small dyke on northern Storø clearly post-dated a phase of brittle fracturing, invading and crossing a set of fractures without being deformed itself (PFN jvg2004-0165).

Structure

The structures in the Storø belt are dominated by the antiformal structures at Qingaaq and north and east of Aappalaartoq and the four main shear zones. Overall three main deformation phases can be recognised, and it is likely that the Amîtsoq gneisses contain a range of older structures, that are often obliterated by the intense migmatisation.

Shear zones

In the area comprising the Storø greenstone belt and surrounding orthogneisses four main shear zones occur. These are in order of decreasing age: basal detachment of the Færingehavn terrane, the Ivinnguit fault, the Storø shear zone, and the Kobbefjord fault. All four consist of ductile shear zones, and only the Kobbefjord fault shows minor brittle reactivation.

Table 3. *Chronology of important regional structures within the Storø greenstone belt.*

Association	Timing	Metamorphic grade	Structures
Kobbefjord fault	Palaeoproterozoic (1900-1800 Ma?)	Greenschist	Ductile shearing and brittle fracturing in the Kobbefjord fault. Drag folding at Serfarsuit
Storø shear zone	Post *c.* 2720 Ma (later than terrane assembly)	Amphibolite	Ductile thrusting on the Storø shear zone and upright to overturned folding in both hanging wall and footwall
Terrane assembly?	*c.* 2720?	Amphibolite	Formation of the regional fabric, during juxtaposition of the different terranes
	?	?	Remnants of an early fabric in the Amîtsoq gneiss

Basal detachment of the Færingehavn terrane

This structure is the least known, and poorest exposed of the four. It occurs on the contacts between the Amîtsoq gneisses and rocks of the greenstone belt throughout the study area. On central and southern Storø the Amîtsoq gneisses occupy the highest structural level, but further north they occur also at a lower structural level, beneath the greenstone belt, indicating that the basal detachment was imbricated. No strain increase is reported towards this contact, which may suggest that a very intense recrystallisation occurred after deformation, or the strain of the emplacement of the terrane was concentrated in a very thin zone, now poorly exposed.

Ivinnguit fault

The trace of the Ivinnguit fault around Storø lies mainly in Godthåbsfjord, but it skims the western shore of Storø. From Storø to the south-west, it crosses Qoornup Sullua and occurs again on south-eastern Bjørneøen. From here it crosses eastern Sermitsiaq and continues through Store Malene, west of Kobbefjord.

The Ivinnguit fault is exposed on the shore in northern Storø, where it is associated with a 800 m wide zone of increased ductile strain, culminating in a *c.* 50 m wide amphibolite. In the orthogneisses on either side, the main foliation intensifies towards the core of the shear zone and is associated with a progressive grain size reduction. The main discontinuity is located at the contact between Nûk gneisses to the west, and banded amphibolite to the east, the latter assumed to be part of the Tre Brødre terrane. The rocks display no obvious mylonitic fabric, and they form predominantly straight gneisses with an S>>L fabric. The foliation in the shear zone dips *c.* 70° to 80° to the east. Lineations are weak or absent, and the few that were measured in or near the shear zone plunge moderately to the NE, which is inconsistent with the overall moderate southerly plunges of the lineations in most of the Storø greenstone belt. Kinematic indicators are rare, and the few that were observed were not consistent. A pegmatite at the contact was virtually undeformed, suggesting that intrusion occurred after the latest penetrative deformation event in the shear zone. Because no obvious overprinting of the Ivinnguit foliation on the regional foliation was noted, it is assumed to be largely of the same age. The grain shape fabric in the straight gneisses is recrystallised, with a good equilibrium texture, indicating that peak metamorphism post-dated the deformation.

The exact trace of the Ivinnguit fault on Storø has been somewhat elusive. From its well defined location on the north shore, it has commonly been drawn coincident with the Storø shear zone, but from aerial photograph interpretation the Ivinnguit fault could be traced southwards to a location on the western shore with a similar set of steeply east-dipping straight gneisses associated with a banded amphibolite (Fig. 39, PFN jvg2004-320). From here, the Ivinnguit fault is assumed to cross the water to occur again on the south-east corner of Bjørneøen. This newly proposed trace of the Ivinnguit fault is sub-parallel with, but distant from the Storø shear zone.

Figure 39. *Banded amphibolite intruded by sheets of granodioritic gneiss, at the Ivinnguit fault western Storø. (PFN jvg2004-0320)*

Storø shear zone

The Storø shear zone also runs parallel with the western shore of the island, but further inland, and is exposed on the western slopes of Qingaaq and Aappalaartoq Mountains, and continues northwards on Kangersuaq (Fig. 2). It forms a zone of straight gneisses approximately 200 to 300m wide, but the whole zone of increased strain is at least 500m wide. It comprises predominantly supracrustal rocks, mica schist, quartzitic gneiss, garnet-sillimanite-biotite gneiss, and heterogeneous amphibolites. It is intruded by abundant pegmatites, which mainly occur in the amphibolites. The metamorphic grade is similar inside and outside the shear zone. The zone truncates structures both in the footwall and the hanging wall, and most of the greenstone belt rocks are excised on northern Storø. The rocks in the core of the shear zone form straight gneisses, but lack obvious mylonitic fabrics. The foliation dips consistently to the SE, with a dip angle varying between 90° and 70°. Elongation lineations are weak, and found mostly in the top of the shear zone, where they plunge approximately down-dip, but have a spread of orientations. Overall, the strain increases downwards from the hanging wall into the shear zone, which is expressed in the progressive transposition of older structures and straightness of the gneisses and pegmatites. Small scale folds become progressively tighter towards the base of the shear zone. Whereas pegmatites in the top of the zone occur both discordant and concordant, in the lower 100 metres all are parallel with the main foliation and strongly deformed. Kinematic indicators do not give a clear indication of the sense of displacement, but antiforms in the hanging wall and a synform in the footwall, south-west of Qingaaq (Fig. 40 panorama of fold) may indicate a thrust movement. Assuming that the Ivinnguit fault is parallel with the regional foliation (see above), this footwall synform would also fold the Ivinnguit fault from predominantly east-dipping as seen on northern Storø, to west-dipping as seen on Bjørneøen and Sermitsiaq. The Storø shear zone is not a terrain boundary since rocks of both the Færingehavn and Tre Brødre terranes occur on either side.

Imbricate, west-dipping shear zones at the eastern margin of the large amphibolite body at Kangaarsuk are associated with upright folds and correlated with the deformation of the Storø shear zone, resulting in a large pop-up structure.

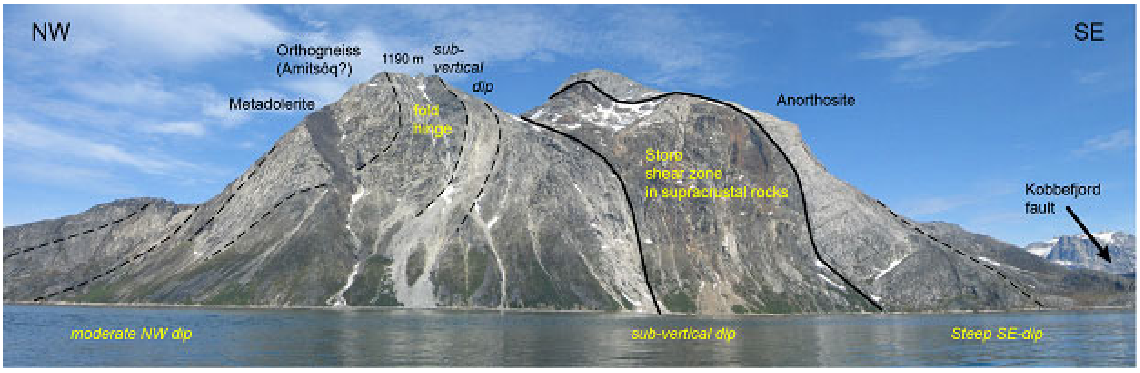

Figure 40. *East-closing synform in the footwall of Storø shear zone, on the south-western slopes of Qingaaq mountain. (PFN jvg2004-0256, 0257, 0258)*

Kobbefjord fault

The Kobbefjord fault is a late NE-trending fault zone that truncates or deforms all other structures (Fig. 2). It can be traced on geological maps and in a distinct signature in the aeromagnetic data (Rasmussen & Garde 2003) from Kobbefjord, east of Nuuk, through central Storø and to Narsap Sermia, the glacier south of Ivisaartoq, in the north-east. It has been described in detail by Smith & Dymek (1983) and the findings of the 2004 fieldwork confirm their observations and interpretations. On Storø it is a *c.* 100 m wide zone of ductile deformation and alteration, while at Kobbefjord it is *c.* 20 m and has a slightly more brittle character. It is dominated by quartz-rich mylonites, that are steeply dipping and have good sub-horizontal lineations (Fig. 41, PFN jvg2004-1442]). Kinematic indicators are fairly consistently dextral, but few sinistral indicators were also observed, presumably the result of heterogeneous shear. Quartz-amphibole-chlorite-epidote rocks in margins of the shear zone suggest intense silicification, and most of the rocks in the core are chloritised (PFN jvg2004-1449). Red staining of pegmatites and felsic orthogneisses, the silicification and hydration of minerals indicates intensive hydrothermal alteration. Fractures occur throughout the zone, but tend to be widely spaced and the lack of slickensides suggests that the brittle reactivation of the fault zone was minor, and not accompanied by large displacements. Smith & Dymek (1983) report the occurrence of breccias to ultra-cataclasites, and pseudotachylites, and also indicate minor associated shear zones adjacent to the Kobbefjord fault. On central–southern Storø, the Qingaaq anorthosite antiform is dextrally displaced by *c.* 3.5 km, with a minor south-block down vertical component. A narrow semi-brittle shear zone running through Serfarsuit north of the Kobbefjord is interpreted as an eastern branch of the Kobbefjord fault. Kilometre-scale drag folds on either side of the zone are consistent with a dextral offset and illustrate the ductile behaviour of the crust at that time.

Dolerite dykes of assumed Palaeoproterozoic age are deformed and fold into the shear zone with a geometry that is consistent with the dextral offset. The original mineralogy of one of these dykes is retrogressed to a biotite-epidote schist at the margin of the shear zone. Smith & Dymek (1983) assume that the age of deformation coincides with the age of Palaeoproterozoic tectonism in the adjoining Nagssugtoqidian orogen, *c.* 1800 Ma.

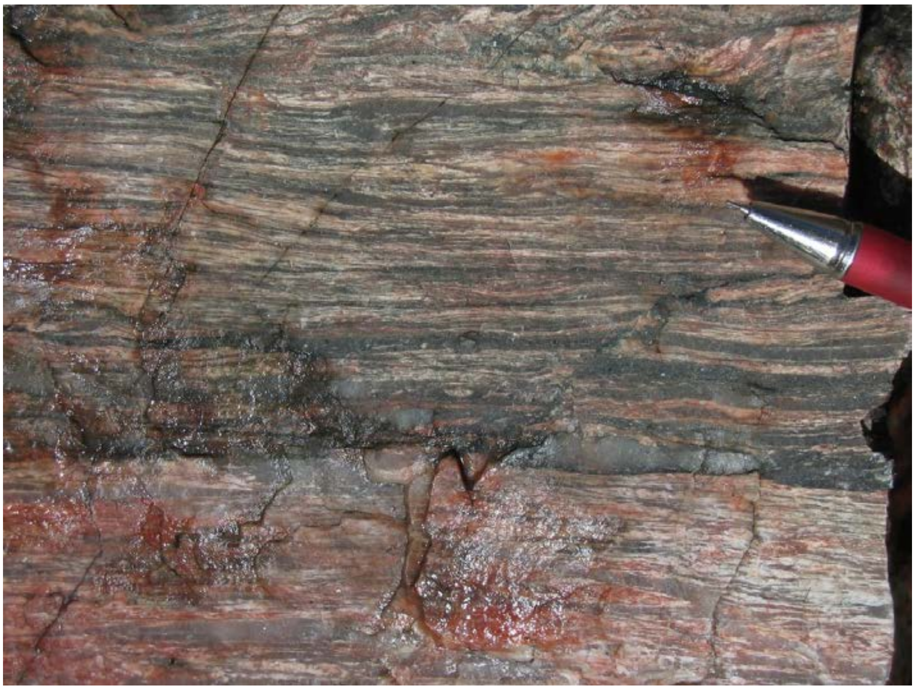

Figure 41. *Mylonitised and silicified pegmatite in the Kobbefjord fault on central Storø. (PFN jvg20041442)*

At least four deformation phases

The dominant structural element common to the whole belt is the regional gneissic fabric, overall parallel with the main terrane boundaries, and generally thought to be of the same age. In few locations in the orthogneisses it is axial planar to isoclinal folds in an older gneissic fabric, and therefore the main foliation is actually at least a second generation structure, mapped as S2 by Grimes (unpublished map, included on the DVD). This fabric has a coarse-grained gneissic character, parallel with leucosomes, and is axial planar to isoclinal and intrafolial folds, some of which have a shear character. A weakly developed lineation is common, but fairly consistent, giving an S>L fabric. Lineations plunge predominantly in southerly orientations. The gneissosity becomes more planar and shows a grain-size reduction towards the Ivinnguit fault, but seems not overprinted by the fault related foliation. Lineations are weak or absent in the shear zone forming the Ivinnguit fault, but the few ones that were measured in and near the shear zone on the north shore of Storø consistently plunge moderately to the NE. Interleaving of amphibolite and mica-schist layers in the upper part of the greenstone belt tectono-stratigraphy is interpreted as a result of thrusting, likely associated with the structural emplacement of the Færingehavn terrane.

