DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2007/20

Characterisation of selected geological environments

Mineral resource assessment of the Archaean Craton (66° to 63°30'N) SW Greenland Contribution no. 1

Henrik Stendal (ed.)

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

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Contents

Summary

By Henrik Stendal

This report comprises three separate contributions concerning three different geological environments described by:

1. Garde, A.A.: A relict island arc complex with synvolcanic epithermal alteration in western Godthåbsfjord, southern West Greenland: field work in 2006 at Qussuk and Bjørneøen.

2. Frei, D. & Konnerup-Madsen, J.: Magmatic environment: The naujat gabbro-anorthosite complex and country rocks – Field report 2006.

3. Stendal, H. & Schérsten, A.: Geological Environments: Oceanic crust and hydrothermal alterations - Field report 2006.

This introduction to the report gives a brief account of the background, aim, activities and includes a compilation of the hitherto published data from the Nuuk project. A summary of each of the contributions in this report is given below:

Ad 1)

Field work in 2006 has greatly expanded the volume and extent of the previously recognized andesitic arc at Qussuk and Bjørneøen in the eastern Akia terrane, and important new localities with well-preserved volcanic and volcaniclastic rocks have been found in both areas. Furthermore, it has been established that the relict arc also comprises common, orthopyroxene-rich mafic to ultramafic intrusives. A number of synvolcanic hydrothermal alteration systems have been located and been studied. There are two types of alteration, leading to respectively siliceous and aluminous rocks associated with gold-copper mineralization, and carbonate-altered rocks with calc-silicates but normally without mineral occurrences.

Ad 2)

The investigated gabbro-anorthosite complex is predominantly composed of relatively homogeneous leucogabbros and anorthosites with minor intercalations of mafic and ultramafic sequences. These intercalations most likely represent mafic and ultramafic cumulate layers and can thus be regarded as formed during the magmatic evolution of the layered mafic intrusion. The extent of the entire gabbro-anorthosite complex exposed at Naujat is smaller than previously believed.

The Naujat gabbro-anorthosite complex is underlain by a lithological varied series comprising heterogeneous orthogneisses and homogeneous, mainly tonalitic orthogneisses inter-

calated with amphibolites and ultamafics that have been regionally metamorphosed and deformed at amphibolite facies (and partly higher) conditions.

The mafic and ultramafic rocks exposed in the lithological varied sequence show a wide compositional and textural range. Origin and genesis, especially of the ultramafic rocks (cumulates, ultramafic intrusions or mantle remnants?), is unkown and should be the focus of further detailed petrological and geochemical investigations.

All amphibolitic rocks exposed, regardless of their tectonic position (whether they occur in the gabbro-anorthosite complex or in the lithological varied sequence) show zones of rusty alteration. These zones are generally only m – dm wide and can be traced for long distances along the strike of the amphibolites. The rusty alterated zones are generally mineralised with pyrite.

Ad 3)

The age of the Tasiusarsuaq terrane is assumed to be within the range of 2.92–2.86 Ga. Investigated mafic complexes are dominated by amphibolite to upper amphibolite facies metamorphic rocks, although greenschist facies rocks are present at Nunatak 1390. Gradations between rocks that more or less preserve primary textures enable correlation of spatially separated mafic-ultramafic units. This led to the belief that greenstones in the region were derived in a similar geo-tectonic environment.

The Kangiata Nuna 1:100.000 geological map sheet consists of a large greenstone granite belt with 20 – 30% of greenstones and at least two generations of tonalite and granodiorite (Tasiusarsuaq terrane). The greenstone granite belt is estimated to make up more than 1200 km^2 and with possible extension towards the south. Mafic sequences and exhalites (greenstones) in the Tasiusarsuaq terrane south and southeast of Kangerdluarsunnguup Tasersua may become economically interesting due to elevated gold and arsenic contents.

Garnet-sillimanite-biotite ±sulphide rocks seem to record a regional phenomenon. The alterations are pervasive and independent of rock types or geological terrane boundaries. The alteration must have occurred after or during the amalgamation of micro continents in the Nuuk region if it is assumed to represent one event.

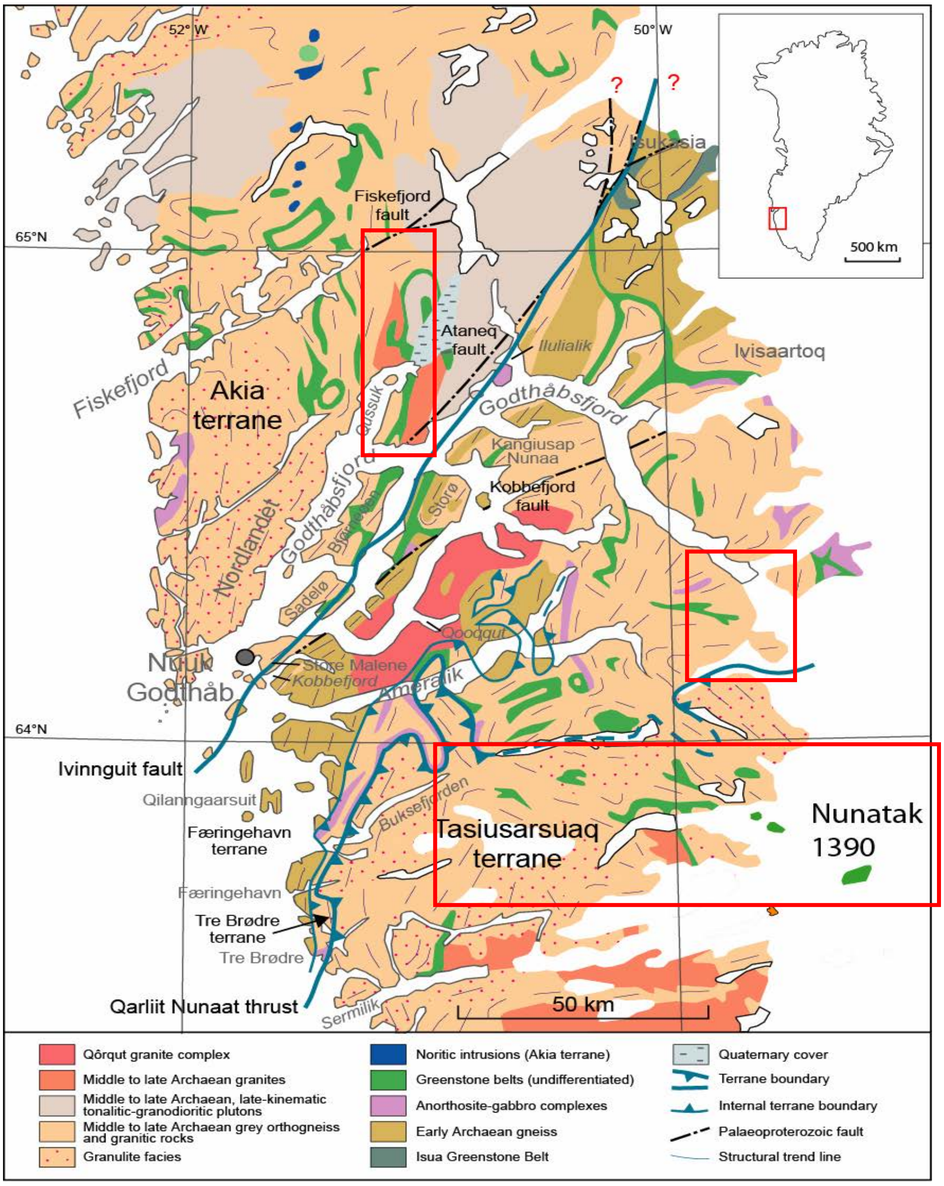

Figure 1. *The selected key areas for investigation of geological environments. The northern part is the Qussuk – Bjørneøen region (island-arc environment), the middle rectangle is the Kapisillit region (The Naujat orthomagmatic environment) and the southern part the Tasiusarsuaq terrane (ocean-floor environment). Modified after Escher & Pulvertaft (1995).*

Background

From 2003 to 2006 GEUS has investigated various aspects of the geology of supracrustal belts in the Nuuk region, in particular focussing on understanding aspects of the primary geological environments and their mineral occurrences, geological setting, and alteration patterns. Detailed mapping of key areas in 2004, 2005 and 2006 and targeted geochemistry and geochronology has identified Mesoarchaean belts. Neoarchaean supracrustals(?) are debated, whether they exist or not. Three major geological environments of particular interest have been identified in the Nuuk region. These are 1) island arc (angular clasts in intermediary composed volcanics), 2) magmatic complexes (magmatic layering), and 3) oceanic environments (pillows). The timing of formation of some of these is well known, and includes especially Mesoarchaean environments, while others remain unconstrained. The geochemical signatures of mafic metavolcanic rocks show both ocean floor and island-arc affinities.

Understanding the primary geological environments of these supracrustal rocks and the alteration patterns is important in relation to understand the formation of mineral occurrences. However, it is complicated by 1) the rarity of preserved primary structures due to hydrothermal alteration, metamorphism, and multiple deformation events; and 2) the recognition of tectonic imbrications of rocks of widely different ages, possibly formed in very different geological environments. To solve some of these difficulties, field work was carried out in three different regions each with its own specific geological environment during the field season 2006. This project is co-financed between Bureau of Mines and Petroleum (BMP), Government of Greenland and GEUS.

Logistics

As in 2005 GEUS joined the NunaMinerals A/S basecamp on Storø from July 4 to August 21, 2006. Greenland Resources A/S (GRAS), Air Greenland, and NunaMinerals A/S helped GEUS with all the practical matters on Storø and in Nuuk. NunaMinerals chartered an AS350 helicopter from Greenland Air. The helicopter was based on Storø and GEUS had guaranteed NunaMinerals A/S to use at least 100 helicopter hours. The logistics were co-ordinated by René Boysen and Jakob Lautrup from GEUS and Claus Østergaard from NunaMinerals A/S.

Fieldwork

(i) detailed mapping (1:10.000) and characterisation of mineral occurrences in the three key areas,

(ii) sampling of key lithologies for geochronological constraints and geochemical characterisation of the primary geological environments as well as potential pre-metamorphic alterations,

(iii) detailed sections for characterisation of lithologies, lithological thicknesses, contact relationships, and settings of mineral occurrences.

The three key areas are (Fig. 1)

1) The southern part of the Qussuk peninsula comprising an island-arc environment.

Gold-bearing supracrustal belts in these areas are interpreted as part of an *island arc complex* (e.g. Hollis 2005; Garde 2006; in press). The supracrustal rocks on the Qussuk peninsula will further be characterised by follow-up mapping south and north of the map done during the field seasons in 2004 and 2005. Mineral occurrences will be documented and their primary setting assessed. For comparison and to follow-up on 2004/2005 findings the mapped supracrustal belt on Qussuk will be compared with Bjørneøen. It is an ideal situation with such a comparison due to the existing geochronology constraints and regional structural cross-sections currently being developed on Bjørneøen.

2) North side and northeast of Kangaassarsup Sermia consists of the recently discovered anorthosite-gabbro complex and represent a magmatic environment.

GEUS mapping in 2005 resulted in the discovery of a previously unknown gabbro-anorthosite complex, which is >100 km^2 in extent. Only a small part of this complex has been mapped and it remains to be characterised in terms of its lithologies, mineral potential, age, geochemistry, and tectonostratigraphy.

3) The area north, east and northeast of Isortuarssuup Tasia representing an oceanic environment.

Mafic metavolcanic rocks with relict pillow structures have been identified during reconnaissance work. The area falls within the Tasiusarsuaq terrane with mafic rocks and granitoids presumable formed between 2900–2800 Ma. On basis of observed greenschist facies float including pillow-basalt and shale-limestone along the ice edge in this area (GEUS 2005). The chance for true greenstones was anticipated to be present in the region. The mapping includes Nunatak 1390 and some of where greenschist facies rocks turned up to be well exposed and well preserved.

Planned analytical work

- Major and trace element geochemical characterisation of supracrustal rocks in order to determine the geochemical affinities of different belts to specific environments of formation. Samples of mineral occurrences within the areas investigated will also be analysed for precious metals. These analyses are all performed by *Actlabs'* commercial laboratories in Canada.

- U-Pb laser ablation ICPMS dating of relevant minerals (eg. zircon, monazite, titanite, apatite) for constraining the timing of formation of key environments and allowing regional correlations.

- Petrographic characterisation of important lithologies via optical microscopy for both translucent and opaque mineralogy (and electron microscopy where relevant) for characterisation of lithological units within constructed tectonostratigraphic sections, and for characterisation of ore minerals and microstructures.

- Pb-Pb analyses on magnetite and sulphides to deduce the source of metal-bearing fluids and step leaching of garnets for Pb isotopes.

Data compilation, interpretation and reporting

The mapping, mineral occurrence, structural, geochemical, and geochronological data obtained in 2006 will add to an already large amount of contributions to the geological dataset for the Nuuk region. The high volume of quality data need considerable effort on data compilation and interpretation to allow the data to be used to its full potential in understanding the geological environments and the local and regional implications. Compilation of all field data as well as lab data will be into GIS-format and published in later GEUS report when the analytical results are obtained.

The contribution of published GEUS reports include the following volumes concerning studies in the Nuuk region: Appel *et al.* (2003/94), Hollis *et al.* (2004/110), Nielsen *et al.* (2004/121), Appel *et al.* (2005/27), Nielsen & Jensen (2005/43), Hollis (2005/42), Hollis *et al.* (2006c/7), Stensgaard *et al.* (2006a/27), Eilu *et al.* (2006/30) and Hollis *et al.* (2006b/45).

Recent publications in GEUS Bulletins, which are relevant contributions for the Nuuk project: Hollis *et al.* (2005, 2006a), Nielsen *et al.* (2006), Steenfelt *et al.* (2006) and Stensgaard *et al.* (2006b).

Recent relevant publications in international journals/abstracts related to the Nuuk projects are: Friend & Nutman (2005), Garde *et al.* (2006), Garde (*in press*), Heijlen *et al.* (2006), Juul-Pedersen *et al.* (2007, *in press*), Polat *et al.* (2007) and Stensgaard *et al.* (2006c) and Thøgersen *et al.* (2006).

The diamond project contributes with data to the target area especially from the Maniitsoq region with GEUS reports Jensen *et al.* (2003/21), Jensen *et al.* (2004/117) and a GEUS Bulletin (Jensen & Secher 2004).

References

Appel, P.W.U., Coller, D., Coller, V., Heijlen, W., Moberg, E.D., Polat, A., Raith, J., Schjødt, F., Stendal, H. & Thomassen, B. 2005: Is there a gold province in the Nuuk region? Report from field work carried out in 2004. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/27**, 79 pp.

Appel, P.W.U., Garde, A.A., Jørgensen, M.S., Moberg, E.D., Rasmussen, T.M., Schjødt, F. & Steenfelt, A. 2003: Preliminary evaluation of the economic potential of the greensone belts in the Nuuk region. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003/94**, 147 pp.

Eilu, P., Garofalo, P., Appel, P.W.U. & Heijlen, W. 2006: Alteration patterns in Au-mineralised zones of Storø, Nuuk region - West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2006/30**, 73 pp.

Escher, J.C. & Pulvertaft, T.C.R. 1995: Geological map of Greenland, 1:2 500 000., Copenhagen: Geological Survey of Greenland.

Friend, C.R.L. & Nutman, A.P. 2005: New pieces to the Archaean terrane jigsaw in the Nuuk region, southern West Greenland: steps in transforming a simple insight into a complex regional tectonothermal model. Journal of Geological Society, London 162, 147-162.

Garde, A.A. In press: A mid-Archaean island arc complex in the eastern Akia terrane, Godthåbsfjord, southern West Greenland. Journal of Geological Society, London.

Garde, A.A., Hollis, J.A., Kelly, N., A., S., Stendal, H. & vanGool, J.A.M. 2006: Archaean island arc - hosted gold mineralisation at western Godthåbsfjord, southern West Greenland. In: The 27th Nordic Geological Winter Meeting, Abstract Volume, Oulu **Special issue I**, 39 only: Bulletin of the Geological Society of Finland.

Heijlen, W., Appel, P.W.U., Frezzotti, M-L., Horsewell, A. & Touret, J.L.R. 2006: Metamorphic fluid flow in the northeastern part of the 3.8-3.7 Ga Isua Greenstone Belt (SW Greenland): A re-evaluation of fluid inclusion evidence for early Archean seafloor-hydrothermal systems. Geochemica Cosmochemica Acta **70**, 3075-3095.

Hollis, J.A. (ed.) 2005: Greenstone belts in the central Godthåbsfjord region, southern West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/42**, 215pp.

Hollis, J.A., van Gool, J.A.M., Steenfelt, A. & Garde, A.A. 2004: Greenstone belts in the central Godthåbsfjord region, southern West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2004/110**, 110 pp.

Hollis, J.A., vanGool, J.A.M., Steenfelt, A. & Garde, A.A. 2005: Greenstone belts in the central Godthåbsfjord region, southern West Greenland. Geological Survey of Denmark and Greenland Bulletin **7**, 65–68.

Hollis, J.A., Freis, D., van Gool, J.A.M., Garde, A.A. & Persson, M. 2006a: Using zircon geochronology to resolve the Archaean geology of the southern West Greenland. In: Sønderholm, M. & Higgins, A.K.(eds): Review of Survey activities 2005. Geological Survey of Denmark and Greenland Bulletin **10**, 49-53.

Hollis. J.A., Kelly, N.M., Frei, D., Schmid, S. & van Gool, J.A.M. 2006b: U-Pb zircon geochronology results for Ujarassuit Nunaat supracrustal belts and surrounding gneisses. Interim report. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2006/45**, 56 pp.

Hollis, J.A., Schmid, S., Stendal, H., van Gool, J.A.M. & Weng, W.L. 2006c: Supracrustal belts in the Godthåbsfjord region, southern West Greenland. Progress report on 2005 field work: geological mapping, regional hydrothermal alteration and tectonic sections. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2006/7**, 171 pp. + 1 CD-Rom.

Jensen, S.M. & Secher, K. 2004: Investigating the diamond potential of southern West Greenland. Geological Survey of Denmark and Greenland Bulletin **4**, 69–72.

Jensen, S.M., Lind, M., Rasmussen, T.M., Schjøth, F. & Secher, K. 2003: Diamond exploration data from West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003/21**, 50 pp.

Jensen, S.M., Secher, K., Rasmussen, T.M. & Schjødt, F. 2004: Diamond exploration data from West Greenland: 2004 update and revision. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2004/117**, 90 pp.

Juul-Pedersen, A., Frei, R., Appel, P.W.U., Persson, M. & Konnerup-Madsen, J. 2007: A shear zone related greenstone belt hosted mineralization in the Archean of West Greenland. A petrographic and combined Pb-Pb and Rb-Sr geochronological study. Ore Geology Reviews **x**, x-xx.

Nielsen, T. F. D. and S. M. Jensen 2005: The Majuagaa calcite-kimberlite dyke, Maniitsoq, southern West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/43,** 59 pp.

Nielsen, B.M., Rasmussen, T.M. & Steenfelt, A. 2004: Gold potential of the Nuuk region based on multiparameter spatial modelling of known gold showings. Interim report 2004. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2004/121**, 155pp.

Nielsen, T.F.D., Jebens, M., Jensen, S.M. & Secher, K. 2006: Archetypal kimberlite from the Maniitsoq region, southern West Greenland and analogy to South Africa. In: Sønderholm, M. & Higgins, A.K.(eds): Review of Survey activities 2005. Geological Survey of Denmark and Greenland Bulletin **10**, 45-48.

Polat, A., Appel, P.W.U., Frei, R., Pan, Y., Dilek, Y., Ordonez-Calderon, J.C., fryer, B., Hollis, J.A. & Raith, J.G. 2007: Field and geochemical characteristics of the Mesoarchean (~3075 Ma) Ivisaartoq greenstone belt, southern West Greenland: Evidence for seafloor hydrothermal alteration in supra-subduction oceanic crust. Gondwana Research **11**, 69-91.

Steenfelt, A., J. A. Hollis & Secher, K. 2006: The Tikiusaaq carbonatite: a new Mezosoic intrusive complex in southern West Greenland. Geological Survey of Denmark and Greenland Bulletin **10,** 41–44.

Stensgaard, B.M., Steenfelt, A. & Rasmussen, T.M. 2006a: Gold potential of the Nuuk region based on multiparameter spatial modelling. Geological Survey of Denmark and Greenland, Copenhagen, 2006/27, 207 pp.

Stensgaard, B.M., Rasmussen, T.M. & Steenfelt, A. 2006b: An integrative and quantitative assessment of the gold potential of the Nuuk region, West Greenland. Geological Survey of Denmark and Greenland Bulletin **10**, 37-40.

Stensgaard, B.M., Chung, C.-J., Rasmussen, T.M. & Stendal, H. 2006c: Assessment of mineral potential using cross-validation techniques and statistical analysis: A case study from the Paleoproterozoic of West Greenland. Economic Geology **101**, 1397-1413.

Thøgersen, G.J.-P., Stendal, H. & Zimmermann, H.D. 2006: Hydrothermal alteration along the Ataneq fault in the Nuuk region, Westgreenland. In: The 27th Nordic Geological Winter Meeting, Abstract Volume, Oulu **Speciel issue I**, 161 only: Bulletin of the Geological Society of Finland.

A relict island arc complex with synvolcanic epithermal alteration in western Godthåbsfjord, southern West Greenland: field work in 2006 at Qussuk and Bjørneøen

By Adam A. Garde

Geological Survey of Denmark and Greenland (GEUS)

Field excursion on Qussuk with Adam Garde as guide.

Introduction and previous work

From 10 July to 11 August 2006 the author and his assistant Thomas R. Hansen, University of Copenhagen, carried out geological field work north and east of the Qussuk bay in western Godthåbsfjord, and in the central part of the adjacent Bjørneøen (Fig. 1). Bo Møller Stensgaard, GEUS, and his assistant also participated on 28–31 July. The study was a continuation of similar work for the Greenland Home Rule authority in the Qussuk area in 2004, which led to the discovery of a relict island arc complex and associated gold mineralisation (Garde in press). This report does not include new geochemical data, because the analytical results of the samples collected in 2006 arrived late, but information about samples collected and their geographical location can be found in Table 1. After the present study had been planned, NunaMinerals A/S took up an exploration concession in parts of the same area and carried out a sampling programme in June–July 2006.

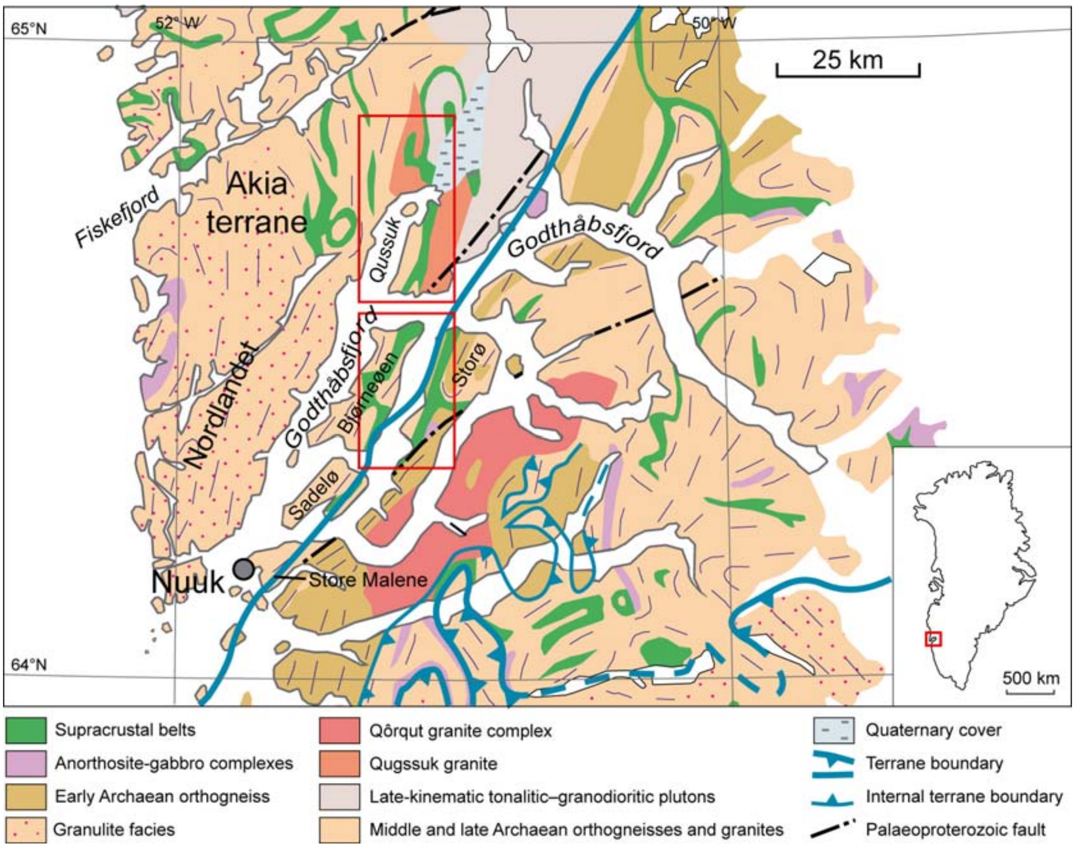

Figure 1. *Geological overview map of the Nuuk region. Red frames show the positions of Figs 2–3. Modified from Escher & Pulvertaft (1995) and Garde (2003).*

Andesitic volcaniclastic rocks with gold mineralisation have previously been reported from central Bjørneøen by Smith (1998) in an unpublished company report, and a large gold prospect on Storø is currently under investigation by NunaMinerals A/S. The current study is a contribution to an important question in this context – namely whether, or to what extent, the Archaean volcano-sedimentary rocks and their gold mineralisation at Qussuk, Bjørneøen and nearby Storø might share a common geological history.

The Qussuk area, Bjørneøen, and the western part of Storø are all located in the eastern part of the Middle Archaean Akia terrane, most of which has previously been mapped at 1:100 000 scale for the Survey's Qôrqut and Fiskefjord map sheets (McGregor 1984; Garde 1989). The present study areas in the eastern Akia terrane consist of grey, c. 3060–3000 Ma tonalitic to trondhjemitic orthogneisses with moderately to steeply inclined, isoclinally folded panels of older supracrustal rocks, as well as younger granites. The metamorphic grade is upper amphibolite facies, transitional into granulite facies in the west. North of Qussuk hints of beginning granulite facies can be observed as local orthopyroxene growth in small partial melt pockets inside mafic supracrustal rocks. The younger granites were mobilised from the grey orthogneisses during a late-kinematic thermal event that has been dated at around 2980 Ma (Garde 1997; Garde et al. 2000; Garde in press).

Volcaniclastic and associated volcano-sedimentary rocks of intermediate composition were first reported from the eastern Akia terrane by Garde (1997) and Smith (1998). However, at that time it was not appreciated that such rocks are very widespread, as volcaniclastic textures themselves are generally very poorly preserved. Thus, it was not discovered until 2004 that large parts of the supracrustal belts at Qussuk and in central Bjørneøen consist of volcaniclastic andesitic rocks, besides associated mafic to ultramafic intrusive rocks.

Garde (in press) obtained a U-Pb zircon age of 3071 ± 1 Ma from an intermediate volcano-sedimentary rock collected by two colleagues in central Bjørneøen in 2004. This age shows that the andesitic rocks are marginally older than their host of tonalitic orthogneisses, which have ages less than c. 3060 Ma. Arc rocks east of Qussuk on strike with the dated volcano-sedimentary unit in Bjørneøen have yielded variably recrystallised zircon grains with metamorphic ages between 2970 and 2990 Ma, but a few cores of not completely recrystallised grains have ages approaching 3070 Ma. The andesitic rocks in the eastern Akia terrane are now interpreted as a relict oceanic island arc complex that was built up just prior to the plutonic emplacement of the oldest tonalitic orthogneiss precursors. The existence of the arc and itself and its slightly younger intrusive counterparts of tonalitic orthogneisses, combined with previous structural evidence of early crustal shortening in most of the Akia terrane, point to the existence of a convergent plate-tectonic system in the North Atlantic craton with subduction of oceanic crust and partial melting of the subducted slab at least 3070 Ma ago (Garde in press).