The youngest main deformation is the shearing in the Storø shear zone which appears to have been coeval with the kilometre-scale folding of the antiforms at Aappalaartoq and Qingaaq. The latter can be traced (with offset on the Kobbefjord fault) to southern Storø. At Aappalaartoq, and eastwards, an antiform-synform-antiform set occurs. Of these, the westernmost is not obvious from the map pattern, since the strike changes only moderately across the hinge, from N-S north of the mountain, to NW-SE east of the mountain. However, the dip direction changes more dramatically, from E-dipping north of the mountain, to SW-dipping east of the mountain. In profile, this is a moderately tight structure. The major fold structures closest to the Storø shear zone are overturned to the west, while they are upright further east. Large-scale fold axes plunge moderately NE in the Qingaaq antiform, but moderately to steeply S in the folds around Aappalaartoq. At both locations the greenstone belt forms a triple point, with greenstone belt rocks diverging in three directions. This geometry can be explained if the two antiforms, that plunge almost towards each other, are joined by a highly attenuated hinge, that possibly is sheared out in the Storø shear zone. A new foliation is formed in and near the Storø shear zone (see below), overprinting the earlier regional foliation and older folds. On a small scale, fold overprinting relationships are abundant in the vicinity of the Storø shear zone.

Alteration and mineralised zones

Sulphide occurrences in the Storø greenstone belt occur predominantly along contacts between metasedimentary rocks (predominantly garnet-sillimanite schist and quartz-muscovite schist) and amphibolites. They are most wide-spread in the concession area, and only few mineralised zones were observed outside this area. Calc-silicate alteration of the amphibolites to diopside and epidote, locally also garnet is common in the greenstone belt. Sulphide occurrences were also observed in the mica schists, commonly with silicification, while amphiboles are common in these alteration zones. Sulphides are pyrite, arsenopyrite, and possibly pyrrhotite. The upper part of the metasedimentary sequence north of Qingaaq is an anomalously garnet-rich quartzo-feldspathic biotite gneiss. This is also seen as an alteration product. A one-metre wide rusty alteration zone with associated sulfides (pyrrhotite or pyrite) was observed within the banded amphibolite at Kangaarsuk. Pyrite and arsenopyrite were also observed in the rusty weathering, altered felsic layers of the mafic to ultrabasic amphibolite sequence on southern Storø.

Gold occurrences in the concession area are concentrated in the core of the NE-plunging antiform on northern Qingaaq (Smith 1998) and around the fold core at Aappalaartoq, in the hanging wall of Storø shear zone. Elevated gold values occur commonly in sheeted quartz veins in discontinuous zones, but also at the sulfide-mineralised contacts between amphibolite and Al-rich metasedimentary rocks. More detailed description of the gold occurrences and exploration results in the concession area are presented in most recent NunaOil A/S company reports in the GEUS archives (Grahl-Madsen 1994; Era Maptec 1995; Trepka-Bloch 1995; Skyseth 1997, 1998; Smith 1998). Summary descriptions of the gold occurrences on Storø are presented by Appel et al. (2000) and Appel et al. (2003).

Hydrothermal alterations occur more commonly in close proximity to the Storø shear zone, but may also be linked to the antiformal structures in its hanging wall. Previously mineral occurrences have tentatively been linked to the intrusion of the Qôrqut granite east of Storø. Potentially, the intrusion of the Ikkattoq gneiss into the base of the greenstone belt may also have provided a heat and fluid source for alteration processes.

Depositional environment

For a discussion of the depositional environment of the rocks in the Storø greenstone belt the following observations are important:

- The finely layered nature and intermediate composition of the lower amphibolites, with thin garnet-mica-schist intercalations.
- Pillow structures in the lower and upper amphibolites.
- Pelitic and semi-pelitic rocks in the sequence, also including a thick quartzite unit.
- Close association between the greenstone belt and gabbro-anorthosite

In the absence of geochemical analyses of the rocks it is difficult to interpret these observations fully. The pillow structures in the amphibolites point towards an ocean floor origin for those rocks, a setting that is also most likely for the occurrence of ultrabasic dykes. But the assumed volcanic (tuffite?) origin of the layered intermediate amphibolite, points towards a shallower depositional environment, which because of the coarse-clastic incursion, represented by the quartzite, needs to have been in the vicinity of a continental source. These observations would fit best with the interpretation of an island arc proximal to a continent, but until geochemical information is available, no more definite conclusion can be drawn.

The close association of the gabbro-anorthosite with the greenstones may suggest that they also are genetically related, although no information is available about the relative age of the greenstone supracrustal rocks and the anorthosites. These intrusive rocks represent a shallow magma chamber. The intrusion of the Ikkattoq and younger gneiss is not strictly associated with the greenstone belt and likely represents a major change in environment.

Geochemistry

Introduction

Chemical data are widely used to discriminate between rocks, and together with other data, such as mineralogy, texture, and setting, they help to deduce the origin and evolution of rock complexes. Thus, there is growing evidence that the chemical composition of supracrustal rocks reflects their plate-tectonic setting and depositional environments. The supracrustal rocks in the greenstone belts in the Godthåbsfjord region have been subjected to deformation, metamorphism, and several events of alteration, so that their original character and setting is difficult to recognise. Comprehensive chemistry (including analysis of appropriate isotope systems) of supracrustal rocks from each of the greenstone belts in the region is therefore an important part of the evaluation of their primary environment(s).

This section contains a preliminary evaluation of new chemical data obtained so far from the central Godthåbsfjord area in 2004 as well as a brief summary of a previous data compilation. In agreement with field observations, the new data indicate that the supracrustal sequences are commonly mineralised, and that some parts have been widely affected by syn- and post-depositional alteration. Owing to their preliminary nature the new data do not allow a reliable interpretation of the plate tectonic setting(s), but they do inform about various kinds of alteration and mineralisations. The new data set also reveals the presence of a hitherto unknown gold occurrence in the Qussuk area, and provides further documentation of a gold occurrence previously discovered by NunaOil A/S at Bjørneøen.

Previous geochemical data from rocks and stream sediments

A previous BMP-financed project by GEUS (Appel et al. 2003) included compilation of available geochemical data from the Nuuk region relevant for evaluation of its gold potential. The numerous gold-bearing rock and stream sediment samples and their spatial distribution document that gold occurs in many parts of the greenstone belts. However, the compilation also showed that the majority of the existing rock data have been acquired in connection with various mineral exploration campaigns for uranium, base metals, scheelite, and gold (see Appel et al. 2003 and references therein). High-quality geochemical data documenting the composition of non-mineralised, non-altered, representative supracrustal rocks are rare outside the Isua greenstone belt.

Stream sediment samples have previously been collected by the Survey at a density of about 1 sample per 30 km^2 over the entire Nuuk region, and geochemical maps based on stream sediment data and airborne radiometric measurements demonstrate that the Godthåbsfjord region is geochemically distinct from the neighbouring Archaean high-grade gneiss terranes by having higher concentrations of K, Rb, Cs, U, and Th (Steenfelt 1990, 1994, 2001; Steenfelt et al. 1990; Tukiainen et al. 2003). This illustrates that the region has preserved rock assemblages formed at a high crustal level, in agreement with the observed relative low metamorphic grade and abundance of granitic veins, pegmatites, and aplites.

A new gridding of the stream sediment data from the Nuuk region is part of an ongoing BMP-financed project on multi-parameter modelling of gold showings (Nielsen, Rasmussen & Steenfelt in prep.). The gridding outlines a NNE-SSW trending zone of elevated Ni/Mg coinciding with high values expressed in the grids of Cs and U. This is illustrated in Fig. 42, which also shows the location of regional stream sediment samples. The distribution of rock samples with high concentrations of Ni and Cs confirm the zonation outlined by the stream sediment data. Lithologically, the high Ni (and also Cr) reflect not only the well-known frequent occurrence of ultrabasic bodies in the greenstone belts, but also the prevalence of mafic lavas with komatiitic affinity (Hall 1980). High Cs, Rb/K, and U reflect abundant pegmatites and zones of hydrothermal alteration in the same region. Together, the geochemical characteristics from stream sediments suggest a favourable environment for vein type gold mineralisation at a relatively high crustal level (Steenfelt et al. 2003).

New analytical results

The new chemical data are derived from 258 rock samples and 73 stream sediment and soil samples distributed as shown in Fig. 43. The rock collection reported on here includes samples collected by GEUS personnel studying the economic potential of the Nuuk region outside the framework of the present project. All samples have so far been analysed for a package of major and trace elements (Au+48) by Activation Laboratories Ltd., Canada, employing a combination of instrumental neutron activation analysis (INAA) and inductively coupled plasma optical emission spectrometry (ICP-OES) upon four-acid digestions (HF, $HClO_4$, HNO_3, and HCl). This combination of methods provides good data for base metals, gold, and gold pathfinder elements (e.g. As, Bi, Sb, Se), but does not determine the important major element Si or important trace element Nb. Other elements, such as, Na, Fe, Cr, Rb, and rare earth elements (REE) are not determined with high precision and accuracy. Table 5 shows elements determined, lower detection limits, and number of samples with concentrations above the detection limit. Table 5 also marks element data that are not used in the context of this study, either because most of the values are below the detection limit or because the other of the two employed methods has better recovery.

The ArcView© project included in the DVD with this report contains a View named Geochemistry. Tables with the results of all analytical data, together with initials of the collector, coordinates, and short sample descriptions are also included. This enables the user to study the ranges and geographical distribution patterns of the analysed elements. The Geochemistry View illustrates the same data in a number of themes. The chemical data for some of the rock samples are evaluated further in the following. The analytical results are also included in spreadsheets in the attached DVD. Table A1 in Appendix A contains main statistical parameters for the stream sediment data.

Two maps displaying distributions of Au and Cr are presented here as examples of the new information. A number of both rock and stream sediment or soil samples have elevated to high gold concentrations (Fig. 44). Most of the gold-bearing samples have been collected in the Qussuk area, where both rock and soil samples indicate the occurrence of a new gold occurrence that deserves further investigation. The rock samples from Bjørneøen have been collected within a gold showing previously discovered by NunaOil A/S (Skyseth 1998; Smith 1998). The distribution of high Cr marks the location of ultrabasic rocks (Fig. 45). The chemical composition of the ultrabasic bodies associated with the supracrustal rocks is used to identify their type and origin, which is important information for the evaluation of the plate tectonic setting.

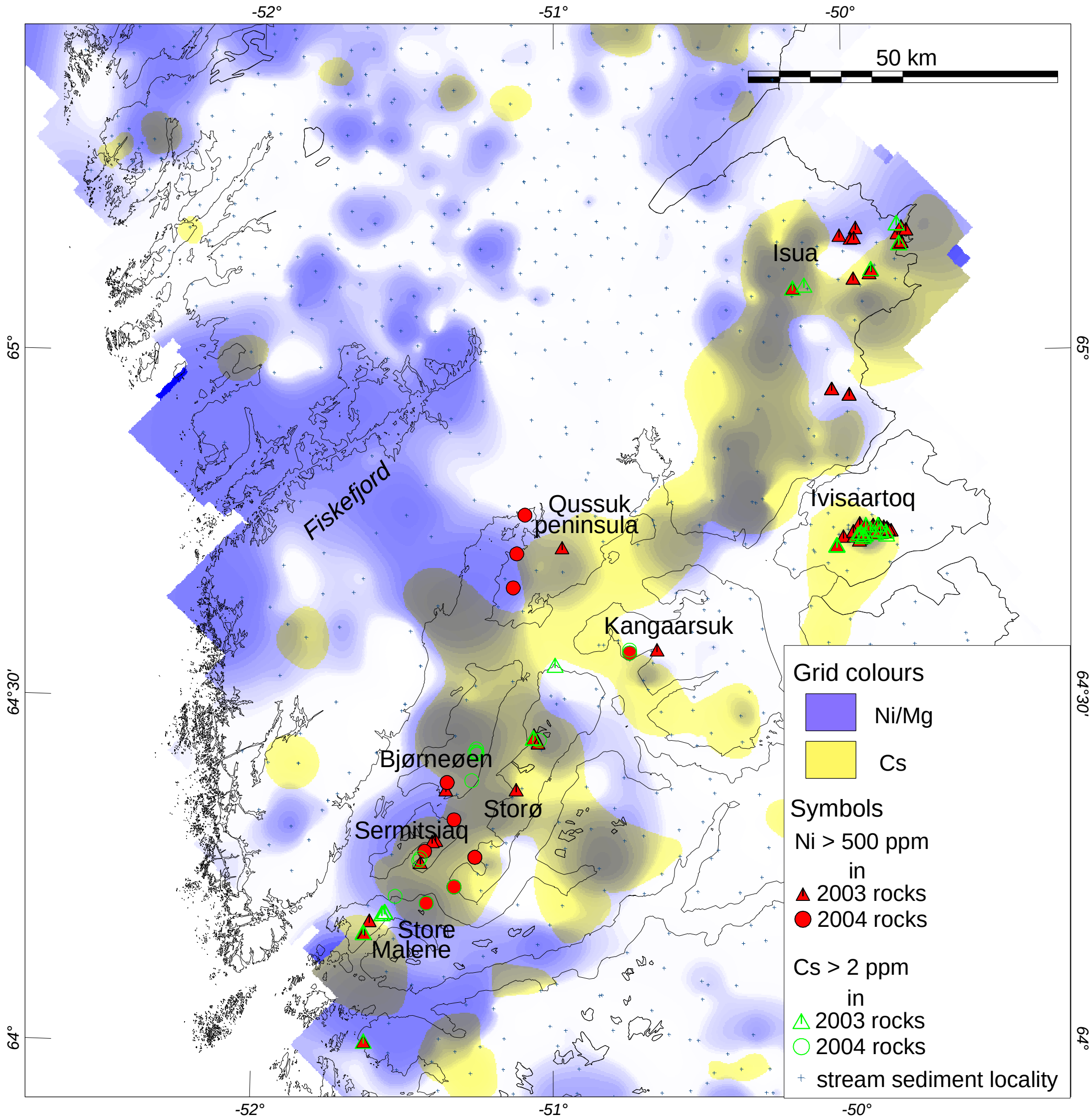

Figure 42. *Map of the larger Nuuk region illustrating a geochemical, NNE-trending zone exhibiting enrichment in both Ni/Mg ratio and Cs. The grids are based on regional stream sediment data. Rock samples with high concentrations of Ni and/or Cs are distributed in the same zone. Data for 2003 rocks are extracted from Appel et al. (2003). Data for 2004 rocks are from analyses carried out as part of the present project.*

Table 4. *Elements determined, lower limits of detection (LLD) and number of recorded samples with concentrations above LLD for rock and stream sediment (including soil) samples (SSS). Data excluded in tables of this report and DVD.*

ICP-OES			Sample type		INAA			Sample type					Sample type	
	Unit	LLD	Rock	SSS		Unit	LLD	Rock	SSS		Unit	LLD	Rock	SSS
Ag	ppm	0.3	91	58	Au	ppb	2	122	20	Sn*	%	0.01	3	0
Cd	ppm	0.3	197	16	Ag*	ppm	0.3	3	1	Sr*	%	0.01	8	3
Cu	ppm	1	255	73	As	ppm	0.5	97	9	Ta	ppm	0.5	40	5
Mn	ppm	1	258	73	Ba	ppm	50	161	73	Th	ppm	0.2	191	73
Mo	ppm	1	170	60	Br	ppm	0.5	58	67	U	ppm	0.5	87	64
Ni	ppm	1	258	73	Ca*	%	0	182	73	W	ppm	1	33	5
Pb	ppm	3	231	72	Co	ppm	1	244	73	Zn	ppm	50	165	35
Zn	ppm	1	258	73	Cr	ppm	2	254	73	La	ppm	0.5	253	73
Al	%	0.01	258	73	Cs	ppm	1	101	51	Ce	ppm	3	224	73
Be	ppm	1	96	67	Fe	%	0	258	73	Nd	ppm	5	146	72
Bi	ppm	0.1	62	16	Hf	ppm	1	189	73	Sm	ppm	0.1	251	73
Ca	%	0.01	258	73	Hg*	ppm	1	5	0	Eu	ppm	0.2	232	71
K	%	0.01	253	73	Ir*	ppb	5	2	0	Tb	ppm	0.5	46	11
Mg	%	0.01	258	73	Mo*	ppm	1	60	35	Yb	ppm	0.2	236	73
P	%	0.001	231	73	Na	%	0	258	73	Lu	ppm	0.05	223	73
Sr	ppm	1	258	73	Ni*	ppm	20	150	56					
Ti	%	0.01	253	73	Rb	ppm	15	122	48					
V	ppm	2	257	73	Sb	ppm	0.1	72	5					
Y	ppm	1	244	73	Sc	ppm	0.1	258	73					
S	%	0.01	249	73	Se*	ppm	3	12	3					

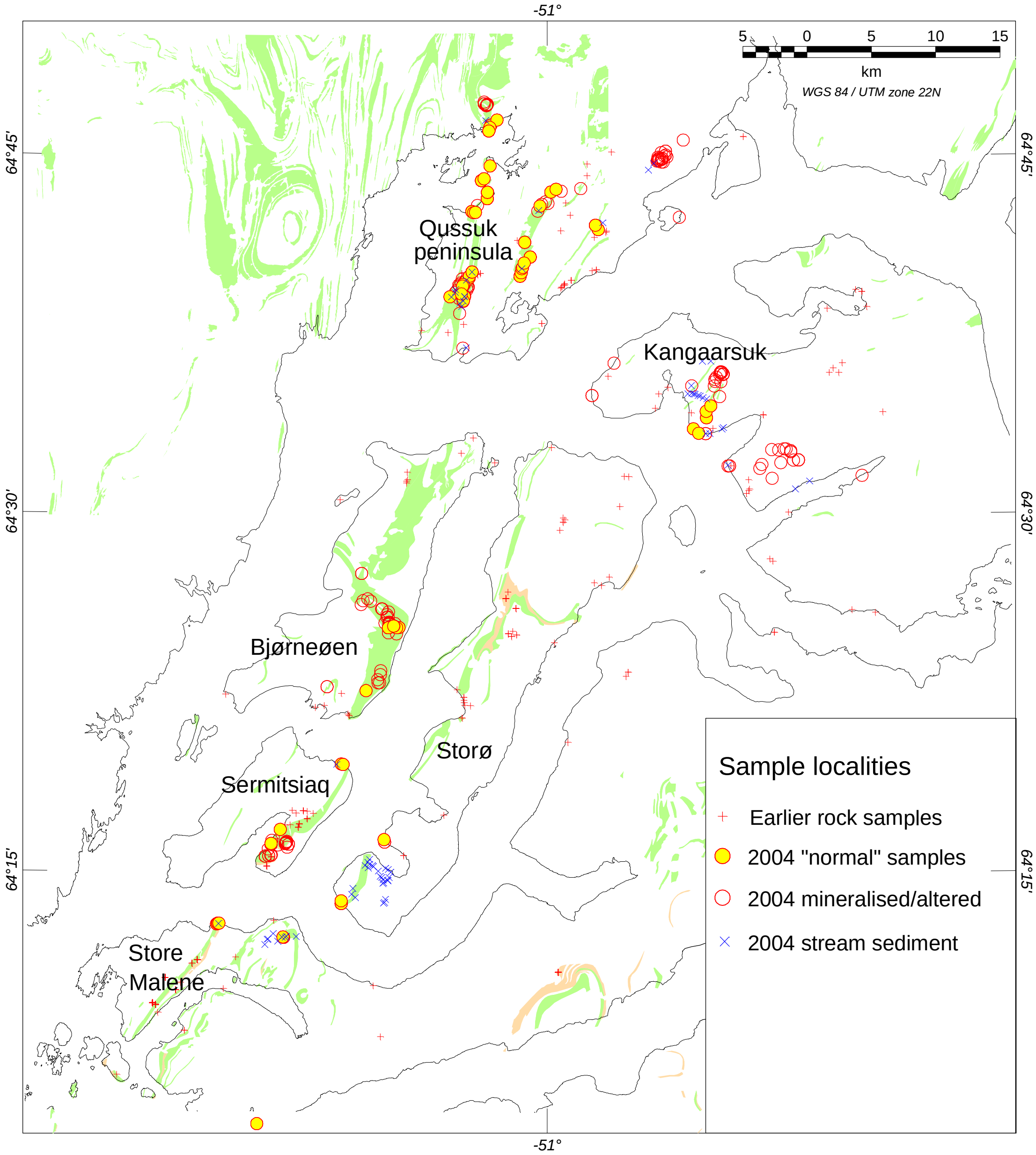

Figure 43. *Distribution of samples analysed for major and trace elements (by combined instrumental neutron activation and ICP-OES) in the central Godthåbsfjord region. Mafic metavolcanic rocks shown in green; metasedimentary rocks in light brown. The chemistry of "Earlier rock samples" are recorded in Appel et al. (2003).*

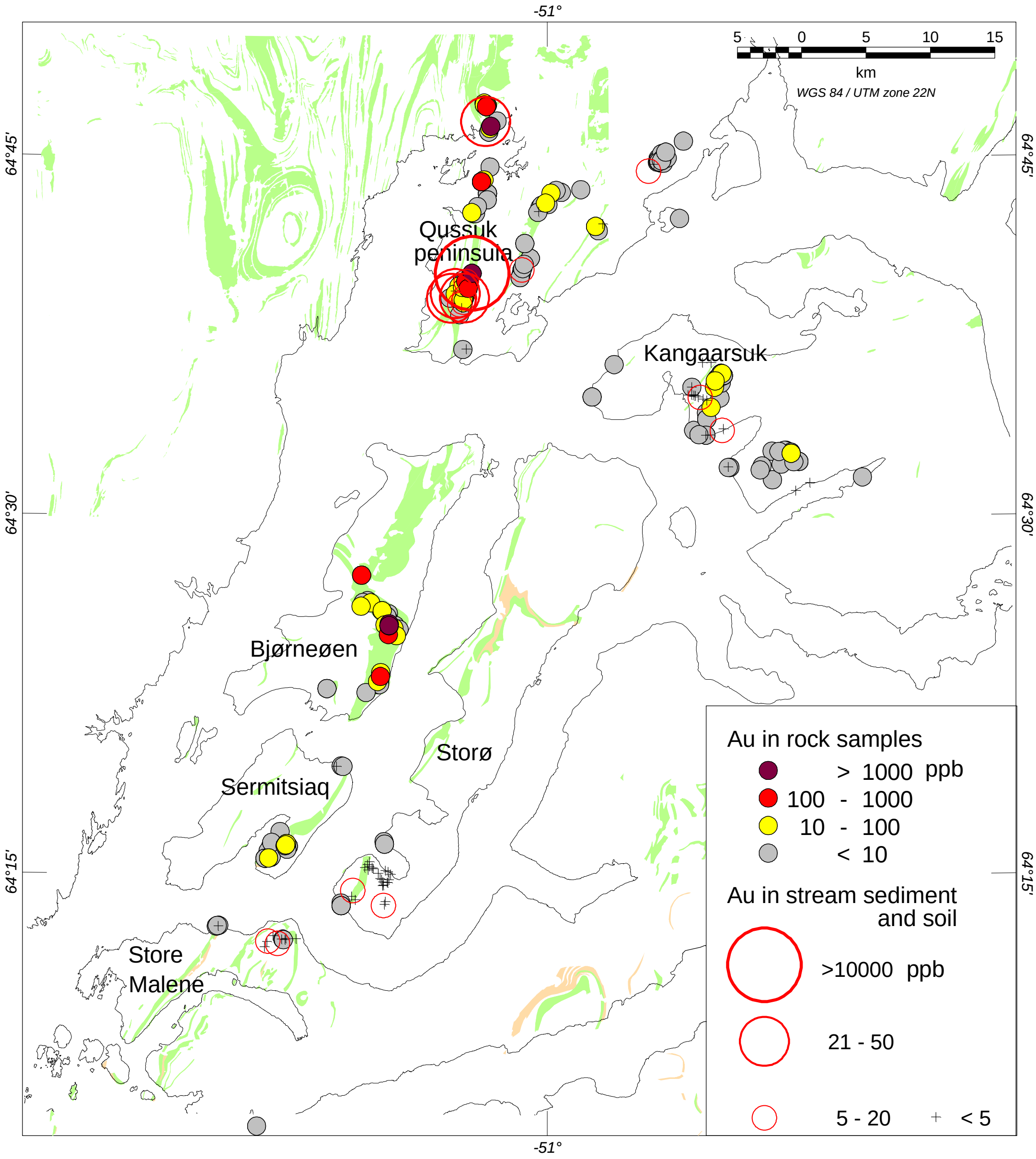

Figure 44. *Gold concentrations of rock, stream sediment, and soil samples collected in 2004 in the central Godthåbsfjord region. Mafic metavolcanic rocks shown in green; metasedimentary rocks in light brown. The data indicate a previously unknown gold potential at the Qussuk peninsula and confirm gold occurrence on Bjørneøen, discovered by NunaOil A/S.*

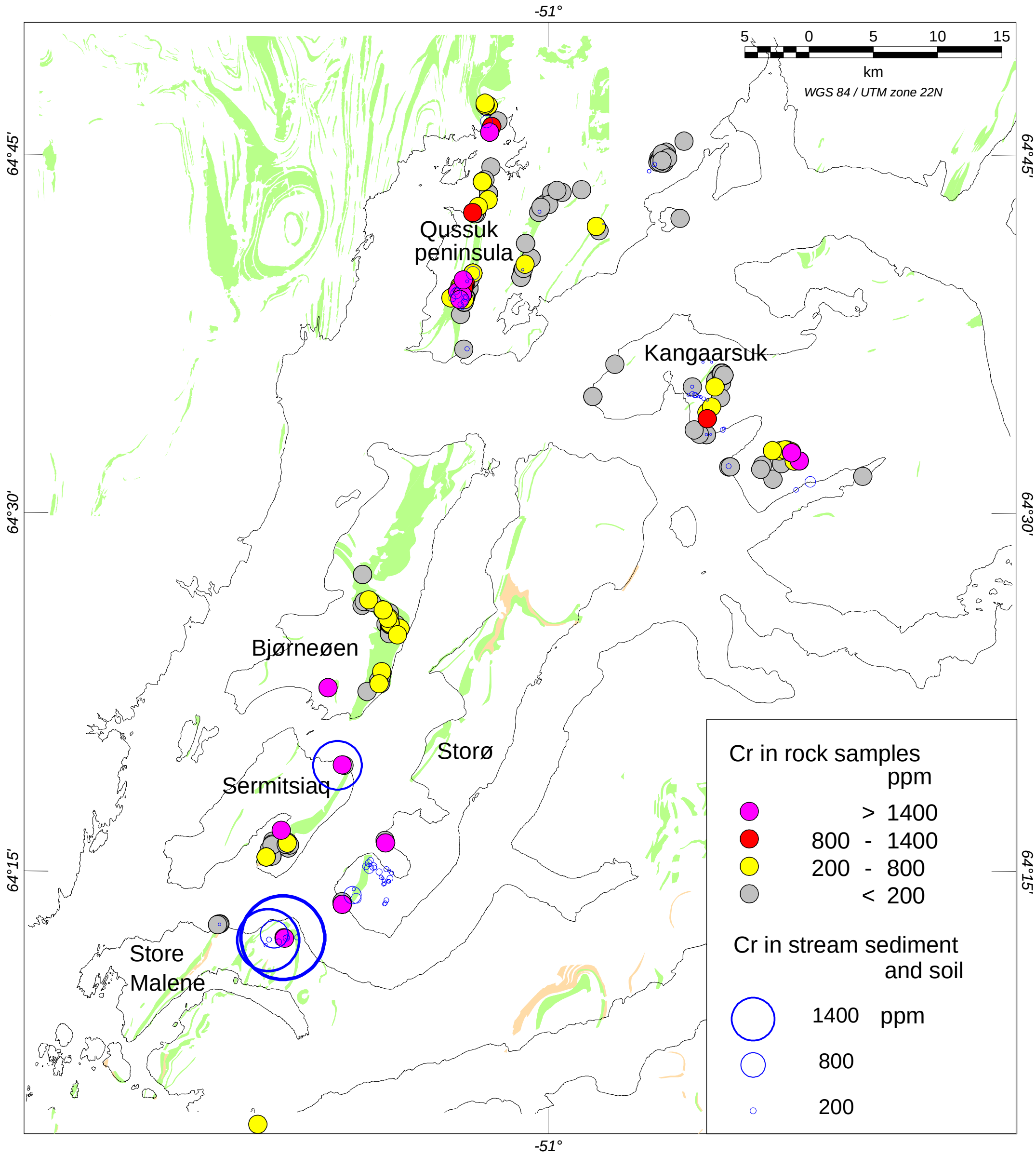

Figure 45. *Chromium concentrations of rock, stream sediment, and soil samples collected in 2004 in the central Godthåbsfjord region. Mafic metavolcanic rocks shown in green; metasedimentary rocks in light brown. High chromium is characteristic of the ultrabasic rocks within the greenstone belts.*