An unexpected but important outcome of the ongoing study was the identification of small pockets of massive siliceous, garnet- and locally sillimanite-rich rocks associated with gold mineralisation within the supracrustal arc rocks (Garde 2005; in press). It is now recognised that such rocks may not be of clastic sedimentary origin, but are likely to represent volcanic and volcaniclastic rocks of mafic to intermediate composition that have undergone massive hydrothermal leaching in the volcanic environment prior to their deformation and metamorphism. Some of the field observations from 2006 that strongly favour this interpretation are presented in a later section.

An overview of the Qussuk area

The field work north and east of Qussuk in 2006 much expanded the understanding and previously established extent of the relict andesitic arc complex (Fig. 2). The two first camps were located north of Qussuk in an area that was only briefly visited in 2004, and where widespread new volcaniclastic rocks were discovered in 2006. A third camp supported by a rubber boat was picked on the north-eastern coast of Qussuk, and a subsequent inland camp was picked on the 'Qussuk peninsula' east of Qussuk.

The new field work north and east of Qussuk was aimed at studying primary rock types and original relationships between different rock units, as well as the early hydrothermal alteration processes and the subsequent deformation and thermal history of the arc and its host rocks. The previous mapping for the 1:100 000 scale Fiskefjord map sheet (Garde 1989) and its distinction between orthogneisses, granites and supracrustal rocks were found to be essentially correct, and the new work did not change the general, previously established map patterns – except that the amphibolites include voluminous meta-andesites, and that rocks previously mapped as clastic metasedimentary biotite-garnet-sillimanite schists have now been re-interpreted as variably hydrothermally altered volcano-sedimentary rocks (see below).

Magmatic, tectonic and thermal history of the Qussuk area

The Archaean geological history of the Qussuk area is simpler than in most other parts of the Akia terrane. The area is characterised by large, isoclinally folded panels up to about 1 km wide, which consist of supracrustal rocks that have been intruded by more voluminous and less deformed, syn- to postkinematic tonalites and granites. The poor state of preservation of the supracrustal rocks only rarely allows one to observe primary volcanic or sedimentary features, and it has not been possible to identify individual volcanic edifices. A first step in the understanding of the primary volcanic environment is therefore an analysis of the large-scale structures.

The isoclinal folds in the supracrustal rocks may originally have been recumbent, but are now upright to overturned, oriented N–S to NNE–SSW, and generally plunge steeply S. The large fold structures are mimicked by numerous outcrop-scale folds with the same shape and orientation. Moderately to steeply N-plunging folds, which apparently belong to the same phase of folding, also occur in some areas. This pattern suggests that the isoclinal folds have been refolded by large, open folds with shallow to horizontal, E–W-trending axes, although outcrop-scale folds with this orientation are only rarely observed. Such refolding may also explain the relatively complex map pattern that occurs a few kilometres north of the head of Qussuk.

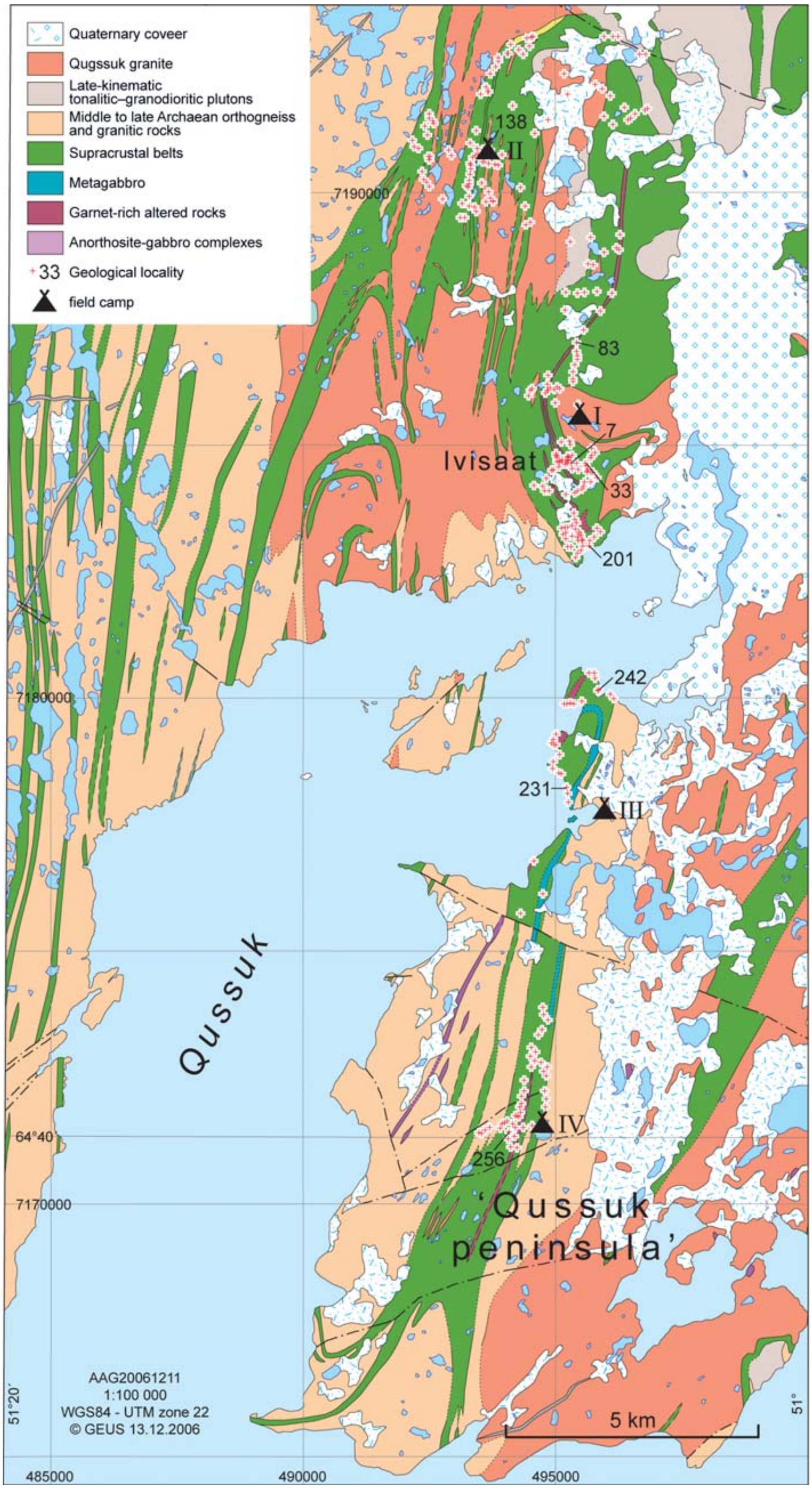

Figure 2. *Geological map of the Qussuk area, showing the positions of field camps and geological localities in 2006. Numbers refer to geological localities described in the text. Simplified and slightly modified from Garde (1989).*

A simple interpretation of the structural and magmatic evolution post-dating the volcanic arc itself can be summarised as follows (see also Garde 1997 and Garde et al. 2000). During lateral shortening of the volcanic arc at around 3070 Ma, an early fabric-forming deformation event affected the supracrustal rocks and the earliest grey gneiss precursors with thrusting and folding into large recumbent, isoclinal folds. Large flat-lying folds of this age can still be seen in the central Fiskefjord area.

From around 3060 Ma and onwards magmatic precursors of the grey gneisses were emplaced from below, overlapping in time with the early isoclinal folds. The magmas were probably both emplaced as subhorizontal intrusive sheets only metres to tens of metres thick, and as larger tabular to dome-shaped plutons. Continued E–W shortening of the growing continental crust led to the formation of large upright, N- to NNE-trending folds of both supra- and infracrustal rocks, whereby the earlier recumbent folds were reoriented into their present steep attitudes. In some parts of the area local refolding by a another phase of large open folds seems to have taken place, now with E–W-trending axes corresponding to N–S compression. At this stage, at around 2980 Ma, a thermal maximum was reached with granulite facies conditions prevailing in the central and southern Akia terrane, and granitic melts were mobilised from parts of the grey gneisses. The last stage of the regional deformation in the Akia terrane was localised in narrow, steep high-strain belts just before its stabilisation at around 2975 Ma. The Akia terrane acted as a stable block during the much later terrane amalgamation in the Nuuk region at around 2700 Ma, and thus, contrary to the central and southern parts of the Nuuk region, the Akia terrane did not receive internal deformation at this time. Much later, presumably In the Palaeoproterozoic, the Akia terrane was faulted and tilted, so that Akia (Nordlandet) in its south-western part was uplifted to expose granulite facies rocks, whereas its marginal easternmost part was thrown down, so that a more shallow crustal level is preserved here to expose amphibolite facies rocks (see also Rasmussen & Garde 2003). During a regional uplift in the Mesozoic, up to several kilometres of the exposed crust may have been removed by erosion.

Overview of central Bjørneøen: a 3071 Ma volcano-sedimentary belt intruded by orthogneisses

Bjørneøen has never been studied in the same detail as the area around Qussuk, and the published geological maps of the island (Fig. 3) to a large extent rely on air photo interpretation. The main lithological components and their tectonic history are probably very similar to those along strike on the 'Qussuk peninsula' (see discussion below), but the rocks in Bjørneøen are generally more flat-lying, with moderate westerly dips, and the supracrustal units are more coherent. The main purpose of the study in Bjørneøen was to compare the (meta) volcanic rocks and hydrothermal alteration systems here with those the Qussuk area. Besides, important new information was obtained about the position and contact relationships of the supracrustal belt, and the tectonic setting of two samples that have been dated by GEUS in 2005 (see below).

Camp V on central Bjørneøen (Fig. 3) was the last field camp in 2006 with only three days of field work. The camp was picked in the middle of the NW–SE-trending part of the supracrustal belt that transects central Bjørneøen. A gold mineralisation in this supracrustal belt has previously been studied by NunaMinerals A/S and was also visited by two other GEUS teams in 2004 and 2006. The present investigation of the footwall and hanging wall contacts of the supracrustal belt, aided by geological photogrammetry, showed that the supracrustal belt is more narrow than depicted on the published geological map (Fig. 3). However, the position of most of the north-eastern footwall contact was not located in the field due to the very limited available time, and the boundary could not be established with certainty using geological photogrammetry. The belt is disrupted by a major late thrust zone at around locality 319 (Fig. 3).

A thorough investigation of the footwall contact of the supracrustal belt at localities 326 and 327 proved beyond any doubt that the contact is of very low strain and that orthogneisses are intrusive into the supracrustal belt (Fig. 4A). A short visit of the hanging wall contact at locality 332 showed that this is also of relatively low strain and probably likewise of intrusive origin (Fig. 4B). Several age determinations of the footwall and hanging wall orthogneisses, which yielded magmatic ages of *c.* 3060–3050 Ma, were recently presented in a GEUS report edited by Hollis (2005). This is the minimum age of the supracrustal belt at central Bjørneøen, since it was intruded by the orthogneisses.

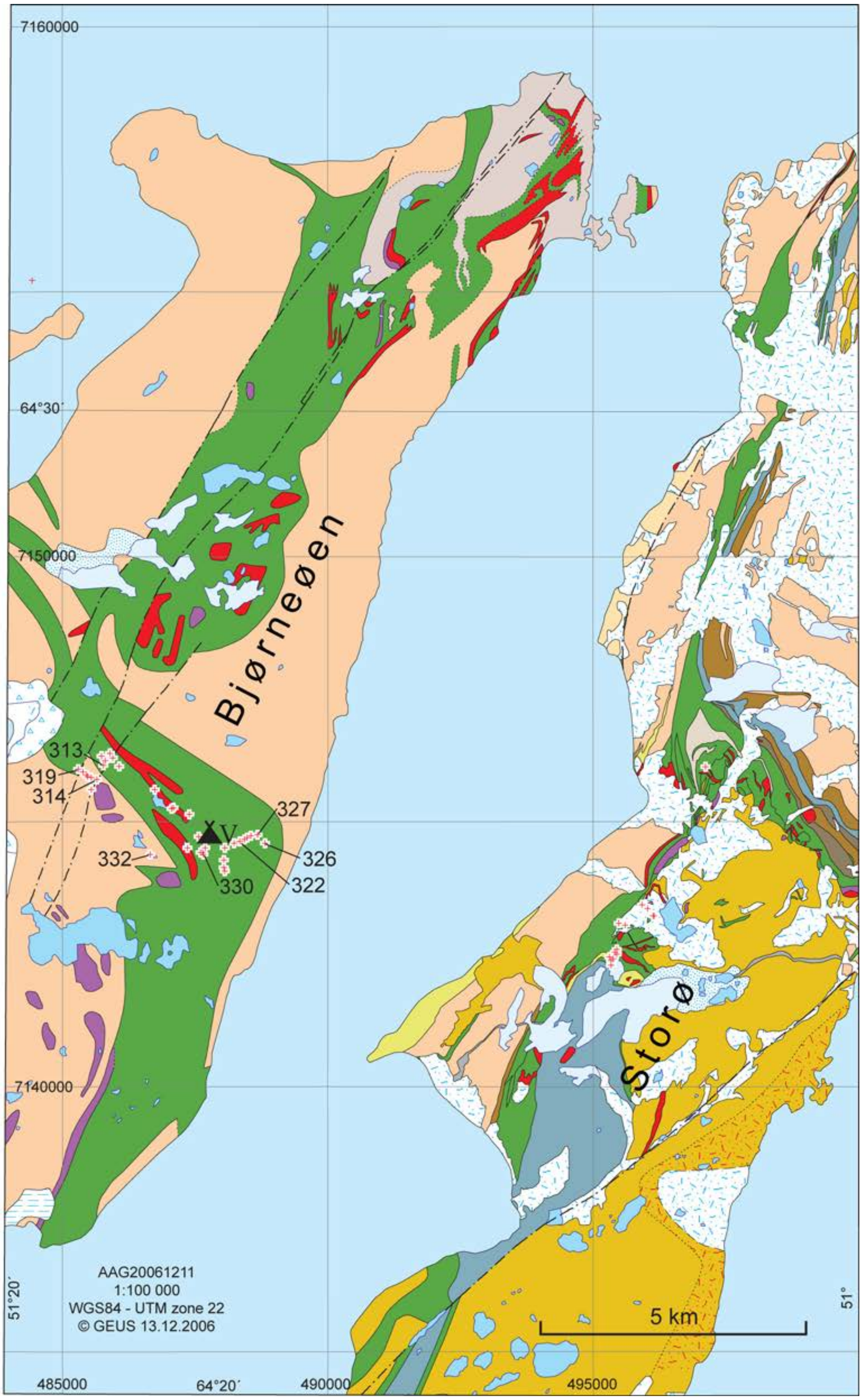

Figure 3. *Geological map of parts of Bjørneøen and Storø (from McGregor 1984 and Hollis et al. 2005), showing the positions of field camps and geological localities in 2006 on Bjørneøen. Numbers refer to geological localities described in the text. Legend as for Figure 2 (Bjørneøen only).*