Geochemical comparison between individual parts of the greenstone belts

Table 6 gives an overview of rock samples collected in each of the areas studied in 2004, for both litho-geochemical and mineralisation assessment purposes. The chemistry of supracrustal rocks (i.e., amphibolites and schists) from each of the greenstone belts is compared to reveal potential regional differences. The rock samples are divided between Bjørneøen, Sermitsiaq, Store Malene, southern Storø, the Qussuk peninsula, and Kangaarsuk, and grouped into amphibolites and metasedimentary rocks according to the sampler's description and the chemistry into main lithological units, and split into "normal" and "mineralised/altered". The main statistical parameters for each group and area are shown to illustrate the chemical variation. The median may be taken to represent the typical composition, the mean is biased by samples of unusual composition, and the maximum values show the grade of mineralisation or alteration. The magnitude of the difference between the median and the mean reflects the degree of heterogeneity within the group.

Table 5. *Number of analysed rock samples from different areas divided into main lithology groups. Numbers in parentheses indicate the number of mineralised samples within the group*

Lithology of collected samples	Qussuk peninsula	Bjørneøen	Sermitsiaq	Kangaarsuk	Storø	Store Malene	Other sites
Amphibolite	35 (12)	15 (6)	16 (8)	21 (8)	1	3	2 (1)
Gneiss/granite	28 (27)	2 (2)		11 (11)			
Grey amphibolite	17 (1)						
Metagabbro	6	1			2		
Metasediment/schist	13 (6)	13 (8)	6 (4)	1		2	
Quartz veined rock or quartz veins	15	5	1	12			1
Ultrabasic rock	5 (5)	4 (3)	2	4 (4)	5 (4)	1 (1)	1
Tourmalinite		1	1				
Other	1		3	1			
Total	120	40	29	51	8	6	4

Amphibolites

In Table 7, containing medians of amphibolite samples, the highest value for each element is shown in bold for the four areas that contain most of the samples. The few samples from the remaining areas are not considered to be representative. In general, the samples from the different areas are similar, but there are some noteworthy differences.

The Qussuk amphibolites are highest in Mg, Ni, and also have high Cr, a signature that probably characterises the original magma. The elevated concentrations of Mn, S, and base metals at Sermitsiaq reflect sulphide mineralisation in the magmatic environment. The high values of Mo, Th, and light REE in the Kangaarsuk samples may be related to the original magma composition, but could also reflect that the rocks have been infiltrated with fluids or melts of granitic origin (see also the section below on depositional environments).

Table 6. *Median of element concentrations in "normal" amphibolites from different areas within the central Godthåbsfjord region. For each element, the highest value recorded among the four areas represented by a reasonable number of samples is marked in bold characters. Results below detection limits are labelled 'nd' (not detected).*

	Mafic metavolcanic rocks					
	Qussuk	Bjørneøen	Sermitsiaq	Kangaarsuk	Storø	Store Malene
No	23	9	8	13	1	3
	Median	Median	Median	Median		Median
Mg	**5.14**	4.00	3.34	3.00	2.72	4.67
Al	**5.39**	5.28	4.87	4.67	6.09	4.53
Ti	0.40	0.62	0.68	**0.72**	0.98	0.64
Fe	7.09	7.86	7.06	7.93	8.13	8.89
Mn	1523	1369	**2213**	1691	1435	1830
Ca	7.37	**7.75**	6.83	6.76	5.39	7.44
Na	1.47	1.06	1.46	1.27	2.08	1.25
K	**0.55**	0.16	0.28	0.38	0.92	0.21
P	0.03	0.06	0.03	0.06	0.09	0.03
S	0.03	0.09	**0.98**	0.22	0.03	0.02
Sc	30.3	30.2	**33.9**	23	15.4	37.4
V	232	243	**333**	226	248	302
Ni	**147**	103	127	77	51	103
Cr	181	158	**187**	32	19	150
Co	43	38	41	34	35	42
Cu	35	85	**307**	181	99	15
Pb	6.9	4.9	**15.4**	10	11.7	4.3
Zn	83	81	**125**	121	99	98
Ba	120	20	125	100	300	20
Sr	110	130	**211**	130	350	99
Y	17.8	16.6	**26.3**	25	24.2	28.5
Au	nd	**7.0**	5.0	0.0	nd	nd
As	nd	nd	nd	**0.9**	nd	nd
Be	nd	nd	nd	**1.3**	1.5	nd
Bi	nd	nd	nd	nd	nd	nd
Br	nd	nd	nd	nd	nd	nd
Cs	nd	nd	**2.0**	nd	nd	nd
Hf	1.0	1.0	2.0	2.0	2.0	2.0
Rb	8.0	8.0	8.0	8.0	8.0	8.0
Sb	nd	0.2	nd	nd	0.0	nd
Ta	nd	nd	nd	nd	1.8	nd
Th	nd	nd	0.4	**1.2**	1.6	0.5
U	0.0	nd	nd	nd	0.0	nd
W	0.0	nd	nd	nd	0.0	nd
Ag	0.0	nd	nd	nd	0.0	nd
Cd	1.1	1.0	0.4	0.4	1.1	1.3
Mo	nd	0.0	nd	**3.1**	6.8	nd
La	2.5	2.9	5.9	**8.3**	9.7	3.1
Ce	7.0	8.0	12.0	**21.0**	26.0	9.0
Nd	2.0	2.0	2.0	**9.0**	13.0	2.0
Sm	1.6	2.1	2.6	2.6	2.1	2.9
Eu	0.6	0.7	0.8	0.8	1.1	0.7
Tb	0.1	0.1	0.1	0.1	0.1	0.1
Yb	1.8	1.6	**2.6**	2.2	1.7	2.8
Lu	0.3	0.2	**0.4**	0.3	0.3	0.4
La/Yb	2.11	1.52	1.98	**4.5**	5.71	1.1
Ni/Mg	28.5	25.7	**38.0**	21.0	18.6	22.1

Table A2 of Appendix A contains statistical parameters based on all samples of amphibolites. The means and maxima of the normal group record that even the normal samples are somewhat mineralised. Commonly, the highest concentrations encountered in the samples are seen in the maxima of the group of mineralised samples. It is observed that Bjørneøen and Sermitsiaq are particularly enriched in Fe, base metal sulphides, Ba, Sr, Au, and Mn, whereas the Qussuk and Kangaarsuk amphibolites show less pronounced enrichment in the same element associations. Concentrations of Ca, the chalcophile elements As, Sb, Bi, and the lithophile elements Cs, K, Rb, Th, W, and LREE are variably elevated (see means and maximum values of "normal" rocks). These element associations suggest that the enrichment patterns reflect a combination of a primary sulphide rich environment and later alterations induced by granitic magmatism. However, detailed studies of the rock samples themselves are required to convincingly discriminate between the possible kinds of enrichment and explain their origins.

Schists

Medians of "normal" schists, provisionally grouped as metasedimentary rocks (Table A3 of Appendix A), do not show significant differences between areas. The samples of mineralised schist from Bjørneøen, Sermitsiaq, and Qussuk exhibit the same kind of mineralisation as that recorded in the amphibolite samples, i.e. base metal sulphides, Mn, Ba, and Au. In addition, variable enrichment in lithophile elements and Hf are also seen in the mineralised or altered schists.

Depositional environment

The original character of the deformed and metamorphosed rocks in the Godthåbsfjord region, now amphibolites and schists, is commonly difficult or impossible to unravel based on their visual appearance alone. Amphibolites may represent mafic lavas, mafic tuffs or intrusive rocks such as dolerite dykes and metagabbros. Likewise, schists may represent clastic sediments, volcaniclastic or volcanic rocks or mixtures between such deposits. Even volcanic lavas and intrusive rocks can become biotite schists upon extreme deformation and alteration. However, the geochemical signature of the greenstone belts is nevertheless important evidence that may be used to interpret their origin, depositional setting and potential for mineral occurrences.

As argued above, the presently available chemical data suggest that some of the metavolcanic rocks have been influenced by mineralisation processes in their depositional environment and may subsequently have been variably altered during metamorphism, intrusion of granitic material and hydrothermal activity. Careful selection of sample material and full chemical analyses are therefore necessary in order to reliably use standard diagrams for the discrimination of different plate tectonic settings. For example, the chemical analysis must include major element oxides and volatiles, Zr, Nb, and a larger suite of REE. Rb, U, Th, Ta, and REE need to be determined with a method that provides a lower detection limit than available with the current dataset. However, it is still possible to draw some preliminary conclusions about the primary settings from a few simple plots and comparisons with chemical data from amphibolites in other parts of southern West Greenland.

Regional correlations

The Mg-Ni variation diagrams Fig. 46 show amphibolite samples from the 2004 collection (a different symbol for each area) together with amphibolites from the 2003 data compilation from Store Malene, Storø, and Ivisaartoq, additional amphibolites from Ivisaartoq (Hall 1980) and amphibolites from the Fiskefjord area in the Akia terrane adjacent to Bjørneøen and Qussuk (Garde 1997). In Fig. 46 a and b, most samples plot around an almost linear correlation trend with a common range of up to 300 ppm Ni and 6 to 7% Mg. Only Ivisaartoq samples reach the upper end of the correlation trend reflecting the occurrence of volcanic rocks of komatiitic affinity (Hall 1980). However, a number of samples from several areas form a scatter above this trend, thus exhibiting selective Ni-enrichment. The numerous samples from Ivisaartoq, Fig. 46c, collected predominantly in scheelite mineralised amphibolites show the same relative Ni-enrichment in many samples. According to the NNE trending high-Ni/Mg zone outlined by the gridded stream sediment data (Fig. 42), this phenomenon appears to be characteristic of the Bjørneøen, Storø, Ivisaartoq, and Isua greenstone belts. A NW-trending branch of high Ni/Mg zones in the stream sediment data seems to embrace the Qussuk area. The stream sediment data may thus reflect the common occurrence of rocks with elevated Ni/Mg ratio in the greenstone belts of the Godthåbsfjord region. The exact nature of the relative Ni-enrichment is presently not known. It may reflect Ni-sulphide mineralisation associated with base metal sulphides. Alternatively, leaching of Mg may have occurred during the widespread syn-depositional carbonate alteration (formation of calc-silicate minerals) or later hydrothermal alteration.

Possible settings

Archaean greenstone belts often contain several groups of mafic volcanic rocks of different composition and provenance. For example in the Superior Province, Canada, the belts within the Wawa Subprovince embrace two volcanic association, intra-oceanic tholeiitic basalt-komatiite sequences and bimodal tholeiitic to calc-alkaline arc sequences (Polat & Kerrich 2000). The two volcanic rock suites are tectonically interleaved, but have been discriminated by their chemistry and the occurrence of other diagnostic rocks such as chert, iron formation and gabbros in the oceanic plateau environment and trench turbidites in the volcanic arc environment.

Mg- and Ni-rich komatiite and basaltic-komatiite sequences are common in Archaean oceanic volcanic plateaux. Chondrite-normalised REE spectra have been shown to be characteristic of the primary environment (Polat & Kerrich 2000). Oceanic plateau sequences have low LREE and flat spectra while arc-related volcanic suites have LREE enrichment and steeper spectra. Although the present analytical data do not include the full suite of REE or have sufficiently low detection limits (see Table 5), the data do allow an indication of the shape of the spectra.

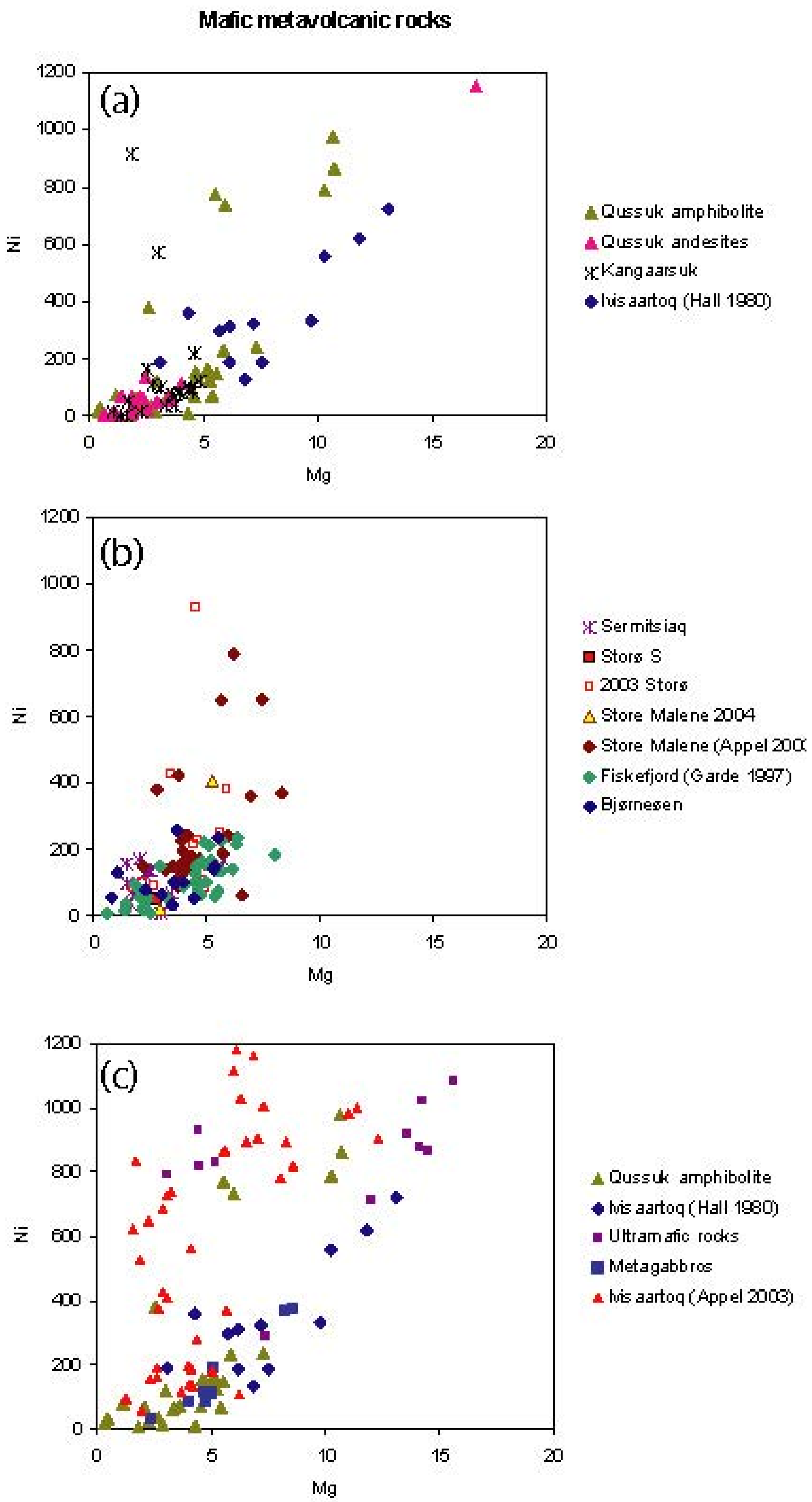

Figure 46. *Variation diagrams of Mg and Ni in samples of amphibolite from different parts of the greenstone belts in central Godthåbsfjord region and vicinity (Ivisaartoq and Fiskefjord, see location in Fig. 42).*

The REE spectra for amphibolites show interesting differences between the areas (Fig. 47). The samples from Bjørneøen itself have flat spectra consistent with an oceanic plateau environment. Samples from the adjacent Fiskefjord area, plotted into the same diagram, exhibit some enrichment in LREE suggesting that the amphibolite protolith formed in a different environment. The samples from Sermitsiaq have mixed spectra, some are flat, and some show LREE enrichment. Although the Sermitsiaq samples appear more disturbed, their REE spectra are generally similar to those from Bjørneøen. The samples of Qussuk grey amphibolite define a clear trend of LREE enrichment different from the flat pattern of the Bjørneøen samples. Such fractionated trends (see also La/Yb in Table 2 of Appendix A) characterise rocks formed in a volcanic-arc environment, and the chemistry therefore supports the interpretation of the field observations. Furthermore, the Qussuk amphibolites s.s. seem to embrace two kinds of volcanic rocks. Samples with fractionated spectra likely belong to the grey amphibolite (meta-andesite?) complex, whereas the samples with flat spectra, also characterising metagabbro samples from this area, suggest the presence of a volcanic association with a different source. More investigations are clearly needed to interpret the implications of these observations. The Kangaarsuk samples seem disturbed, but their REE spectra are generally similar to those of the Qussuk samples.

Conclusions and recommendations

The preliminary examination of the chemical data (newly acquired together with data from previously collected samples) suggest that, when carefully screened, samples of mafic metavolcanic rocks from different parts of the greenstone belts hold geochemical signatures, such as REE variation, reflecting their origin and plate tectonic setting. Several kinds of alteration and mineralisation may be discerned, some of which may be related to gold mineralisation, and some to preferential nickel enrichment. The detection of high Au values in several rock and soil samples from the Qussuk peninsula is a strong indicative for prospective gold occurrences. However, the measured high Au concentrations need to be ascertained by assay methods to test their validity.

The geochemical evidence presented here should only be considered as preliminary examples of the usefulness of chemical data and encourage more detailed scrutiny of the available data set and acquisition of additional chemical and isotopic data. It is therefore recommended to increase and refine the geochemical data base for the Nuuk region by collecting and analysing more samples of unaltered metavolcanic and metasedimentary rocks from all recognisable units of the supracrustal sequences, and by employing analytical methods that determine an appropriate suite of elements at low concentration levels.

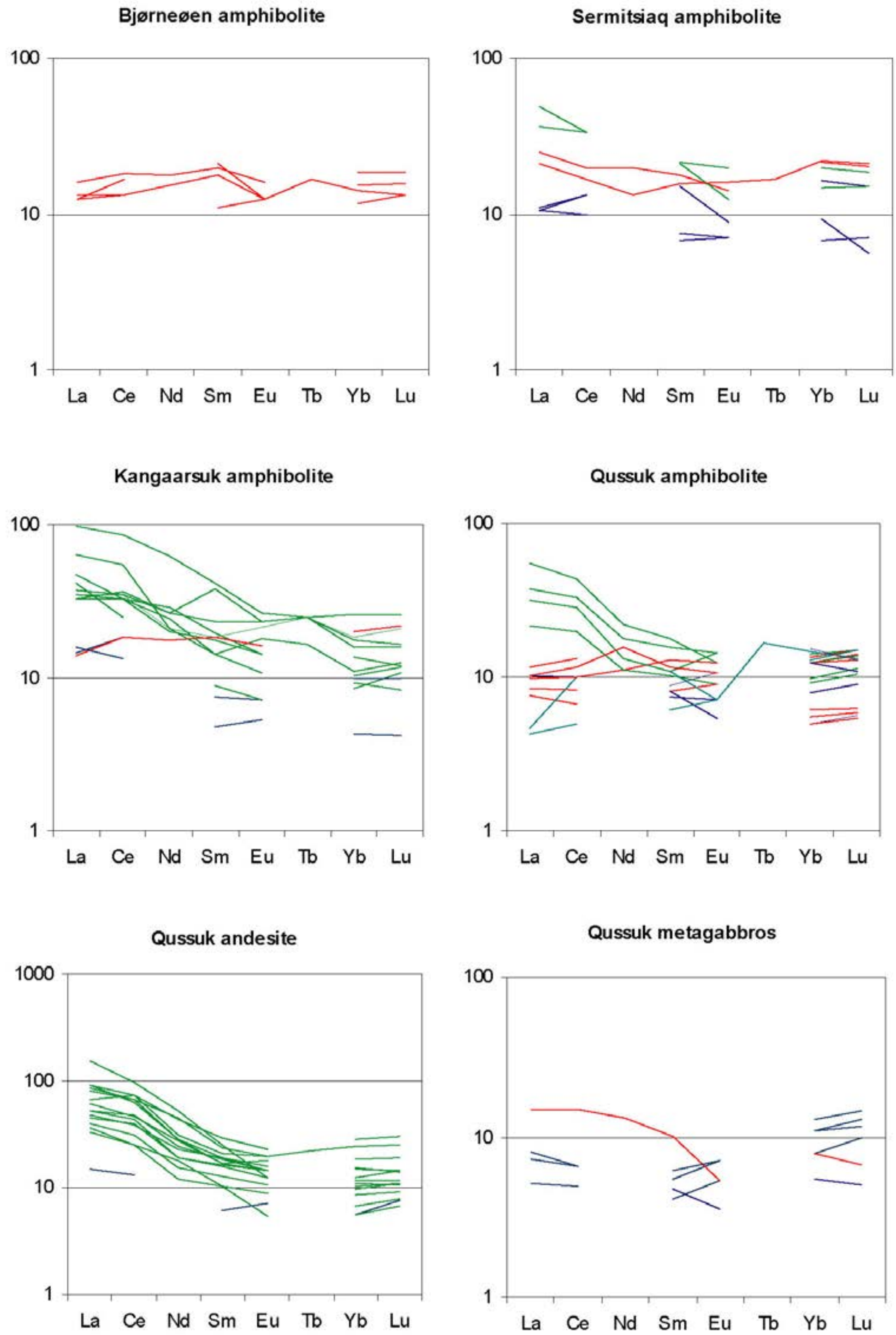

Figure 47. *Diagrams of chondrite normalised concentrations of rare earth elements (REE) for amphibolites and metagabbros from different parts of the greenstone belts in central Godthåbsfjord region. Three types of REE variation patterns are illustrated by their colours: La-Ce enrichment in green, flat patterns in red, and very low concentrations in dark blue. The breaks in the lines reflect that concentrations are below detection limit.*

Geochronology

Over 70 structurally constrained samples were collected in 2004. These include metasedimentary rocks, metavolcanic rocks, orthogneiss, felsic dykes, and granitic pegmatites. Only preliminary sample preparation for geochronological studies was achievable within the short time-scale of the current project. This section outlines the main issues we aim to address via future geochronological studies and the progress of sample preparation.

Main goals

Timing of development of structures

A major shear zone cutting Sermitsiaq and eastern Bjørneøen (and parallel structures to the west on Bjørneøen) is interpreted as being related to terrane amalgamation and in-part forms the tectonic boundary between the Akia and Tre Brødre terranes (i.e. the Ivinnguit fault). Structures of this association will be dated using deformed and undeformed cross-cutting felsic dykes. Samples are available from several localities on Bjørneøen and on north-west Storø. The timing of development of the main deformation event on the Qussuk peninsula will be dated using cross-cutting folded granitic sheets.

Constraints on the location of terrane suture

Given the similarity in composition and appearance of some of the major orthogneiss units in the region, geochronology provides an important tool for distinguishing these, particularly in areas of intense deformation where characteristic textural and mineralogical features are largely obscured. On north-west Storø orthogneiss on either side of the inferred Ivinnguit fault will be dated to provide further evidence for the position of the terrane boundary in this area.

Major sources of metasedimentary rocks, timing of their deposition

Most work on the source and timing of deposition of metasedimentary rocks in the Gothåbsfjord area has been focussed on the outer Godthåbsfjord region (e.g. Rypeo, Buksefjoden) and the Isua belt. No detrital zircon data are available for the central greenstone belt from Sermitsiaq or Bjørneøen, or for the eastern belt on Storø. Detrital zircon ages will be investigated for representative samples of quartzo-feldspathic metasedimentary rocks from throughout the region. These will give an indication of the likely depositional sources of these rocks and the minimum age of deposition. This will also allow assessment of correlations made between supracrustal rocks across the region.

Timing of deposition of metavolcanic rocks

Several important units of heterogeneous banded and fragmental rocks interpreted as metavolcanic in origin have been identified from the Storø, Bjørneøen, and Qussuk belts. These include outcrops in the Serfarsuit-Kobbefjord region, Storø, Sermitsiaq, Bjørneøen, and Qussuk. The timing of formation of these units will be investigated via analysis of zircon populations from the felsic components of these units. Samples of cross-cutting felsic dykes are also available from some localities, which should provide a minimum age constraint on these rocks.

Timing of metamorphism of greenstone belts

One metamorphic age has been reported for a metasedimentary sample from central Storø and for orthogneiss and granitic sheets within the Færingehavn and Tre Brødre terranes (Friend et al., 1996), all of which fall in the range 2725 to 2710 Ma. The same authors found no evidence of metamorphic zircon growth in rocks of the Akia terrane.

We aim to investigate further the evidence for metamorphic zircon growth in metasedimentary and metavolcanic rocks of the Akia and Tre Brødre terranes, and supplement this with studies of monazite from metasedimentary rocks and Ar-Ar dating of hornblende and/or biotite. In-situ dating, supplemented by REE measurements will be used to constrain the timing of radiometric mineral growth with respect to the metamorphic assemblages.

Sample preparation

By the end of 2004 all samples for geochronological work will be ready for mineral separations to be carried out. This preparatory work being completed this year involves crushing, sieving to < 400 μm, and washing to remove any fine powder. The samples then go through a preliminary separation stage in which heavy minerals are concentrated using a shaking table.

In January 2005 all samples will be ready for mineral separations to be made. This involves further concentration of the heavy mineral component using $CHBr_3$ (2.7 gcm^{-3}), an intermediate magnetic separation using a Frands separator, followed by further heavy liquid separation using methylene iodide (3.3 gcm^{-3}). Zircon and monazite are hand-picked from the final heavy mineral separate and mounted in epoxy resin.