Figure 4. *Footwall (A) and hanging wall (B) contacts with low strain of the NE–SW-trending supracrustal belts on central Bjørneøen. The orthogneisses at both contacts have intrusive relationships into the (meta)volcanic rocks, and have been dated at around 3055 Ma, which is the minimum age of the supracrustal belt. Note the flattened apophysis in the lower central part of Fig. 4A. Localities 327 and 332.*

Two U-Pb zircon age determinations from two samples of volcaniclastic/volcano-sedimentary rocks from the supracrustal belt collected in 2004 by N. Kelly and D. Frei have yielded very different results. One sample yielded a very precise volcanic age of 3071 ± 1 Ma (locality 314, sample 479827, ion probe data, Garde in press). Also here the published map is inaccurate; the sampled locality lies inside the supracrustal belt. The other sample also comes from a locality with distinct volcaniclastic textures (Fig. 5A–B; locality 313, sample 479745). The zircon age data from this sample (obtained with both ion probe and laser ICP-MS techniques, Hollis et al. 2005) comprise a range of roughly concordant ages between 2908–2742 Ma with a cluster at about 2825 Ma, which was thought to be a volcano-sedimentary detrital age. However, the surrounding orthogneisses have U-Pb zircon ages of around 3050 Ma as quoted above. Hollis et al. (2005) interpreted the age data from both localities in terms of a rather complicated tectonic model of the eastern margin of the Akia terrane, in which the younger supracrustal rocks with an apparent volcanic or detrital age of around 2825 Ma were sandwiched by thrust movements between older orthogneisses in their footwall and still older volcaniclastic rocks in their hanging wall.

The new field observations challenge this interpretation. The intrusive nature of the orthogneisses into the supracrustal rocks was firmly established in the field, and the present author could not find any tectonic contact between the two dated rocks, which are lithologically very similar and very well preserved. Therefore the apparently concordant cluster of c. 2825 Ma $^{207}Pb/^{206}Pb$ zircon ages in sample 479745 hardly represents a detrital age. The $^{207}Pb/^{206}Pb$ ages of the zircon grains have probably been partially reset already in the Archaean, most likely by late Archaean heating and fluid movement at around 2630 and 2550 Ma; major pegmatite-forming thermal events of these ages interval are recorded on nearby Storø (Hollis et al. 2005). In any case and regardless of the age data, the field observations from 2006 themselves mean that the thrust stacking model for Bjørneøen of Hollis et al. (2005) has to be discarded. On the contrary, the new observations suggest that the magmatic and tectonic evolution may have been similar on central Bjørneøen and in the Qussuk area.

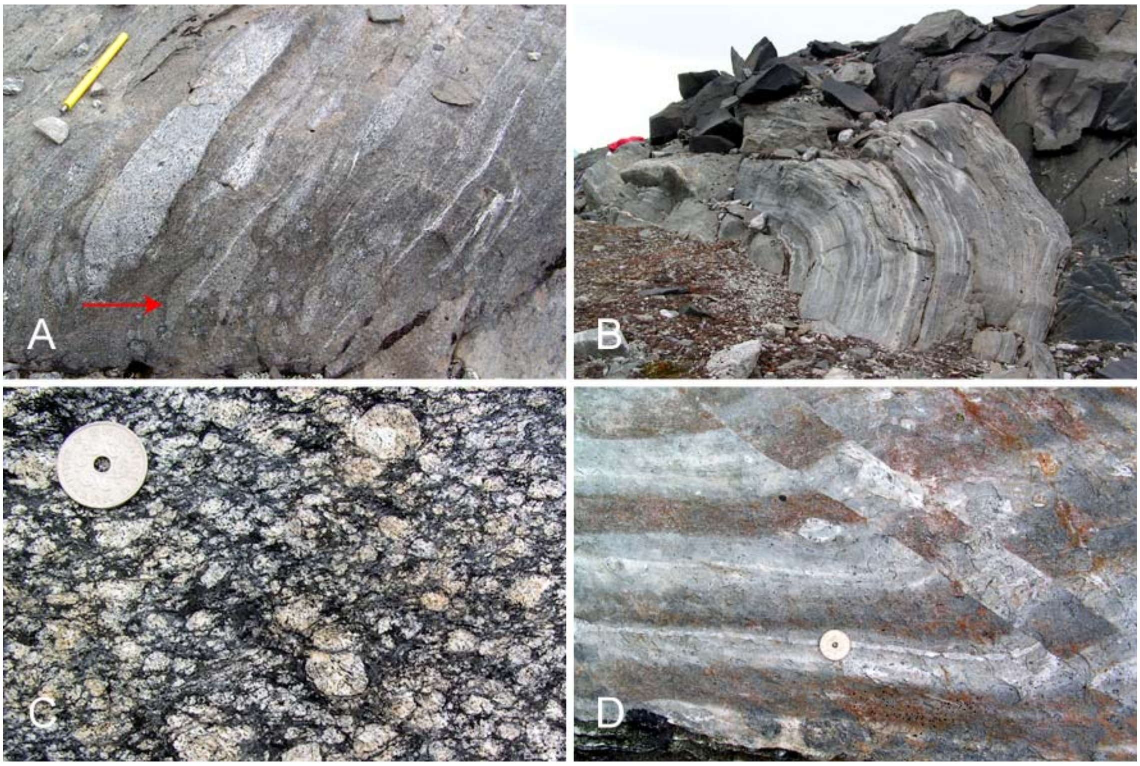

Figure 5. *Primary volcanic and sedimentary textures in the supracrustal belt of central Bjørneøen.* ***A, B****: folded volcaniclastic rocks at locality 313, cut by a Palaeoproterozoic dolerite dyke. Note the fiamme texture in the clast at the red arrow.* ***C, D****: undeformed, pale grey, very fine-grained volcanic clasts in a fine-grained dark matrix, and fine-grained volcano-sedimentary rock displaying graded bedding. Locality 322.*

Most of the supracrustal belt in central Bjørneøen consists of little to moderately deformed, black to dark grey amphibolite which locally preserves remarkable examples of primary volcaniclastic and volcano-sedimentary textures (see below). A prominent boudinaged, mafic–ultramafic horizon of probable intrusive origin occurs in the central part of the belt, probably erroneously shown as pegmatite on the published map of Fig. 3. This horizon may be genetically related to similar units in the Qussuk area described below. Premetamorphic carbonate alteration is widespread in some parts of the supracrustal belt, whereas alteration of the type prominent at Qussuk that has led to siliceous and sulphidic rocks seems largely restricted to the two auriferous localities described by Smith (1998).

Rock types and patterns of hydrothermal alteration in the relict island arc complex

Undifferentiated (meta)volcanic and volcano-sedimentary rocks of intermediate to mafic composition

Most of the relict volcano-sedimentary arc complex consists of monotonous fine-grained, variably foliated to strongly schistose, grey, dark grey and almost black rocks consisting of plagioclase, biotite and hornblende ± quartz and/or clinopyroxene. Such rocks form the bulk of the flanks of the isoclinally folded supracrustal panels, where the strong deformation has destroyed most or all primary features and mutual relationships. They probably comprise a variety of volcanic breccias, submarine and/or subaerial lava flows, tuffs and tuffites.

Meta-andesitic volcaniclastic rocks

Rocks of intermediate composition with distinct and unmistakable volcaniclastic textures are locally well preserved throughout the Qussuk area, particularly in the cores of fold hinges, and in central Bjørneøen. The recognition of these volcaniclastic textures is important, because they document widespread explosive volcanism and hence shallow subaqueous or subaerial volcanic activity. Some of the volcaniclastic rocks in central Bjørneøen contain clasts with distinct fiamme textures (Fig. 5A). Other rocks nearby contain small rounded, almost undeformed, very fine-grained clasts (Fig. 5C), and adjacent volcano-sedimentary rocks display rhythmic graded bedding and transitional brittle–ductile faulting and weak folding, surviving from a previous lower *P-T* regime (Fig. 5D). Other examples of well-preserved volcaniclastic rocks occur in the Qussuk area. Figure 6 from the east coast of Qussuk shows an exposure of a fold core at right angles to the fold axis, with numerous angular volcanic clasts which largely preserve their original shapes in the exposed section. The clasts are stretched along the fold axis perpendicular to the exposed surface, and also progressively flattened towards the flanks of the fold. Some clasts preserve concave terminations reminiscent of fiamme textures (Fig. 6B).

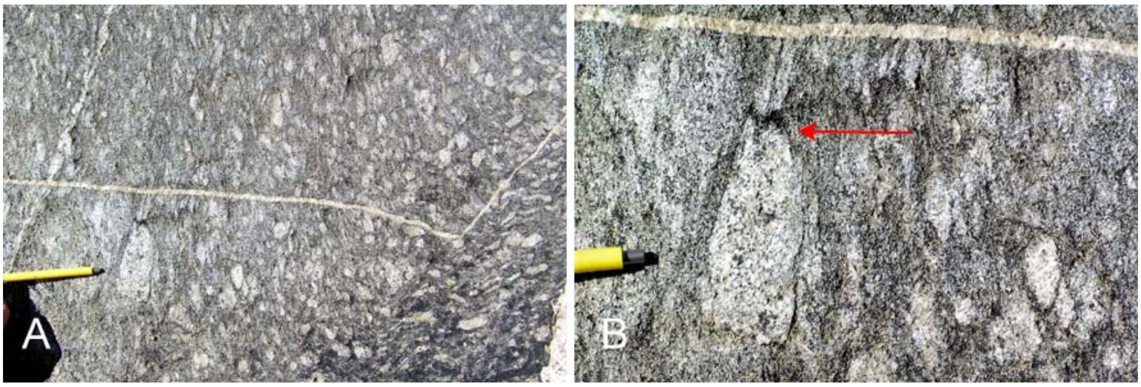

Figure 6. *Overview and detail of folded volcaniclastic rocks displaying pale, angular volcanic clasts. Note fiamme texture at the arrow. The clasts have been stretched parallel to the fold axis, along the direction of view. Locality 231, east coast of Qussuk.*

A different mechanism of clast preservation that is not dependent on low-strain fold cores has also been described by Garde (2004) from east of Qussuk, where hydrothermal carbonate impregnation in the volcanic environment and subsequent diagenetic growth of calc-silicate minerals rendered the rocks more competent than their surroundings and enabled the fragmental fabric to survive strong deformation.

Mafic–ultramafic intrusive rocks

Stocks, plugs and sheets of homogeneous, medium- to coarse-grained, metamorphosed mafic to ultramafic intrusive rocks are common within the meta-andesites especially in the area north of Qussuk and in Bjørneøen. The rocks are strongly deformed and more or less conformable with their meta-andesite hosts. They commonly form trains of elongate, lens-shaped bodies up to hundreds of metres long and a few tens of metres wide, which appear to be tectonic mega-boudins (Fig. 7A).

Figure 7*A*. *View along an ultramafic body within the volcaniclastic sequence, interpreted as intrusive. B: boudinaged hornblendite layer in metatuff, interpreted as an intrusive vein related to the larger ultramafic bodies. View towards north from locality 138 north of Qussuk.*

These mafic–ultramafic bodies are interpreted as intrusive, although no definite intrusive contacts have been found, probably due to the strong deformation and large ductility contrast at the margins. The bodies are confined to the supracrustal panels and are thus regarded as older than the grey gneisses, and interpreted as belonging to the relict arc. Where best preserved they are coarse-grained, homogeneous and rich in orthopyroxene, commonly partly altered to hornblende, and with interstitial fine-grained hornblende and plagioclase. In places indistinct magmatic layering on a scale of centimetres to decimetres is observed. At one locality (138, near camp II) an internal layer 20 cm thick with appreciable magnetite was found. Relict dykes that range from few centimetres to c. 1 m in thickness and now consist of coarse-grained hornblendite, have been observed within the meta-andesite in the immediate vicinity of some of the larger ultramafic bodies, and are interpreted as their feeder or satellite dykes (Fig. 7B).

A key locality of low strain with metatuffs displaying graded bedding, predeformation hydrothermal alteration, and younger tonalite with intrusive contacts

The low-strain fold core near the head of Qussuk at locality 242 is a key locality, which displays several different, well-preserved volcaniclastic, tuffaceous and volcano-sedimentary rocks of intermediate to mafic composition, clear evidence of pretectonic and premetamorphic acid hydrothermal alteration in unconsolidated rocks, and contacts of an undeformed grey gneiss precursor magma intruding into a volcano-sedimentary rock with a delicate older, first tectonic fabric. The fold is about 1 km wide, isoclinal and S-plunging, and forms the head of the peninsula in north-eastern Qussuk (Fig. 1).