The mounted grains are polished to their mid-sections and their internal structures characterised using back-scattered electron imaging using our in-house scanning electron microscope. U-Pb analyses (and REE profiles of selected grains) of zircon and monazite will be collected using our in-house Element II laser-ICPMS. In-situ analysis of monazite grains using electron microprobe analysis (at the University of Edinburgh) will be carried out if appropriate samples are identified.

Summary and conclusions

Introduction

This report describes the preliminary results of detailed field investigations in a number of Archaean greenstone belts in the central Godthåbsfjord region in July-August 2004. The report also contains the first, preliminary results of geochemical analyses of rocks, stream sediment and soil samples collected in 2004.

The supracrustal belts in the North Atlantic craton of southern Greenland are remnants of Archaean basic volcanic rocks and associated minor chemical and clastic sediments, which occur both within and between a number of distinct tectono-stratigraphic terranes or micro-continents that together form the craton. The supracrustal belts may thus have been formed in different plate-tectonic environments and have different ages and histories of evolution. Furthermore, the history of the different microcontinents and their boundaries, which might seem a purely academic matter, is also important for the correct correlation and interpretation of the supracrustal belts. Moreover, the highly strained boundaries between the individual terranes are possible loci for fluid movement.

The supracrustal rocks in southern West Greenland are generally intensely deformed and metamorphosed at upper amphibolite to granulite facies conditions, or have been retrogressed from granulite facies. However, the region between Nuuk and Isukasia is of somewhat lower, middle amphibolite facies grade, and the supracrustal rocks in this region, which are dominated by mafic metavolcanic rocks, may therefore be considered to be true greenstone belts and comparable to Archaean greenstone belts described from e.g. eastern Canada and western Australia. Archaean greenstone belts worldwide are known to host economic gold deposits, and also the Nuuk region contains several gold occurrences including the high-grade occurrence at Storø currently being investigated by NunaMinerals A/S.

The greenstone belts and their primary environments

Our work in 2004 was focussed on studying the lithologies, mineralisation, structures, metamorphism, and signs of early and later alteration of three main greenstone belts in the central Godthåbsfjord region:

- Qussuk greenstone belts (comprising two parallel greenstone belts of similar size and nature east of Qussuk)
- Bjørneøen greenstone belt (supposedly related greenstones lying along strike on Bjørneøen, Sermitsiaq and Store Malene)
- Storø greenstone belt (greenstones on Storø and in the Kangaarsuk area)

The Qussuk and Bjørneøen belts both belong to the *c.* 3.2 to 3.0 Ga Akia terrane and may be contiguous, whereas the Storø belt is considered to be part of the adjacent, *c.* 2.82 Ga

Tre Brødre terrane. However, no depositional ages are known so far. Both the Bjørneøen and Storø greenstone belts straddle the Akia - Tre Brødre terrane boundary (the Ivinnguit fault), which from our new observations appears to be a more complicated structure in this area than previously believed. Therefore, the allocation of these two belts to the respective terranes is only provisional and needs to be confirmed.

Our field observations and preliminary chemical data reveal that both the Bjørneøen and in particular the two Qussuk greenstone belts contain widespread fragmental, very heterogeneous grey amphibolite (or on Bjørneøen, intermediate schist) intimately associated with grey, compositionally layered, fine-grained plagioclase-rich metasedimentary rocks. In the Qussuk area these grey amphibolites are of andesitic chemical affinity, with light rare earth element (LREE) enrichment, and are interpreted as deformed and metamorphosed pyroclastic and volcaniclastic rocks and associated re-sedimented tuffites in a subaerial to shallow-water volcanic environment. The metavolcanic rocks are intruded by plutonic tonalitic and granitic rocks previously dated at 2975 Ma. We have thus identified the remnants of a previously unrecognised middle Archaean island arc in the eastern part of the Akia terrane.

In addition to the above mentioned intermediate schist, the Bjørneøen greenstone belt mainly comprises voluminous, compositionally layered amphibolite s.s., which we interpret as former basic pillow lava, in accord with a previously known coastal exposure of well-preserved pillow lava in south-eastern Bjørneøen. These rocks and their associated homogeneous, metagabbroic amphibolite (of likely hypabyssal intrusive origin) have flat REE spectra at about ten times chondrite values and are interpreted to represent an ocean floor environment with spreading-related volcanism. This is supported by the occurrence of a thick package of ultrabasic rocks at the presumed original base of the Bjørneøen greenstone belt, and to a lesser extent intercalated with the amphibolites. These preserve relict igneous orthopyroxene and olivine and show some evidence for hydrous alteration early in the tectonometamorphic history. They may represent ultrabasic dykes associated with ocean-floor magmatism, or alternatively relict cumulate rocks formed in the same setting. Similar ultrabasic rocks are found to a lesser extent in both the Qussuk and Storø greenstone belts.

The Storø greenstone belt also preserves evidence for both continental and oceanic sources. Intermediate composition amphibolite with intercalated thin garnet-mica-schist, and the occurrence of quarzite units is consistent with proximity to a continent. However the occurrence of mafic amphibolite with rare pillow structures, ultrabasic rocks, and the association with a basal gabbro-anorthosite complex is consistent with an ocean floor setting. These rock associations could be related to an island arc proximal to a continent.

Volcanogenic-exhalative rocks, chemical sediments and disseminated sulphide occurrences

Tourmaline-rich rocks of supposed volcanogenic-exhalative origin have previously been shown to be widespread at Store Malene and parts of Sermitsiaq. A new thin layer of this lithology was found this summer on south-east Bjørneøen and in the western Qussuk belt, where it is associated with unusual, commonly coarse-grained quartz- and garnet-rich rocks. We have also found latter lithology elsewhere within both the Bjørneøen and Storø greenstone belts, and similar rocks have been reported from the gold mineralised zone itself at central Storø. The origin of the tourmalinites and garnet-quartz rocks predates the main events of deformation and metamorphism, and are considered by us to be volcano-genic-exhalative.

Narrow layers up to a few metres wide with disseminated iron sulphides occur inside each of the greenstone belts and may be continuous for more than one kilometre along strike. The host rocks of the disseminated iron sulphides may be ordinary amphibolite, amphibolite mildly enriched in quartz, biotite, diopside and/or garnet, or more rarely quartz-garnet or quartz-tourmaline rocks (in the case of the Qussuk and Bjørneøen belts) such as described above. Sulphide occurrences (pyrite, pyrrhotite) in the Storø belt were observed mainly along amphibolite-metasedimentary rock contacts. These mineralised zones may be of syn-depositional origin, as they appear to follow original stratigraphic zones in the green-stones (although such zones are admittedly difficult to identify) but do not appear to be related to late Archaean high-strain zones or Palaeoproterozoic faults.

Calc-silicate alteration

Up to 200 m long and 50 m wide, dark greenish, diopside- and zoisite-rich lenses of altered grey fragmental amphibolite are common in parts of the western Qussuk greenstone belt. The matrix between the volcanic clasts is more thoroughly altered than the clasts themselves and the smaller lenses occur as tectonic boudins. These observations point to alteration by CO_2-rich fluids prior to deformation, presumably at the sea floor or during early diagenesis. Similar diopside-rich lenses are common throughout the amphibolites in the Bjørneøen and Storø greenstone belts, but unlike in the Qussuk area the timing of development of the latter lenses is unclear.

Gold occurrences

On Storø, known gold occurrences are concentrated in the core of NE-plunging antiforms on northern Qingaaq (Smith 1998) and Aappalaartoq, in the hanging wall of Storø shear zone. High gold values are associated with sheeted quartz veins and with sulfide-mineralised contacts between amphibolite and metasedimentary rocks.

At the time of writing only part of the rock samples collected in 2004 have been analysed for gold. However, this incomplete data set has revealed the presence of a hitherto unknown gold-bearing strata in the Qussuk area. This data also provides further documentation of a gold occurrence previously discovered by NunaOil A/S on Bjørneøen. Two samples of quartz-tourmaline rock and amphibolite with minor disseminated iron sulphide from the western Qussuk greenstone belt yielded 2.2 and 1.4 ppm Au respectively, and a sample of local rusty soil at the latter showing yielded 14 ppm Au. Several other rock and soil sediment samples from the Qussuk greenstone belts (including quartz-garnet rock intimately associated with amphibolite) contain gold in the low to intermediate ppb range. It is worth noting that none of the anomalous gold is associated with the calc-silicate lenses, or with localised zones of intense deformation or late hydrothermal alteration.

In summary, the auriferous samples collected in 2004 are located within the greenstone belts, mainly in lithologies that we have interpreted in the field as volcanogenic-exhalative. The observations in 2004 therefore suggest that the regional NNE-trending belt in the Nuuk region with anomalous gold is not related to a major shear zone, but simply reflects the NE-trending distribution of the greenstone belts in this region. It may be speculated that the work in 2004 has contributed to the identification of primary host rocks for gold mineralisation in volcanic environments: a pattern may be beginning to emerge, but the factors controlling the detailed distribution of gold within these greenstone belts require much further investigation. We also note that the Nuuk region is a tract of lower metamorphic grade than the neighbouring regions and indeed than most other parts of the North Atlantic Craton - with noticeable exceptions such as parts of the Disko Bugt region in central West Greenland, which also host gold.

High-strain zones of presumed late Archaean age

NE-trending high-strain zones occur throughout the central Godthåbsfjord region and vary from amphibolite to greenschist facies. Owing to the general parallelism of these structures and the potential for reworking of older structures it is difficult to correlate these over large areas. Some of the steep, high-strain zones and associated large fold structures in the central Godthåbsfjord region are of presumed late Archaean age based on existing geochronology data. The oldest of these regional structures is the Ivinnguit fault, forming the tectonic boundary between the Akia and Tre Brødre terranes. Our observations at eastern Bjørneøen Sermitsiaq and western Storø in 2004 suggest that the Ivinnguit fault in this area has a more complex history and is a more complex structure than previously assumed, but more field observations are needed to confirm this. The Storø shear zone post-dates the Ivinnguit fault, and forms a 300m-wide NNE-trending steeply E-dipping shear zone on north-west Storø and Kangersuaq. The Storø greenstone belt is thrust over Ikkattoq gneiss along this boundary. Associated kilometre-scale antiforms occur in the hanging wall and a synform on the footwall.

Palaeoproterozoic fault systems and associated hydrothermal alteration

Our studies in 2004 along the Palaeoproterozoic Ataneq and Kobbefjord faults confirmed previous observations by several authors that that massive late, low grade hydrothermal alteration has taken place along particularly the Ataneq fault. However, we have not identified any signs of associated gold occurrences.

Recommendations for further work

- Additional geochemistry and further interpretation of available chemical data

- Additional field work, particularly focussed on potential host rocks for early gold mineralisation
- Follow-up of the newly discovered gold occurrence in the Qussuk area
- Geochronology, to determine the depositional ages of greenstone belts and ages of bounding structures

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Appendix A: Geochemistry of rock and stream sediment samples

The tables included in this appendix contain information discussed in the Geochemistry chapter.

Table A1 shows main statistical parameters for stream sediment and soil data. Samples from the Qussuk peninsula are soil, whereas remaining samples are stream sediment. Bold numbers mark noteworthy concentrations.

Table A2 shows main statistical parameters for ”normal” samples of amphibolite from different areas in central Godthåbsfjord region together with maximal concentrations recorded in mineralised or altered amphibolite (min./alt., data in italics) from the same area.

Table A3 shows main statistical parameters for samples of metasedimentary rocks from different areas in central Godthåbsfjord region in groups of ”normal” and ”mineralised” where appropriate.