Figures 8–11 are photographs from locality 242. The proximal part of Fig. 8 displays several nearly undeformed beds of fine- to coarse-grained tuff or tuffite, each about 20 cm thick, with concordant to discordant granite veins up to a few centimetres thick, and small irregular patches of pegmatite. Most of the veins and patches are localised in certain beds, the compositions of which must have been appropriate for *in situ* partial melting. The thickest bed in the central part of Fig. 8 displays fining-upwards graded bedding and shows that the sequence is right way up. The contact to the overlying bed is rusty weathering, and contains sporadic iron sulphides and small garnets up to 5 mm in size. These minerals are interpreted as metamorphic expressions of chemical changes that took place along the contact during early hydrothermal alteration in the volcanic environment. The localised alteration indicates that the percolating hydrothermal fluid used bedding contacts as convenient passageways. Figure 9A is a close-up photo of the graded bedding and hydrothermal alteration shown in Fig. 8; a faint oblique tectonic fabric perpendicular to the yellow pen is visible; glacial striations are also apparent.

The wall in the distal part of Fig. 8 shows an inclined but otherwise undisturbed primary depositional contact (red arrow) between the grey tuff or tuffite in the in the footwall, and an overlying, finely layered and fine-grained mafic tuff member. This important contact relationship shows that intermediate and mafic volcanic rocks were contemporary. Interlayered, strongly deformed intermediate and mafic metavolcanic rocks are common in the Qussuk area, but here it can be demonstrated that their mutual boundary is not tectonic. Figure 9B displays several volcaniclastic and tuffaceous beds, each 10–30 cm thick, as well as perpendicular zones of beginning partial melting which are axial planar to the large fold encompassing the locality.

Figure 9C shows a weakly layered and foliated metatuff, which preserves a highly irregular, delicately preserved magmatic contact to an intrusive tonalite – a rare example of an undeformed grey gneiss precursor intruding its overlying arc, and thus providing a glimpse of the earliest continental crust in formation in the arc. Both rocks are cut by younger pegmatite.

Figure 8. *Bedded, low-strain, intermediate and mafic metatuffs with graded bedding (foreground). A primary, essentially undeformed contact between intermediate and mafic metatuff is visible in the background (red arrow). Synvolcanic hydrothermal alteration has taken place along a bedding surface (blue arrow). See also Figs 9–10. Locality 242, north-east corner of Qussuk (see Fig. 2).*

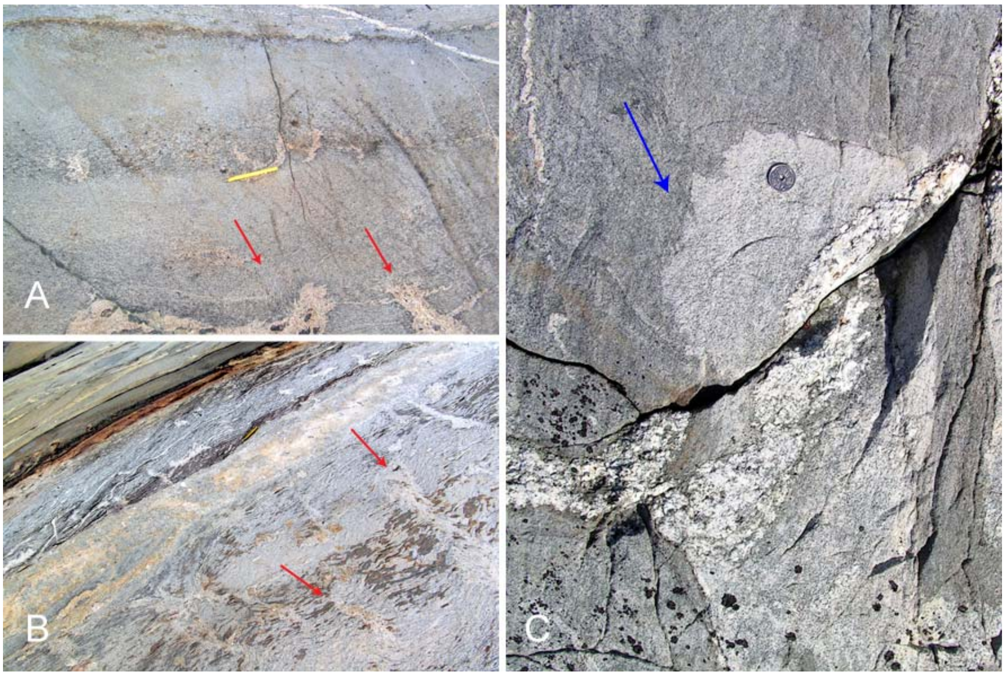

Figure 9*A–B*. *Close-up photo of intermediate metatuff with graded bedding (Fig. 9A from Fig. 8). Red arrows mark a weak foliation parallel to the axial plane of a large fold, as well as elongate, axial planar partial melt patches. C: Weakly bedded and foliated andesitic metatuff and intrusive tonalite, displaying a highly irregular magmatic contact. The tonalite is interpreted as the plutonic counterpart of the volcanic arc. Blue arrow marks foliation in the metatuff. Locality 242, north-east Qussuk.*

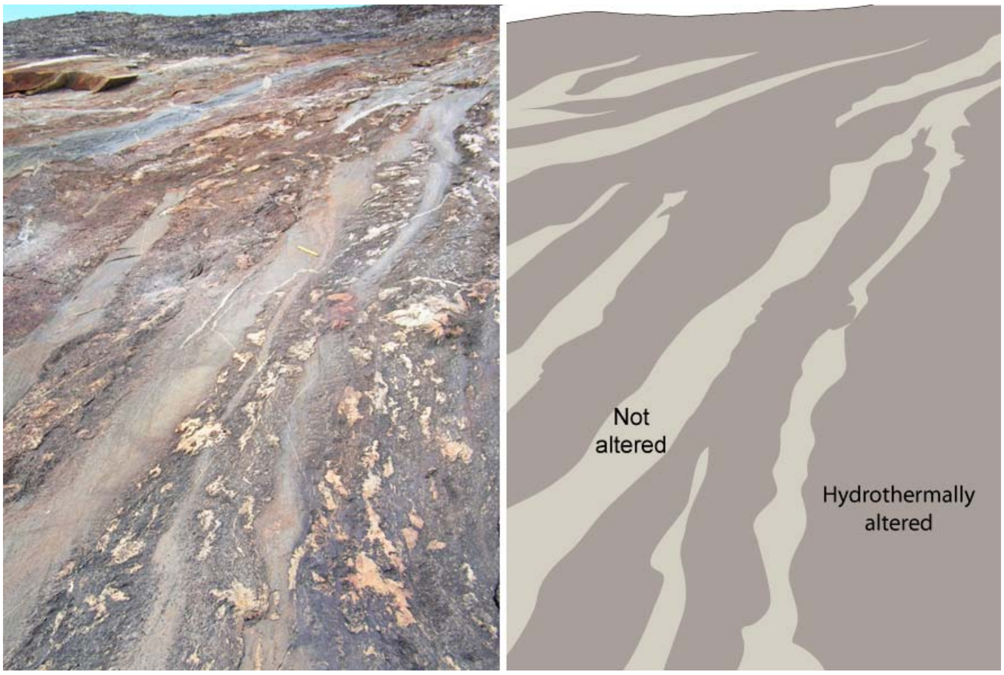

Figure 10. *Grey andesitic metatuff with a voluminous, interfingering network of rusty weathering, quartz-, garnet- and biotite-rich rocks in areas which were leached in a synvolcanic hydrothermal system and subsequently metamorphosed. Locality 242, north-east Qussuk.*

Figure 10, still from the key locality 242, shows an outcrop of grey, fine-grained, ice-polished metatuff which hosts a voluminous irregular, interfingering, vein-like system of coarser, rusty weathering rock with rough surfaces. This rock contains abundant quartz, biotite, garnet and iron sulphide and is interpreted as hydrothermally altered; note that the oblique 'foliation' visible in the lower left of the exposure is glacial striation. The close-up photo of Fig. 11 (again disregarding the glacial striations) displays the grey, ice-polished metatuff, sandwiched between semiconcordant altered zones on either side. A thin alteration zone *inside* the unaltered metatuff tapers out above the yellow pen and disappears by the blue arrow. The roughly bedding-parallel, but interfingering and locally discordant distribution of the altered rock displayed in Figs 10 and 11 impersonates the original hydrothermal fluid passageways and shows that they were formed prior to deformation. The garnet-rich metamorphic mineral parageneses in the rusty weathering areas are metamorphic expressions of the original hydrothermal alteration.

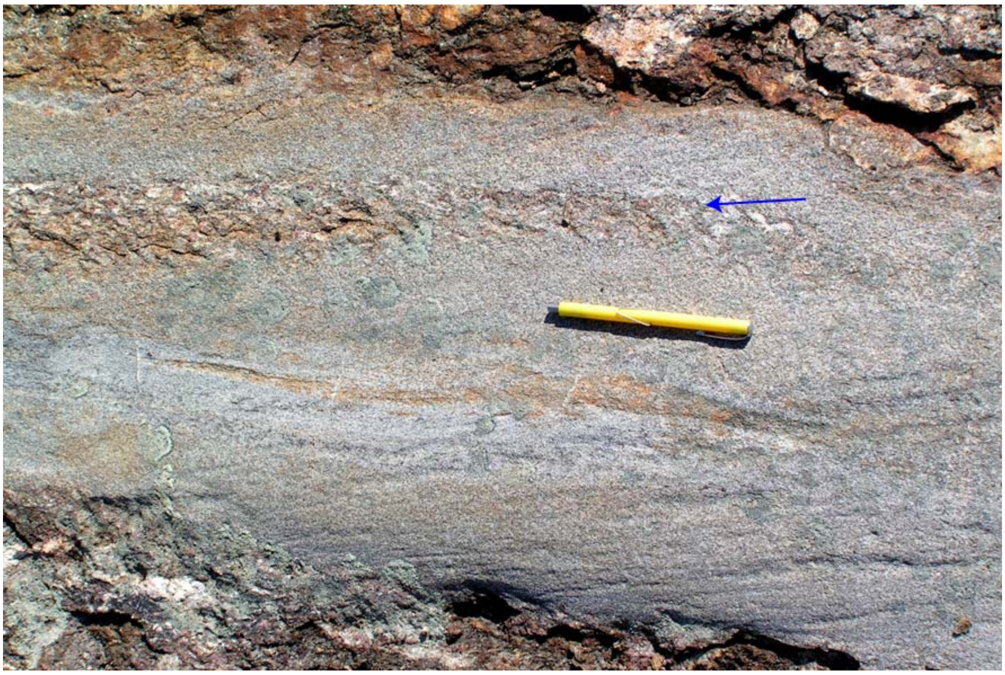

Figure 11. *Grey andesitic metatuff sandwiched between rusty weathered, chemically altered, quartz-, garnet- and biotite-rich rocks with minor disseminated iron sulphides resulting from metamorphism of a synvolcanic hydrothermal system. Blue arrow shows the termination of a smaller vein-like, former hydrothermal alteration zone inside the unaltered metatuff. The metatuff surface displays glacial striation. Compare Fig. 13. Locality 242, north-east Qussuk.*

Hydrothermally altered rocks with quartz, biotite, garnet, iron sulphides ± feldspar, sillimanite and fuchsite at other localities

Thin rusty weathering horizons of volcaniclastic and tuffaceous metavolcanic rocks, about 1 m thick and up to 3 km long, are relatively common in the more highly deformed parts of the relict arc. The rusty weathering rocks are mostly andesitic in composition and contain fine-grained, disseminated pyrrhotite in textural equilibrium with the silicate assemblages. Metre-thick layers with up to semi-massive sulphides also occur locally, for instance at locality 234 near the head of Qussuk. Lenses and layers of granular garnet-quartz±biotite rock up to 5 m thick, locally with thin (≤ 10 cm) discordant garnet-quartz veins, and pockets and layers of massive siliceous, commonly garnet-rich and aluminous rocks up to 5 m thick commonly occur adjacent to such pyrrhotite-bearing horizons. Abundant lozenge-shaped sillimanite pseudomorphs after andalusite are common in these rocks, and also locally fuchsite. This peculiar rock association and its immediate host rocks may be gold mineralised up to the ppm range (Garde 2005). Near locality 256 east of central Qussuk such a garnet-rich, altered lens surrounds a football-sized pocket of unaltered and undeformed amphibolite with a gradational contact into the altered rock (Fig. 12). Like at locality 242, also this outcrop shows that the garnet-quartz-biotite-rich, aluminous rocks are metamorphosed hydrothermal alteration products of the host volcanic rocks. Furthermore, the alteration must have taken place prior to the regional deformation, since the unaltered pocket of amphibolite would otherwise have been deformed.

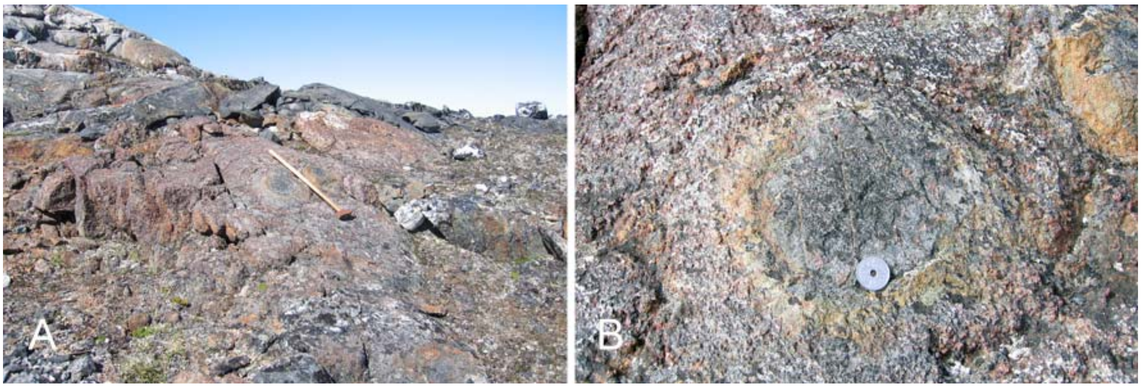

Figure 12. *Overview and detail of a football-sized enclave of surviving, unaltered and undeformed amphibolite (metatuff) inside a lens several metres across of garnet-rich rock, interpreted as similar tuff that was hydrothermally altered and then metamorphosed. Note the gradual transition from dark grey amphibolite in the centre of the enclave into garnet amphibolite and then garnet-rich rock. Near locality 256, 'Qussuk peninsula'.*

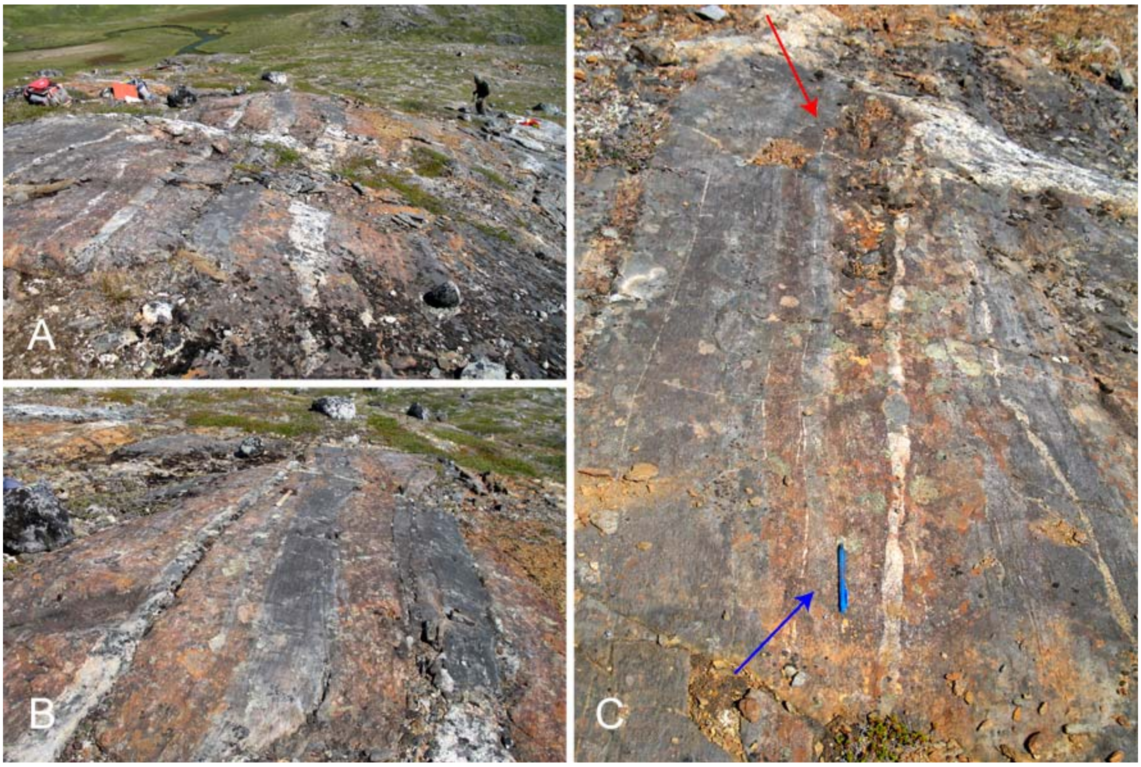

Figure 13. *Interfingering grey andesitic metatuff and chemically altered, rusty weathering quartz-garnet-biotite-rich rocks ± sillimanite and minor disseminated iron sulphides, which represent a strongly deformed and metamorphosed synvolcanic hydrothermal alteration system. Red and blue arrows mark the terminations of a wedge-shaped altered rock panel, and vice versa. Compare Figs 10–11, which display the same relationship in low-strain rocks. Locality 83 north of Qussuk.*

Rusty weathering, garnet-rich altered rocks also occur north of Qussuk, in a tract of alteration several kilometres in length that was originally mapped as aluminous metasedimentary rocks. Figure 13 from locality 83 in this tract shows strongly deformed, unaltered andesitic metatuff alternating with altered, garnet-, biotite- and quartz-rich rocks. The strain is high, but the relationship is in principle the same as that previously described from locality 242 (Fig. 10). The arrows in Fig. 13 point to places where the altered rock tapers into the unaltered rock (red arrow), and vice versa (blue arrow). A close inspection at the outcrop also reveals that the lithological change from feldspar- to garnet- and quartz-rich rock is generally gradational and symmetrical, i.e., the most strongly altered rocks occur in the central parts of the alteration zones.

The most voluminous and intense alteration in the Qussuk area occurs at and near the top of the mountain of Ivisaat north of Qussuk (Fig. 14). The altered, mostly garnet-rich rocks outline an overturned isoclinal fold. The core of the fold, which also forms the brown-weathering ‘hat’ of the mountain itself (Fig. 14A–B) consists of a very characteristic, 2–3 mm-grained sillimanite quartzite ± fuchsite, which possesses a distinct foliation but commonly no clear compositional layering (although there are exceptions as shown by the layered and outcrop-scale folded variety of Fig. 14C). The quartzitic core of the fold is followed to the west by a zone up to 100 m wide of very garnet-rich rocks. To the east, around the south-facing nose of the fold, the garnet-rich rocks grade into more homogeneous, granular, garnet- and biotite-bearing quartzofeldspathic rocks with minor disseminated iron sulphides. A related zone of intensely altered, garnet-rich rocks, locally including thin layers of sillimanite-fuchsite quartzite, can be followed down to the coast of Qussuk at around locality 201. It may be speculated that the position and geometry of the isoclinal fold was controlled by the quartzitic and garnet-rich layers with their different competence and limited thickness compared to the surrounding, compositionally homogeneous andesitic rocks.

The mineralogical composition of the altered rocks corresponds to a prominent apparent enrichment in Al, Si and Cr (besides Fe, Ti and a few additional elements). These elements are all very immobile. Accordingly the composition of the altered rocks is not due to enrichment in these elements but to depletion of most other major and trace elements. This particular type of alteration points to acid leaching under low pressure, a process which is very characteristic of epithermal, high-level, low-pressure hydrothermal mineralisation systems with gold and copper in modern andesitic arcs (e.g. Sillitoe & Hedenquist 2003). A low-pressure hydrothermal system such as that occurring in near-surface volcanic environments, with or without boiling, is a prerequisite for acid leaching by strong acids such as sulphuric or hydrochloric acid. Higher pressures prevent dissociation of hydrogen ions from the strong acids (Sillitoe & Hedenquist 2003).

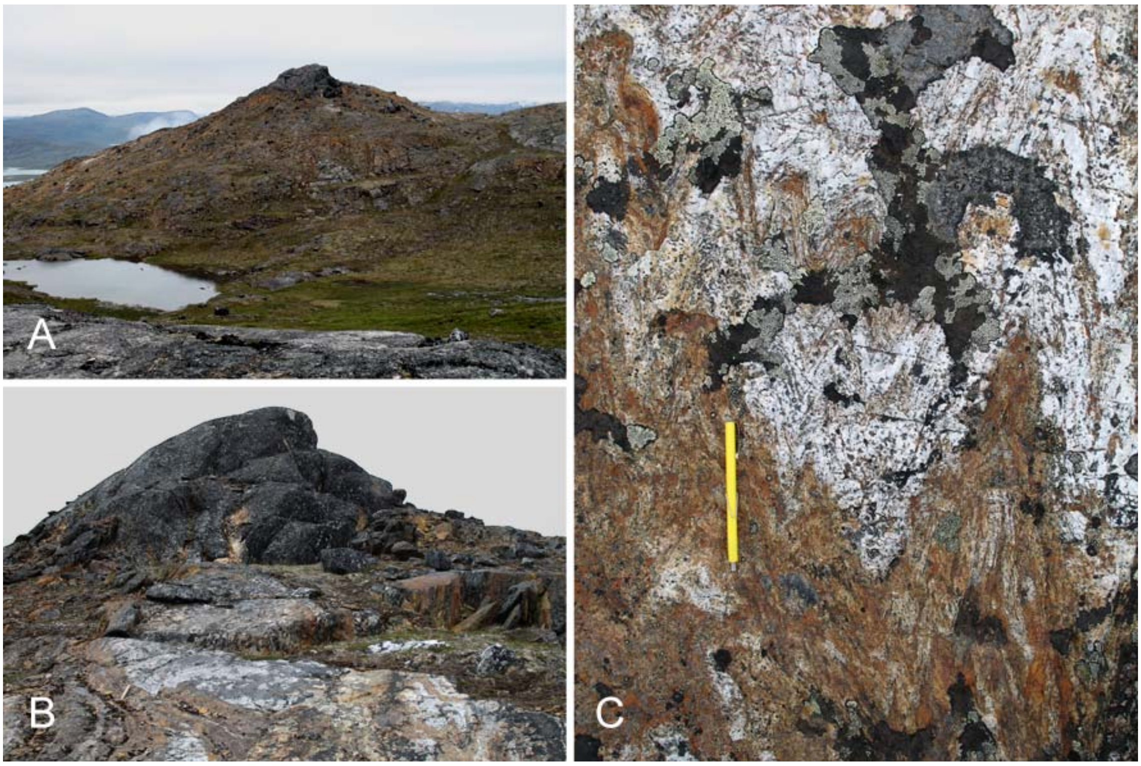

Figure 14. *The top of Ivisaat mountain, which consists of sillimanite-fuchsite quartzite, the deformed and metamorphosed product of hydrothermal leaching of andesitic volcanic rocks in an epithermal, near-surface volcanic environment. C: close-up of folded sillimanite-fuchsite quartzite at the top of Ivisaat mountain. Locality 7 north of Qussuk.*

The mineralogical composition of the altered rocks corresponds to a prominent apparent enrichment in Al, Si and Cr (besides Fe, Ti and a few additional elements). These elements are all very immobile. Accordingly the composition of the altered rocks is not due to enrichment in these elements but to depletion of most other major and trace elements. This particular type of alteration points to acid leaching under low pressure, a process which is very characteristic of epithermal, high-level, low-pressure hydrothermal mineralisation systems with gold and copper in modern andesitic arcs (e.g. Sillitoe & Hedenquist 2003). A low-pressure hydrothermal system such as that occurring in near-surface volcanic environments, with or without boiling, is a prerequisite for acid leaching by strong acids such as sulphuric or hydrochloric acid. Higher pressures prevent dissociation of hydrogen ions from the strong acids (Sillitoe & Hedenquist 2003).

Calc-silicate-bearing, carbonate-altered arc rocks

Carbonate alteration is common in most parts of the relict volcanic arc, and is visible as decimetre- to metre-scale impregnation of volcano-sedimentary and intrusive rocks with calc-silicate minerals, mainly diopside and epidote (Fig. 15). Quartz veins about 5–20 cm thick may also be present. Strongly discordant veins have not been observed, and free calcite only occurs locally as layers up to few centimetres thick in the centres of larger calc-silicate veins. This indicates that also the carbonate alteration occurred prior to deformation and metamorphism. Besides, carbonate alteration has not been observed in the plutonic granitoid rocks that have intruded the arc. Previous analytical work has shown that this type of alteration is not associated with gold mineralisation (Garde 2005). However, it may well have been synchronous with the acid alteration and belong to lateral parts of the same large volcanic-related hydrothermal system(s). Very acidic and CO_2-dominated hydrothermal alteration systems are commonly seen side by side in the centres and flanks, respectively, of modern andesitic arcs (Sillitoe & Hedenquist 2003).

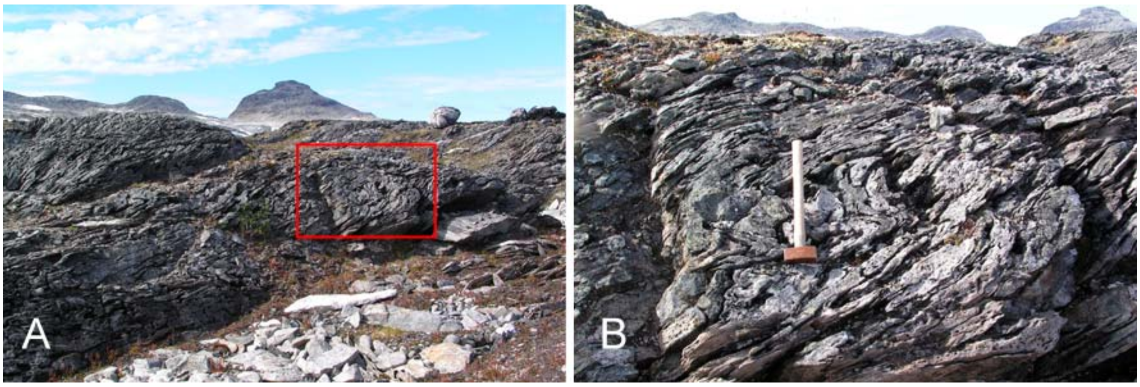

Figure 15. *Overview and detail of carbonate-altered andesitic metavolcanic rocks. The calcite-rich parts have weathered out (mantled by actinolite-diopside-epidote-rich rock formed by metamorphic reactions with the silicate host). Central Bjørneøen, locality 330.*

Conclusions

Field work in 2006 has greatly expanded the volume and extent of the previously recognised andesitic arc at Qussuk and Bjørneøen in the eastern Akia terrane, and important new localities with well-preserved volcanic and volcaniclastic rocks have been found in both areas. Furthermore, it has been established that the relict arc also comprises common, orthopyroxene-rich mafic to ultramafic intrusives. A number of new occurrences have been found, where synvolcanic hydrothermal alteration systems can be studied. There are two types of alteration, leading to respectively siliceous and aluminous rocks associated with gold-copper mineralisation, and carbonate-altered rocks with calc-silicates but without mineralisation. Especially an almost undeformed locality within a fold hinge displays primary volcanic and intrusive textures, as well as altered rocks in which some of the original passageways of the hydrothermal fluids can still be identified down to a scale of centimetres.