Table A1: Stream sediment and soil samples

Sample_ID		Qussuk peninsula				Kangaarsuk				Southern Storø				Serfarsuit				Sermitsiaq
No		17				18				26				10				1
	Unit	Min.	Median	Mean	Max.	Min.	Median	Mean	Max.	Min.	Median	Mean	Max.	Min.	Median	Mean	Max.	
Mg	%	0.76	2.05	2.18	5.05	0.91	1.44	1.43	2.59	0.70	1.41	1.55	3.43	1.24	2.06	5.80	14.32	9.05
Al	%	3.31	5.04	5.51	9.17	3.19	4.96	5.80	9.60	3.33	6.77	6.35	8.94	2.51	4.91	5.24	9.57	3.92
Ti	%	0.24	0.49	0.49	0.77	0.18	0.28	0.30	0.73	0.19	0.24	0.26	0.47	0.19	0.30	0.32	0.49	0.29
Fe	%	3.14	9	10	23	2.22	3	3.69	7	2.19	3	3.20	5.44	3.39	4.375	5.377	10.3	8.07
Mn	%	446	665	720	1344	406	608	652	1223	390	516	546	884	590	774	995	2091	1347
Ca	%	0.63	2.65	2.53	4.00	2.06	2.64	2.65	3.20	1.92	2.56	2.55	3.12	2.31	2.95	2.99	4.26	4.01
Na	%	0.99	2.33	2.12471	3.4	1.4	2.655	2.50389	2.89	2.46	2.925	2.89038	3.24	0.7	2.565	2.101	3.02	1.67
K	%	0.64	1.68	1.86	3.61	1.34	1.91	2.02	2.96	1.64	2.31	2.28	2.80	0.43	1.67	1.54	2.75	0.70
P	%	0.052	0.101	0.100	0.152	0.029	0.060	0.058	0.097	0.043	0.066	0.068	0.112	0.014	0.054	0.049	0.068	0.049
S	%	0.023	0.529	0.547	1.766	0.014	0.032	0.043	0.228	0.010	0.025	0.026	0.056	0.016	0.044	0.052	0.096	0.029
Ag	ppm	0	0.62	2.02	**25.12**	0	0.66	0.60	1.22	0	0.68	0.84	2.25	0	0.23	0.28	0.73	0.00
Cd	ppm	0	0	0.09	0.53	0	0	0.09	0.64	0	0	0.11	0.73	0	0	0.14	0.64	0.00
Cu	ppm	9	130	269	**1930**	10	25	50	388	9	21	33	115	19	60	106	423	31
Mo	ppm	1.19	2.72	3.40	8.18	0.00	2.33	3.66	**22.60**	0.00	2.22	1.90	7.02	0.00	1.77	2.22	6.34	0.00
Ni	ppm	7	37	39	92	29	60	64	127	36	62	79	229	39	103	524	1730	444
Pb	ppm	10	16	21	82	19	28	30	50	27	32	33	47	0	24	23	54	9
Zn	ppm	35	76	104	368	43	67	71	127	38	60	83	**437**	52	85	102	276	85
Be	ppm	0	1.09	1.03	3.48	1.33	1.57	1.64	3.42	1.48	2.16	2.11	2.35	0	1.46	1.30	2.21	0
Bi	ppm	0	0	1.33	6.98	0	0	0.12	2.20	0	0	0.28	2.71	0	1.22	4.13	**13.21**	5.87
Sr	ppm	79	259	275	528	132	297	300	402	203	273	266	314	68	222	201	325	113
V	ppm	65	125	137	215	45	69	77	186	46	58	63	96	55	98	92	141	154
Y	ppm	8	13	17	58	14	25	26	39	8	23	23	42	8	27	27	48	12
Au	ppb	0	15	859	**14400**	0	0	0.8	8	0	0	0.7	9.0	0	0	1.7	6	0
As	ppm	0	0	1.09	17.3	0	0	0.90028	12.9	0	0	0.14	2.13	0	0	0.13	1.28	0
Ba	ppm	340	550	579	800	218	540	550	800	270	505	518	750	100	425	382	680	125
Br	ppm	5	14	15	43	0	10	12	36	0	12	15	69	0	13	19	90	17
Co	ppm	7	12	13	31	9	21	21	34	9	14	17	40	12	22	48	134	65
Cr	ppm	55	151	196	444	67	109	131	352	98	148	182	570	95	190	679	**2740**	1590
Cs	ppm	0	3.0	2.3	5.0	0	2.0	2.4	8.0	0	2.0	2.1	8.0	0	3.5	4.0	**11.0**	4
Hf	ppm	4	5	6.29412	13	5	9.5	10.2222	18	7	12	13.0769	32	2	6.5	6.9	14	2
Rb	ppm	0	61	60	111	0	8	58	213	0	100	84	158	0	58	51	96	37
Sb	ppm	0	0	0.01	0.1	0	0	0	0	0	0	0.03	0.4	0	0	0.04	0.4	0
Sc	ppm	10	18	18	25	7	11	12	23	8	10	11	16	10	14	15	23	29
Se	ppm	0	0	1.71	**18.00**	0	0	0	0	0	0	0	0	0	0	0	0	0
Ta	ppm	0	0	0.16	1.80	0	0	0.24	4.3	0	0	0.24	3.60	0	0	0	0	0
Th	ppm	3.2	6.4	6.7	13.1	4.7	12.9	15.3	**51.0**	6.2	13.0	13.1	25.3	0.7	4.8	5.1	12.3	2.6
U	ppm	0	1.7	1.4	3.2	2.0	13.9	15.5	37.3	0	8.1	9.4	22.7	0	4.0	14.6	**109.0**	1.1
W	ppm	0	0	0.24	4.00	0	0	0.89	7.00	0	0	0.12	3.00	0	0	0	0	0
La	ppm	14	25	36	108	25	47	70	**388**	33	48	55	162	4	35	32	60	14
Ce	ppm	28	46	59	145	29	73	96	**425**	54	72	81	232	10	65	57	114	29
Nd	ppm	0	14	22	89	15	40	54	**246**	19	31	34	68	5	20	20	45	10
Sm	ppm	2.2	3.8	4.9	12.0	4.1	7.5	8.8	**30.5**	4.2	5.5	5.9	11.9	1.1	4.8	4.9	10.8	2.3
Eu	ppm	0.40	0.80	0.99	2.30	0	1.30	1.37	**2.30**	0	1.30	1.28	1.80	0.30	1.00	1.04	2.10	0.60
Tb	ppm	0	0	0.10	1.20	0	0	0.22	**1.00**	0	0	0.05	1.40	0	0	0.37	1.80	0.00
Yb	ppm	0.90	2.10	2.01	3.40	1.20	2.55	2.64	**4.50**	1.20	1.75	1.85	3.30	0.90	2.05	2.56	5.20	1.30
Lu	ppm	0.16	0.29	0.30	0.52	0.19	0.37	0.38	**0.63**	0.15	0.27	0.26	0.46	0.16	0.31	0.39	0.73	0.21

Table A2: Mafic metavolcanic rocks

		Qussuk amphibolite				Qussuk grey amphibolite			Bjørneøen				Sermitsiaq				Kangaarsuk				Store Malene			
		"Normal"			*Min./alt.*	"Normal"			"Normal"			*Min./alt.*	"Normal"			*Min./alt.*	"Normal"			*Min./alt.*				
No		23				16			9				8				13				3			
	Unit	Median	Mean	Max	*Max*	Median	Mean	Max	Median	Mean	Max	*Max*	Median	Mean	Max	*Max*	Median	Mean	Max	*Max*	Median	Mean	Max	
Mg	%	5.14	5.33	10.74	*7.29*	2.30	3.18	16.94	4.00	4.08	5.49	*3.68*	3.40	3.50	5.74	*2.89*	3.00	2.86	4.46	*4.87*	4.67	4.29	5.26	Mg
Al	%	5.39	5.36	8.75	*6.59*	5.09	5.39	7.69	5.28	5.41	7.22	*5.26*	4.87	5.13	7.01	*5.58*	4.67	4.30	7.81	*12.63*	4.53	4.76	5.73	Al
Ti	%	0.40	0.49	1.09	*0.87*	0.44	0.44	0.75	0.62	0.54	0.96	*0.46*	0.71	0.87	1.51	*0.99*	0.72	0.69	1.84	*0.96*	0.64	0.60	0.96	Ti
Fe	%	7.09	7.15	12.90	*12.64*	4.70	5.09	7.41	7.86	6.67	8.88	*23.13*	7.13	8.40	14.90	*19.40*	7.93	9.41	27.90	*14.80*	8.89	8.73	12.00	Fe
Mn	%	1523	1594	2993	*1914*	975	922	1401	1369	1305	1915	*21462*	2221	2118	2677	*5429*	1691	1558	2063	*11413*	1830	1832	2190	Mn
Ca	%	7.37	7.15	9.27	*15.11*	3.68	3.78	6.92	7.75	7.40	11.61	*5.57*	6.61	7.37	12.44	*11.41*	6.76	6.08	8.74	*11.82*	7.44	9.06	13.62	Ca
Na	%	1.47	1.42	2.46	*2.56*	2.13	1.91	2.68	1.06	1.02	1.78	*0.45*	1.33	1.35	2.90	*1.48*	1.27	1.21	2.39	*1.89*	1.25	1.05	1.62	Na
K	%	0.55	0.61	1.89	*2.50*	1.08	1.24	3.64	0.16	0.33	1.12	*2.10*	0.31	0.70	2.83	*2.47*	0.38	0.49	1.29	*4.69*	0.21	0.18	0.23	K
P	%	0.03	0.04	0.20	*0.09*	0.05	0.06	0.10	0.06	0.05	0.08	*0.07*	0.03	0.05	0.09	*0.09*	0.06	0.06	0.12	*0.36*	0.03	0.04	0.08	P
S	%	0.03	0.16	1.33	*5.95*	0.03	0.32	2.69	0.09	0.41	2.63	*13.75*	0.89	0.93	2.13	*14.01*	0.22	0.42	1.31	*6.50*	0.02	0.09	0.25	S
Sc	ppm	30.3	28.2	37.6	*39.4*	15.2	18.7	39.7	30.2	26.8	40.6	*28.5*	35.0	37.1	52.3	*31.6*	22.8	20.7	42.2	*45.9*	37.4	37.6	42.7	Sc
V	ppm	232	229	391	*265*	143	147	307	243	231	397	*457*	333	375	647	*312*	226	207	459	*330*	302	272	333	V
Ni	ppm	147	238	977	*772*	57	121	1150	103	126	257	*258*	126	102	168	*406*	77	104	571	*918*	103	177	405	Ni
Cr	ppm	181	381	1550	*1349*	119	272	2520	158	183	501	*444*	188	143	235	*176*	32	189	1180	*4230*	150	630	1710	Cr
Co	ppm	43	45	92	*194*	20	25	91	38	48	145	*272*	43	45	68	*204*	34	32	78	*132*	42	46	55	Co
Cu	ppm	35	80	642	*1366*	44	73	421	85	197	1074	*1127*	238	274	699	*813*	181	263	814	*6533*	15	50	132	Cu
Pb	ppm	7	7	28	*15*	7	8	25	5	5	14	*37438*	12	13	22	*102*	10	13	35	*27*	4	5	8	Pb
Zn	ppm	83	97	221	*244*	80	107	278	81	73	155	*99999*	116	172	613	*197*	121	139	316	*255*	98	89	103	Zn
Ba	ppm	120	178	680	*767*	433	426	890	20	78	403	*2394*	150	139	310	*125*	100	72	170	*900*	20	20	20	Ba
Sr	ppm	110	185	1070	*496*	176	169	268	130	150	290	*557*	196	201	300	*1819*	130	170	537	*561*	99	98	123	Sr
Y	ppm	18	20	56	*74*	16	23	64	17	18	33	*23*	29	27	45	*63*	25	25	46	*60*	28	33	58	Y
Au	ppb	0	8.6	81.0	*2260*	3.0	96.7	1430	7.0	27.1	199	*1316*	2.5	4.5	15.0	*98*	0	2.9	11.0	*12*	0	0	0	Au
As	ppm	0	0.5	2.8	*1.5*	0.0	0.0	0.0	0	0.40	2.62	*8.98*	0	0.6	2.6	*2.5*	0.9	2.6	20.8	*2.0*	0	0	0	As
Be	ppm	0	0.3	1.7	*4.2*	0.5	0.6	1.4	0	0.16	1.47	*0*	0	0	0	*5.6*	1.3	1.5	4.7	*6.8*	0	0	0	Be
Bi	ppm	0	1.0	7.4	*5.4*	0	1.0	13.9	0	0.26	2.34	*2.88*	0	0.5	3.9	*13.3*	0	1.3	6.6	*3.7*	0	0.78	2.34	Bi
Br	ppm	0	1.0	11.3	*15.3*	0	0.5	8.2	0	0.38	3.41	*0*	0	0.6	2.5	*20.7*	0	0	0	*1.5*	0	0	0	Br
Cs	ppm	0	0.3	2.0	*2.0*	1	1.1	3	0	0.80	3.00	*7.98*	2.0	3.5	12.0	*14.0*	0	1.0	8.0	*4.0*	0	0	0	Cs
Hf	ppm	1.00	1.13	4.00	*6.57*	3.00	3.06	7.00	1.00	0.83	3.45	*2.86*	2.00	1.50	3.00	*3.00*	2.00	1.85	3.00	*4.00*	2.00	1.67	3.00	Hf
Rb	ppm	0	18	63	*99*	42	44	112	0	14	40	*48*	8	47	128	*449*	8	25	146	*101*	0	0	0	Rb
Sb	ppm	0	0.02	0.20	*0.22*	0	0.11	0.90	0.20	0.14	0.30	*138.60*	0	0.24	1.40	*0.30*	0	0	0.60	*0*	0	0.07	0.20	Sb
Ta	ppm	0	0.13	1.80	*0.60*	0	0.16	1.60	0	0	0	*0.80*	0	0	0	*3.20*	0	0	2.40	*1.50*	0	0	0	Ta
Th	ppm	0	0.54	2.60	*6.83*	2.75	3.10	7.00	0	0.42	3.08	*2.28*	0.35	0.44	1.10	*1.75*	1.20	2.08	8.30	*6.60*	0.50	0.33	0.50	Th
U	ppm	0	0	0	*2.50*	0	0.33	1.50	0	0.16	1.40	*2.50*	0	0	0	*5.70*	0	2.10	8.60	*15.90*	0	0	0	U
W	ppm	0	0	0	*2.00*	0	3.1	47.0	0	0.33	3.00	*42.04*	0	0	0	*347*	0	0	4.00	*2.00*	0	0	0	W
Ag	ppm	0	0.17	2.25	*1.05*	0	0.1	0.9	0	0	0	*140.84*	0	0	0.5	*2.0*	0	0	0.9	*3.3*	0	0	0	Ag
Cd	ppm	1.10	0.94	2.08	*2.15*	1.01	1.03	1.83	1.03	1.18	2.32	*2284*	0	0.51	1.66	*1.23*	0	0.69	1.84	*1.00*	1.26	1.21	1.29	Cd
Mo	ppm	0	0.49	2.19	*15.38*	0.53	0.99	2.33	0	0.36	1.64	*5.23*	0	0.79	3.20	*3.56*	3.1	2.68	5.27	*44.35*	0	0.58	1.74	Mo
La	ppm	2.5	6.4	54.9	*24.1*	12.2	13.0	21.5	2.9	3.4	11.7	*28.0*	5.5	5.8	11.4	*365.0*	8.3	8.6	22.9	*14.6*	3.1	3.2	5.3	La
Ce	ppm	7.0	13.6	92.0	*42.3*	27.0	27.1	45.0	8.0	8.3	25.8	*52.4*	11.5	13.6	22.0	*611.0*	21.0	20.2	52.0	*34.0*	9.0	10.0	18.0	Ce
Nd	ppm	2.0	6.1	42.0	*18.0*	10.3	10.6	20.5	2.0	4.3	12.0	*13.7*	2.0	4.6	12.0	*230.0*	9.0	8.8	28.0	*11.0*	2.0	5.0	11.0	Nd
Sm	ppm	1.60	2.01	6.40	*3.70*	2.5	2.5	4.8	2.10	1.98	3.59	*3.65*	2.45	2.64	5.60	*23.70*	2.60	2.52	6.10	*3.60*	2.90	3.03	5.60	Sm
Eu	ppm	0.60	0.60	1.50	*1.00*	0.8	0.8	1.3	0.70	0.65	1.20	*1.48*	0.75	0.76	1.30	*5.30*	0.80	0.85	1.50	*1.10*	0.70	0.70	1.10	Eu
Tb	ppm	0.10	0.20	1.30	*0.80*	0.1	0.1	0.8	0.10	0.21	0.60	*0.63*	0.10	0.26	0.90	*1.40*	0.10	0.32	0.90	*0.10*	0.10	0.50	1.30	Tb
Yb	ppm	1.80	1.94	7.30	*9.42*	1.85	2.1	4.7	1.64	1.69	3.00	*1.46*	2.65	2.58	3.60	*5.30*	2.20	2.28	4.20	*6.20*	2.80	3.13	5.60	Yb
Lu	ppm	0.27	0.29	1.01	*1.42*	0.27	0.3	0.72	0.25	0.26	0.45	*0.28*	0.37	0.36	0.51	*0.79*	0.30	0.35	0.62	*0.94*	0.39	0.44	0.79	Lu
La/Yb		1.4	3.3	7.5	*2.6*	6.7	6.3	11.9	1.8	2.0	3.9	*19.2*	2.1	2.2	3.2	*68.9*	4.5	4.2	10.7	*7.6*	1.1	1.0	0.9	La/Yb
Ni/Mg		29	45	91	*106*	25	38	68	26	31	47	*70*	37	29	29	*141*	21	35	190	*494*	22	41	77	Ni/Mg