Table 1. *Rock samples collected at Qussuk–Bjørneøen 2006 by A.A. Garde*

Sample	Chem	Loc.	Easting	Northing	Description
477619		6	495255	7184651	Qtz-sill(-?pyrrh) rock with secondary, ?colloform goethite.
477620		7	495272	7184701	Sillimanite-quartz-?pyrrhotite-?fuchsite rock
477621	x	18	495031	7186154	Fine-grained mafic variety of amphibolite from finely (millimetre-scale) and very indistinctly layered, otherwise homogeneous unit representative of the mafic metavolcanic component. No signs of alteration. No garnets.
477622	x	19	494976	7186105	1 mm-grained, grey bt-?hbl-plag-qtz rock, member of the andesitic association, near-homogeneous, un-migmatised, from an area with decimetre-scale compositional layering. Representative sample, for chemical composition and geochronology.
477623	x	20	494898	7186140	Rusty weathering, fine-grained grey meta-andesite, relatively siliceous and rich in bt. Sampling site on photo # 46.
477624	x	20	494898	7186140	Rusty weathering, rather siliceous, dark grey meta-andesite/amphibolite s.l. from the most rusty weathering zone, 3 m from 477623.
477625	x	21	494866	7186090	Medium- to coarse-grained grt-bt-qtz-?fsp-pyrrh rock. One of several layers *c.* 10 cm thick.
477626		21	494866	7186090	Hand sample of fine-grained ?meta-andesite or hydrothermal rock with patches of coarse bt, a few garnets, and common magnetite (cf. alteration zone at Storø).
477627	x	23	494803	7186044	Medium-grained grt-sill-bt-qtz rock, un-migmatised, interpreted as leached and metamorphosed andesite.
477628		16	495000	7185836	Large hand specimen of opx-rich (intrusive) ultramafic rock with *c.* 1 cm opx crystals, and cpx + possibly ol in the groundmass.
477629	x	32	495701	7184752	Grey, volcaniclastic meta-andesite
477630	x	48	495364	7183665	Quartz-sillimanite-fuchsite rock with crude gneissic foliation on a scale of few millimetres. Interpreted as residual from synvolcanic-epithermal leaching.
477631	x	59	495339	7184809	1–2 mm-grained, bt-rich, grey meta-andesite with very minor disseminated sulphides.
477632	x	59	495339	7184809	1–2 mm-grained, bt-rich, grey meta-andesite with a few garnets ≤ 0.5 cm large and disseminated sulphides.
477633	x	60	495251	7184785	Uniform, c. 2 mm-grained, rather siliceous qtz-?plag-bt-pyrrh rock with anonymous aspect, presumably hydrothermally altered and metamorphosed andesite. No garnets.

Sample	Chem	Loc.	Easting	Northing	Description
477634	x	61	495272	7184770	Uniform, c. 2 mm-grained, distinctly siliceous qtz-?plag-bt-pyrrh rock with anonymous aspect, presumably hydrothermally altered and metamorphosed andesite.
477635	x	62	495262	7184726	Quartz-sillimanite-fuchsite (?-pyrrhotite) rock, *c.* 2 mm-grained, for chemistry and zirconology.
477636	x	63	495219	7184684	Grey meta-andesite relatively rich in grt, *c.* 1–2 mm-grained, with bt, and not siliceous appearing. A little disseminated iron sulphide (pyrite?).
477637	x	65	495096	7184665	Grt-bt-qtz (-fsp?)-Fe-sulphide rock, 1–5 mm grained, with ≤2 cm thick quartz-rich schlieren (± grt, ± bt).
477638	x	65	495096	7184665	Grt-bt-qtz (-Fe-sulphide) rock rich in garnets, *c.* 2–3 mm grain size, indistinct centimetre-scale layering. Interpreted as hydrothermally altered andesitic rock.
477639	x	74	495020	7184805	Grey bt-bearing meta-andesite with a moderate garnet content and coarse biotite, near the western margin of a garnet-rich zone.
477640	x	75	495040	7184796	Fine-grained amphibolitic metadyke, post-hydrothermal alteration, but pre-metamorphism and deformation.
477641	x	75	495040	7184796	Quartz- and sillimanite-rich rock with minor grt, bt and Fe-sulphide, adjacent to thin mafic metadyke.
477642	x	83	495415	7187043	Grt-qtz-bt-pyrrh(?-plag) rock, medium grained, hydrothermally altered and metamorphosed andesite.
477643	x	83	495415	7187043	Grey, fine- to medium-grained meta-andesite with rare garnets, adjacent to sample 477642.
477644	x	83	495415	7187043	Grt-qtz-bt-minor sill(?-plag) rock, medium grained, hydrothermally altered and metamorphosed andesite.
477645	x	93	496795	7192737	Rust-stained local block of meta-andesite, collected at the first exposure uphill from loc. 92.
477646	x	94	495966	7196428	Fine-grained, homogeneous meta-andesite.
477647	x	96	496242	7200782	Relatively leucocratic amphibolite with disseminated iron sulphides and quartz veins ≤ 1 cm thick.
477648		100	490513	7198522	Ultrabasic rock, ?dunite, grain size around 2 mm, apparently homogeneous. Large hand sample.
477649		100	490513	7198522	Ultrabasic rock, ?dunite, grain size around 2 mm. Large hand sample.
477650		100	490513	7198522	Ultrabasic rock, ?dunite with magmatic layering. Large hand sample.
477651	x	96	496242	7200782	Fine-grained, apparently layered meta-andesite, from locality with volcaniclastic texture.

Sample	Chem	Loc.	Easting	Northing	Description
477652		102	493583	7190860	Opx-hbl-layered, deformed ultramafic rock. Presumably originally mainly consisting of coarse-grained opx. Representative sample.
477653	xx	110	492488	7190726	Hornblendite, medium grained, probably metamorphic variety of originally opx-rich mafic-ultramafic intrusion.
477654	x	112	492194	7190913	Amphibolite of presumed intrusive origin with disseminated sulphides. Silica content possibly increased by pre-metamorphic hydrothermal leaching.
477655	x	117	492509	7191469	Fine-grained, compositionally layered meta-andesite with disseminated iron sulphide. The lithology appears more than average siliceous (?hydrothermally leached). From the most conspicuous horizon 2–3 m thick.
477656	x	126	496584	7191568	Grey, fine-grained meta-andesite, indistinctly layered, with scattered pyrrhotite grains ≤1 mm large.
477657	x	134	495247	7191956	Meta-andesite, fine grained, indistinctly layered, with disseminated pyrrhotite grains ≤1 mm large.
477658	x	135	494164	7191727	Hornblendite of presumed intrusive origin in layered meta-andesite, medium grained, predating the granite (and deformation?).
477659	x	136	493585	7190616	Sample for geochronology of an unusually felsic member of the meta-andesite, collected *c.* 30 m east of the large ultramafic body. The sample is fine-grained, contains plag-bt-qtz, and is indistinctly compositionally layered on a scale of centimetres.
477660	x	138	493572	7190730	Rusty weathering horizon 20 cm thick in ultramafic body, with medium-grained hbl-cpx, magnetite, and possibly opx or ol. No sulphides visible.
477661	x	138	493572	7190730	Opx-hbl layered ultramafic rock, strongly deformed, from the central part of the body.
477662		138	493572	7190730	Calcite vein and part of the diopsidic reaction rim.
477663		138	493572	7190730	Vein quartzite, with calcite-diopside margin.
477664	x	139	493805	7190562	Dark grey meta-andesite, 1 mm-grained, layered on centimetre-scale, bt-?hbl-bearing, intermediate to mafic.
477665	x	140	493871	7190546	Dark grey meta-andesite, 1 mm-grained, similar to that at loc. 139, adjacent to rusty weathering zone *c.* 5 m wide.
477666	x	140	493871	7190546	Dark grey meta-andesite, fine grained, with pyrrhotite, disseminated and also seen along a hair-line joint.

Sample	Chem	Loc.	Easting	Northing	Description
477667	x	141	493543	7190201	Grey meta-andesite. Completely fresh, very homogeneous, fine-grained, with barely recognisable compositional layering.
477668	x	143	493774	7189845	Typical grey meta-andesite near the western margin of the eastern rusty weathering zone.
477669	x	144	493721	7189893	Grey meta-andesite with disseminated pyrrhotite near the western rusty weathering zone.
477670	x	144	493721	7189893	Typical grey meta-andesite (without pyrrhotite) at the western margin of the same rusty weathering zone.
477671		156	493300	7190246	Very coarse-grained opx-mica rock from ultramafic body.
477672		156	493300	7190246	Diopsidic rock with carbonate veins (hand specimen only).
477673	x	170	494518	7193079	Fine-rained, apparently almost completely homogeneous meta-andesite.
477674	x	170	494518	7193079	Rusty weathering variety of fine-rained, apparently almost completely homogeneous meta-andesite, with disseminated pyrrhotite grains < 1 mm in size.
477675	x	173	493873	7192674	Dark grey, bt-hbl-bearing meta-andesite, locally layered on a scale of 5 cm, a little more mafic than most.
477676	x	180	496290	7189175	Sillimanite-garnet-quartz (-biotite) rock, rusty weathering.
477677	x	182	496207	7188904	The local met-andesite host (here with minor hornblende), 1 mm-grained, not migmatised, with minor diopside and very minor disseminated pyrrhotite. *C.* 35 m west of the sillimanite-garnet zone.
477678		187	493663	7190870	Bt orthogneiss, light grey, very homogeneous, medium grained. Representative for orthogneiss intruding the supracrustal rocks of the arc system.
477679	x	199	492448	7190215	Medium-grained, homogeneous hornblende metagabbro, weakly deformed.
477680	x	207	495442	7183200	Grey meta-andesite, fine grained, with unusually much very fine-grained pyrrhotite, and apparently silicified (=leached?) to some extent.
477681	x	217	495824	7183364	Typical example of apparently strongly silicified (i.e., leached) meta-andesite with disseminated pyrrhotite.
477682	x	231	495226	7178253	Meta-andesite with volcanic clasts, unmigmatised, no granite or pegmatite. for zirconology, 2 bags.
477683	x	234	495079	7178532	Meta-andesite with pyrrhotite mineralisation. Chips from several local blocks within 2 m across strike.

Sample	Chem	Loc.	Easting	Northing	Description
477684	x	234	495079	7178532	Quartz vein within pyrrhotite-mineralised zone of meta-andesite.
477685	x	242	495860	7180166	Sample of garnet-biotite-quartz-sulphide lens with possible sulphides inside garnet.
477686	x	242	495860	7180166	Grt-bt-qtz (-py-pyrrh) rock, from the alteration zone under the big hammer (photo 282).
477687	x	242	495860	7180166	Mafic metatuff (the photographed locality).
477688	x	242	495860	7180166	Adjacent (hanging wall) andesitic metatuff.
477689		249	495090	7184676	Hydrothermally altered and metamorphosed rock with blackish grey garnets and blue quartz, from the garnet-rich zone at Ivisaat.
477690		257	494067	7171276	Siliceous, fine- to medium-grained quartz-garnet-magnetite-?biotite rock with minor Fe sulphides. Presumed hydrothermally altered.
477691	x	283	494340	7172128	15 m SW of loc. 283, the apparently unaltered host meta-andesite, fine grained and strongly deformed.
477692	x	283	494340	7172128	Fine-grained, rusty weathering meta-andesite from the central part of the mineralised zone, with hairline rusty weathering seams. The lithology appears more siliceous than 477691 and 477693 (leached).
477693	x	283	494340	7172128	25 m NE of loc. 283, the apparently unaltered host meta-andesite, fine grained, darker (more mafic) than 477691.
477694	x	244b	494320	7175762	Fine-grained meta-andesite with disseminated iron sulphides.
477695	x	244c	494746	7176149	Fine-grained meta-andesite with disseminated iron sulphides.
477696	x	286	494113	7171119	Sample from the central, bleached part of the hydrothermal alteration zone, consisting of quartz, ?plagioclase, and minor muscovite, garnet, and in places biotite. Looked for sillimanite but did not spot any. Some 100 m farther north the rusty weathering zone is concealed by Quaternary cover.
477697	x	294	493482	7171399	Meta-andesite with disseminated to semi-massive iron sulphide.
488801	x	300	488047	7144140	Quartz-?muscovite-?plagioclase-biotite(-garnet)-(Fe-sulphide) rock, fine grained, finely layered (?tectonically), from the central part of the sul-phide mineralised zone. Probably felsic metatuff rather than a thoroughly hydrothermally altered rock.
488802	x	300	488047	7144140	Very fine-grained, indistinctly layered amphibolite, typical of the rocks surrounding the mineralised zone.
488103		313	485785	7146073	Volcaniclastic meta-andesite.
488104		321	488229	7144601	Display piece, mafic metatuff.

Sample	Chem	Loc.	Easting	Northing	Description
488105		322	488346	7144636	Felsic metasedimentary rock, representative.
488106		322	488346	7144636	Hand sample of lithic tuff with centimetre-sized felsic clasts.
488107		323	488436	7144668	Volcaniclastic rock with ?fiammes, from fold hinge. Hand sample only.
488108		325	488553	7144739	Sample of intrusive tonalite sheet 30 cm thick, for geochronology.

References

Escher, J.C. & Pulvertaft, T.C.R. 1995: Geological map of Greenland, 1:2 500 000. Copenhagen: Geological Survey of Greenland.

Garde, A. A. 1989: Geological map of Greenland, 1:100 000, Fiskefjord 64 V.1 Nord. Copenhagen: Geological Survey of Greenland.

Garde, A.A. 1997: Accretion and evolution of an Archaean high-grade grey gneiss-amphibolite complex: the Fiskefjord area, southern West Greenland. Geology of Greenland Survey Bulletin **177**, 114 pp.

Garde, A.A. 2003: An overview of the Archaean evolution of the Nuuk region: from long-lived evolution of a sea of gneisses to episodic accretion of small continental terranes along boundary structures. Geologiske Undersøgelse Rapport **2005/42**, 19–44.

Garde, A.A. 2005: A mid-Archaean island arc complex with gold mineralisation at Qussuk, Akia terrane, southern West Greenland. In Hollis, J.A. (ed.) Greenstone belts in the central Godthåbsfjord region, southern West Greenland, 179–213. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/42**.

Garde, A.A. in press: A mid-Archaean island arc complex in the eastern Akia terrane, Godthåbsfjord, southern West Greenland. Journal of the Geological Society (London).

Garde, A.A., Friend, C.R.L., Nutman, A.P. & Marker, M. 2000: Rapid maturation and stabilisation of middle Archaean continental crust: the Akia terrane, southern West Greenland. Bulletin of the Geological Society of Denmark **47**, 1–27.