Table A3: Metasedimentary rocks

		Qussuk			Qussuk			Bjørneøen			Bjørneøen			Sermitsiaq			Store Malene	Kangaarsuk	
		Normal			Mineralised			Normal			Mineralised								
No		7			6			5			9			6			1	1	
	Unit	Median	Mean	Max	Median	Mean	Max	Median	Mean	Max	Median	Mean	Max	Median	Mean	Max			
Mg	%	1.24	1.61	3.19	3.82	3.96	6.74	2.65	2.61	3.79	2.92	3.54	7.13	2.92	4.04	8.61	1.31	2.24	Mg
Al	%	4.83	5.49	9.15	5.94	5.89	7.15	6.28	6.26	7.61	5.29	4.81	6.04	5.27	5.24	6.18	5.52	6.04	Al
Ti	%	0.38	0.41	0.76	0.40	0.48	0.71	0.38	0.42	0.69	0.38	0.35	0.46	0.50	0.49	0.89	0.32	0.52	Ti
Fe	%	3.70	4.23	7.29	5.93	6.09	7.89	4.29	4.55	5.81	6.53	6.48	9.91	4.70	5.30	9.66	2.85	4.98	Fe
Mn	%	618	743	1195	1225	1218	2125	859	1048	1904	722	902	3059	786	989	2086	558	749	Mn
Ca	%	2.85	3.02	5.27	0.35	0.59	1.81	4.56	4.23	5.69	0.91	2.81	17.55	5.94	4.80	8.82	3.03	1.09	Ca
Na	%	2.25	2.05	3.00	0.27	0.40	1.03	1.68	1.44	2.45	0.54	0.55	1.19	0.84	0.90	1.80	2.22	1.43	Na
K	%	1.72	1.40	2.41	2.45	2.68	3.84	1.76	2.00	3.16	0.96	1.18	3.72	1.15	1.21	2.22	0.89	1.54	K
P	%	0.06	0.07	0.12	0.07	0.07	0.09	0.06	0.09	0.17	0.06	0.05	0.10	0.04	0.05	0.15	0.06	0.03	P
S	%	0.02	0.38	1.52	2.81	3.23	5.94	0.05	0.90	2.97	1.92	2.59	6.26	0.37	0.55	1.41	0.02	0.03	S
Sc	ppm	13	13	26	17	17	23	15	18	30	15	16	20	11	14	33	9	25	Sc
V	ppm	72	82	169	142	146	216	126	155	271	144	147	254	149	170	342	75	191	V
Ni	ppm	31	41	109	106	94	125	90	91	124	120	119	208	45	42	90	34	73	Ni
Cr	ppm	70	85	185	162	160	266	132	136	230	177	186	287	47	44	78	36	264	Cr
Co	ppm	14	15	33	27	27	31	25	24	31	31	35	54	17	19	42	12	25	Co
Cu	ppm	21	69	338	248	246	478	60	130	344	548	877	2623	105	145	414	8	63	Cu
Pb	ppm	8	10	27	13	210	1184	16	23	49	25	28	51	11	10	15	20	8	Pb
Zn	ppm	54	55	75	454	1762	8295	81	119	200	121	129	207	189	314	1045	114	76	Zn
Ba	ppm	400	453	890	450	950	3300	480	474	670	115	206	475	245	247	550	390	490	Ba
Sr	ppm	165	167	248	31	60	227	278	247	361	99	90	140	158	174	451	222	113	Sr
Yt	ppm	30	24	41	9	9	12	20	18	28	5	13	75	22	21	34	11	16	Yt
Au	ppb	0	3.3	23.0	30.0	34.0	67.0	11.0	54.6	248.0	898.3	1206.7	4237.2	6.5	12.3	49.0	0	0	Au
As	ppm	0	0.2	1.1	1.0	0.9	1.8	0.0	0.6	2.8	1.3	1.6	3.3	0	0.5	1.7	5.6	0	As
Be	ppm	0	0.5	1.3	1.3	1.3	2.9	1.2	0.8	1.3	0.0	0.6	1.8	0.6	0.9	2.8	0	0	Be
Bi	ppm	0	0	0	0	0	0	0	0	0	0	2.1	5.9	0	3.5	18.4	0	0	Bi
Br	ppm	0	0.1	1.0	0	0	0	0	0	0	0	0	0	0	0.2	1.1	0	0	Br
Cs	ppm	1.0	1.0	2.0	2.0	1.7	3.0	5.0	4.6	7.0	4.0	6.1	23.3	11.5	18.3	55.0	2.0	4.0	Cs
Hf	ppm	4.0	4.4	7.0	3.0	3.5	5.0	3.0	2.8	4.0	3.0	2.9	4.4	2.5	4.3	13.0	3.0	3.0	Hf
Rb	ppm	69	54	108	73	80	129	40	37	68	0	25	87	27	38	92	38	62	Rb
Sb	ppm	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.5	0.3	0.3	0.8	0.2	0.3	1.0	0.0	0.0	Sb
Ta	ppm	0.0	0.2	1.4	0.0	0.2	0.8	0.0	0.0	0.0	0.0	0.3	1.5	0.0	0.4	1.8	0.0	0.0	Ta
Th	ppm	5.4	4.9	7.2	4.6	4.2	5.8	4.4	5.0	7.2	3.3	2.9	4.2	1.6	3.1	8.0	2.7	3.7	Th
U	ppm	0.8	0.6	1.5	0.0	0.3	1.7	1.5	1.5	2.1	2.0	2.4	8.2	0.6	1.7	5.9	0.0	1.4	U
W	ppm	0	1.3	5.0	0	0	0	0	0.8	3.0	0	6.3	27.0	6.0	22.7	80.0	0	3.0	W
Ag	ppm	0	0.1	0.6	0.8	1.5	5.2	0	0.7	3.4	1.7	2.3	6.1	0.5	0.5	1.3	0	0	Ag
Cd	ppm	0.9	0.9	1.4	0.6	5.1	27.9	1.3	1.4	2.1	1.8	2.1	4.1	0.6	0.7	1.5	0.8	1.0	Cd
Mo	ppm	2.6	2.3	5.3	2.3	2.4	4.3	0.0	0.7	2.1	1.8	2.4	7.1	5.5	10.7	41.8	1.4	2.9	Mo
La	ppm	12.7	16.5	29.7	18.7	20.9	37.0	19.5	22.7	38.7	3.2	9.3	37.1	10.0	21.1	51.4	17.9	17.6	La
Ce	ppm	27.0	32.9	61.0	39.0	41.0	69.0	36.0	41.2	71.0	8.0	17.6	64.8	21.5	50.3	121.0	34.0	33.0	Ce
Nd	ppm	11.0	11.2	20.5	16.5	20.2	46.0	16.0	17.8	32.0	5.0	8.8	27.0	12.0	27.8	71.0	11.0	13.5	Nd
Sm	ppm	2.30	2.69	4.80	2.70	2.75	3.90	1.60	2.02	3.60	1.51	1.72	5.04	2.25	4.03	13.50	1.90	3.00	Sm
Eu	ppm	0.80	0.84	1.20	1.00	0.97	1.30	0.80	0.82	1.60	0.24	0.56	1.41	0.80	1.62	4.30	0.60	0.90	Eu
Tb	ppm	0.10	0.20	0.80	0.10	0.17	0.50	0.10	0.46	1.40	0.10	0.20	1.00	0.10	1.27	3.70	0.10	0.60	Tb
Yb	ppm	1.80	2.61	5.90	1.40	1.63	3.00	1.40	1.68	2.80	1.29	1.77	6.40	2.35	7.75	22.00	0.90	2.30	Yb
Lu	ppm	0.28	0.44	0.95	0.21	0.24	0.48	0.26	0.27	0.42	0.25	0.30	0.89	0.34	1.18	3.25	0.14	0.39	Lu
La/Yb		9.3	8.6	14.1	11.6	15.1	33.6	13.9	12.6	17.9	2.5	7.1	29.9	3.4	4.7	9.9	19.9	7.7	La/Yb

Appendix B: Sample preparation

Close to one thousand samples have been collected by us from the central Godthåbsfjord region in 2004 for the purpose of petrographic, geochemical, mineral chemical, and geochronological studies. One hundred and twelve rock samples and 75 stream sediment samples have so far been analysed for the following suite of trace elements at Activation Laboratories in Ancaster, Canada:

- Au, As, Ba, Br, Ce, Co, Cr, Cs, Eu, Fe, Hf, Hg, Ir, La, Lu, Na, Nd, Rb, Sb, Sc, Se, Sm, Sn, Ta, Th, Tb, U, W, Yb and Lu via neutron activation analysis (INAA)
- Ag, Al, Be, Bi, Ca, Cd, Cu, K, Mg, Mn, Mo, Ni, P, Pb, S, Sr, Ti, V, Y, Zn via a "near total" four-acid digestion (HF, $HClO_4$, HNO_3 and HCl), inductively coupled plasma optical emission spectrometry technique.

These analyses are discussed in the Geochemistry section and full results are given in the ArcView© project on enclosed DVD. The 112 rock samples above will be returned to GEUS before end 2004 and subsequently analysed for major elements at GEUS in January 2005. The results will be reported shortly afterward. Initially we aimed to complete these analyses in 2004, but ship-ping problems from Canada prevented this.

Approximately 200 petrographic samples have been submitted for thin and polished sections. A limited number of these have been completed and these form the basis for part of the discussion of mineral assemblages and textures in this report. They will also form the basis for any future petrographic and mineral chemical work, and microstructural studies.

Approximately one hundred samples collected for geochronological studies have been crushed in preparation for mineral separation work. See also the Geochronology section.

Appendix C: Explanatory notes to the DVD

This DVD contains the full report and compiled field maps in PDF format, as well as an ArcView© project file containing geo-referenced compiled field data including localities, lithological descriptions, sample locations, structural data, and references to digital photographs (see below). It also contains digital photographs in reduced resolution in jpeg format from the 2004 fieldwork. Descriptions of the views in the ArcView project, maps, geochemistry data, and photographs stored on the DVD can be found in the Explanatory_notes.txt file. Some information is provided as PDF-files for use in Adobe Acrobat Reader©. An installation kit for Acrobat Reader version 6.0 is included on the DVD. After installation, the PDF-files can be open from within the reader, or just by double-clicking the files.

Directory structure

The DVD contains the following directories and main files

Directories:
AcrobatReader6
Field_maps
Geochemistry
Geochemistry_spreadsheets
Geology
Photographs
Topography

Files in the root directory:
_Godthaabsfjord2004.apr
Explanatory_notes.pdf
frontispiece.jpg
GEUS2004R110.pdf
Terms_of_Delivery.pdf

Use of the DVD

1. Place the DVD into DVD reader
2. Read the Explanatory_notes.pdf file. This provides explanations of the contents of the DVD
3. Run ArcView© 3.2 on your computer
4. Open the ArcView© file
5. The file Godthåbsfjord2004.apr will open on a cover view. When this cover view is closed, a list of available views will become visible. Choose the desired view to begin exploring the data.

ArcView© project

The ArcView© project (constructed in ArcView© GIS version 3.2) contains the geo-referenced data collected during the 2004 field work, as well as new geochemical data and pre-existing 1:100 000 geological maps. The data are placed in separate views and can be explored and combined within the program.

Views in the project

The following is a list of the views within the ArcView© GIS project file (Godthåbsfjord2004.apr), containing different types of digital data sets. More detailed descriptions of the contents of each of these views can be found in the Explanatory_notes.pdf file on the DVD.

0.1 Frontispiece
1.1 Index map - location of the Godthaabsfjord region
1.2 Topographic map
1.3 Digital geological maps 1:100 000
1.4 Scanned geological maps 1:100 000
2.1 Visited outcrop locations
2.2 Geological observations
2.3 Samples collected 2004
2.4 Structures
2.5 Photographs
3.1 Rock geochemistry
3.2 Stream sediment chemistry