Hollis, J.A. (ed.) 2005: Greenstone belts in the central Godthåbsfjord region, southern West Greenland: Geochemistry, geochronology and petrography arising from 2004 field work, and digital map data. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/42**, 215 pp., 1 DVD.

McGregor, V.R. 1984: Geological map of Greenland, 1:100 000, Qôrqut 64 V. 1 Syd. Copenhagen: Geological Survey of Greenland.

Sillitoe, R.H. & Hedenquist, J.W. 2003: Linkages between volcanotectonic settings, ore-fluid compositions, and epithermal precious metal deposits. In: Simmons, S.F. & Graham, I. (eds): Volcanic, geothermal, and ore-forming fluids; rulers and witnesses of processes within the Earth. Special Publication, Society of Economic Geologists **10**, 315–343.

Smith, G.M. 1998: Geology and mineral potential of the Bjørneøen supracrustal belt, Nuukfjord, West Greenland. Unpublished report, Nunaoil A/S, 13 pp. (in archives of the Geological Survey of West Greenland, GEUS Report File 21649).

Magmatic environment: The Naujat gabbro-anorthosite complex and country rocks – Field report 2006

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Zoned ultramafic layers in heterogeneous orthogneiss, SW of Akuliarusersuaq

Introduction – Geographical and geological setting

GEUS mapping in the field season 2005 resulted in the discovery of a previously unknown gabbro-anorthosite complex (Solgevik & Piazolo in press). The extent of this complex is estimated to be > 100 km2 (Solgevik & Piazolo in press). However, only a small part of this igneous complex has been mapped and its lithological variation, mineral potential, geochemical and geochronological characteristics, as well as its tectono-stratigraphical position is only poorly understood. The aim of the 2006 fieldwork campaign was therefore to improve our understanding of the evolution of the gabbro-anorthosite complex and its relationships to the country rocks with respect to their general mineral potential by

(a) carring out detailed mapping (on a 1:10.000 scale) in order to confirm the extent of the gabbro-anorthosite complex, describe its lithological variation, identify possible mineral occurrences, and to characterise the lithological variations of the country rocks and their tectono-stratigaphic relationships to the gabbro-anorthosite complex; and

(b) sampling the key lithologies for subsequent detailed geochemical and geochronological investigations.

The field work focussed on the area that lies in between the Akuliarusersuaq to the north, and the Naujat kûat to the west, Akuliaruserssuaq to the east and Kangaussarsuup sermia to the south and southeast (Fig. 1) on the Tre Brødre terrane (Friend and Nutman 2001, 2005). The investigations comprised geological mapping of three selected areas; the detailed studies comprised gabbroic-anorthositic sequences, their country rocks (mainly heterogeneous gneisses and amphibolites), as well as mafic-ultramafic lithologies occurring in both the gabbro-anorthosite complex and its surrounding country rocks. Locations of the field camps are located in Fig. 1 and the field sketch map of the mapped area is shown in Fig.2. A sample list is given in Table 1.

The available published GEUS/GGU 1:500.000 Frederikshåb Isblink - Søndre Strømfjord geological map sheet (compiled by Allaart 1982; with a description by Kalsbeek & Garde 1989), an unpublished sketch of the Kapisillit map sheet, a geological field map from the GEUS archives (1:50.000) from a field campaign in 1976, as well as a preliminary geological sketch map from the GEUS 2005 field campaign (1:50.000; based on mapping by Elis Hoffmann, Clark Friend, Sandra Piazolo and Henrik Solgevik; compiled by Henrik Solgevik) formed the basis for the selection of work areas. Further descriptions and references of the investigated areas can be found in Kalsbeek & Garde (1989) and Hollis *et al.* (2006).

Detailed mapping was made on 1:10.000 scale topographic map sheets (Kangaasarsuup Sermia) drawn by the Geological Mapping Department at GEUS. The maps used are Kangaasarsuup Sermia map sheets # 1, 2, 4 and 5. These maps lie within the 1:100.000 Geological map Kapisillit 64 V.2 Syd (in preparation).

The sampling of rock samples was focussed on collecting representative lithologies and mineralised rocks for subsequent detailed geochemical (major, minor and trace elements) and/or geochronological (U-Th-Pb age dating of e.g. zircon, monazite, titanite etc.) analysis.

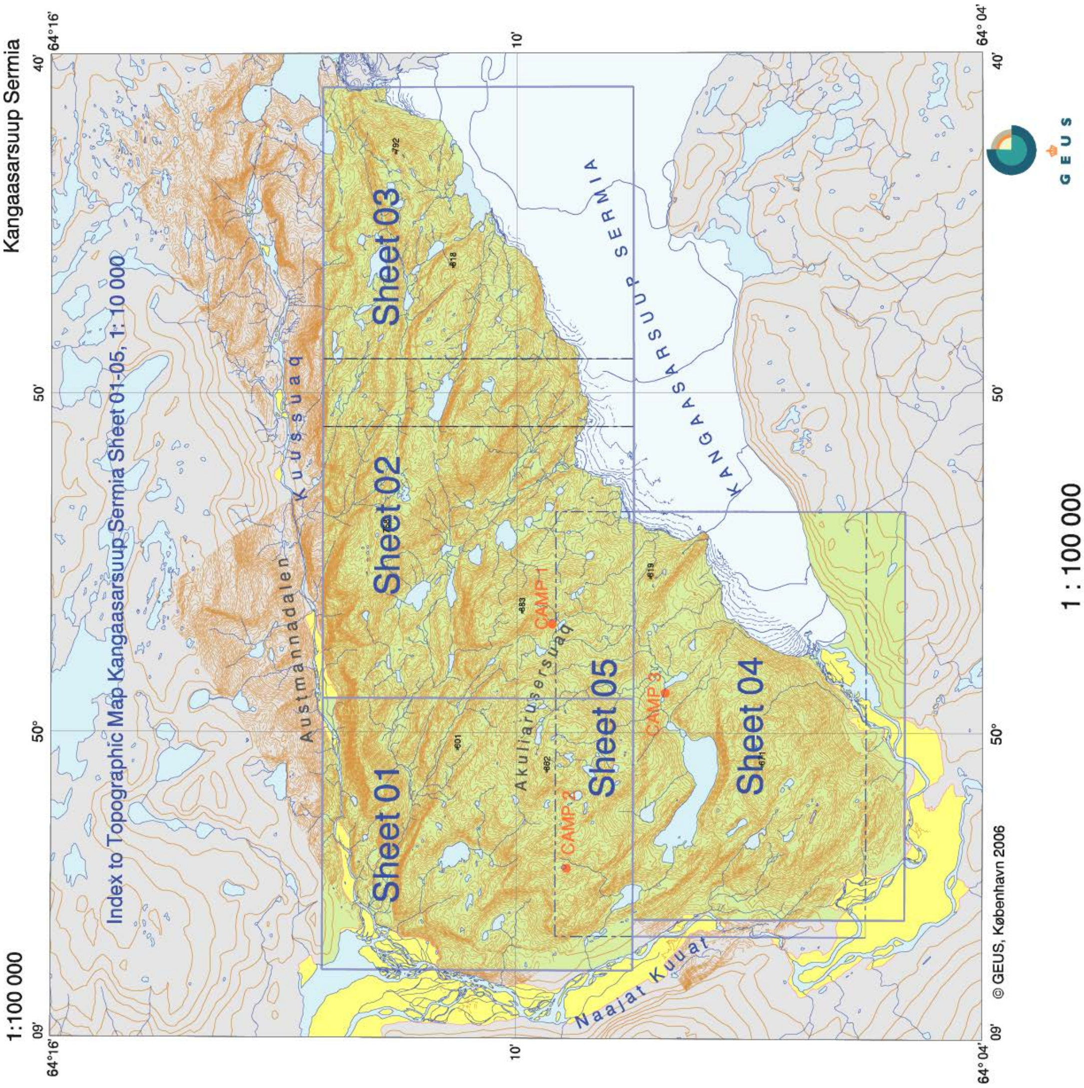

Figure 1. *Index map of the study area showing camp locations.*

Tre Brødre terrane

The Tre Brødre terrane (e.g. Friend & Nutman 2001, 2005) is mainly comprised by the amphibolite facies Ikkattoq gneisses that are dominantly of granodioritic composition. Unpublished SHRIMP U-Pb-zircon ages from Friend and Nutman (personal communication) on the Ikkattoq gneisses shows suggests that their age range is narrow (2820 – 2828 Ma) throughout their extent. Unpublished whole rock Sr, Nd, and Pb isotopic data of the Ikkattoq gneisses (Baadsgaard, personal communication) provides evidence for a significant contribution from older crustal materials. The Ikkatoq gneisses have abundant sequences of gabbro-anorthosite and amphibolites.

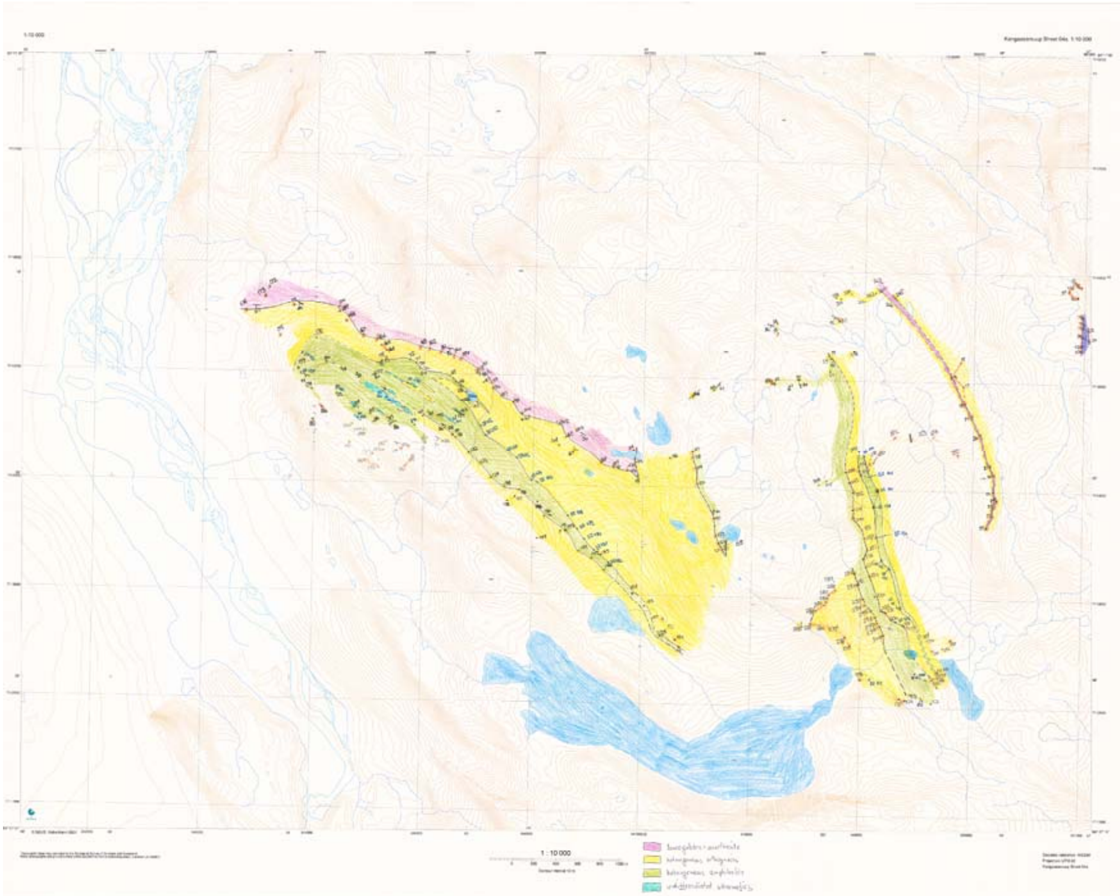

Figure 2. *The field sketch map of mapped areas within the Tre Brødre terrane . Colours: green – amphibolites; purple - ; yellow – heterogeneous orthogneisses; turquoise – ultramafic rocks. One square length is one km and N is upwards.*

Camp 1 – Cross section through layered intrusives (leucogabbros – anorthosites – amphibolites – ultramafics) E of Akuliarusiarssuk

The area north of Camp 1 (64°15.87’ - 49°94.61’; Fig. 1) allowed examining an approximately 1 km thick cross-section through rocks belonging to the leucogabbroic/anorthositic layered intrusives towards the NE of the campsite. The cross-section comprises, in addition to leucogabbros and anorthosites, heterogeneous amphibolites and ultramafic rocks that are interpreted as of igneous origin, i. e. they are most likely representing former mafic to ultramafic cumulate layers within the layered intrusion. Directly at the campsite, the leucogabbro-anorthosite has a transitional contact towards homogeneous orthogneisses in the W and SW. This transitional boundary is marked by a NNE - SSE striking shear zone that is a couple of 100 m wide. All investigated lithologies are regionally metamorphosed at upper amphibolite facies (or even higher) conditions and are highly folded and deformed.

The leucogabbro/anorthosite is medium to coarse grained and occurs either as massive plagioclase layers with very few melanocratic minerals (plagioclase ± amphibole ± biotite ± pyroxene) or as leucogabbro with a higher modal content of melanocratic (dominantly amphibole) minerals and a typical metagabbroic texture. The leucogabbro/anorthosite is usually broken up by orthogneisses into both undeformed and deformed enclaves and boudins.

Towards the E the anorthosite grades into more coarse grained, massive, white rocks. In the vicinity of the transitional contact to the orthogneisses in the W and SSW, the leucogabbro/anorthosite is highly strained and deformed and is best described as anorthositic gneiss (Fig. 3). This anorthositic gneiss is in parts highly migmatised, has a high proportion of pegmatitic veins and is locally epidotised.

Figure 3. *Highly strained anorthositic gneiss close to the transitional contact towards homogeneous gneiss.*

The mafic and ultramafic rocks within the leucogabbro/anorthosite form a layered complex with homogeneous amphibolites and gabbros, leucocratic amphibolites, as well as two approximately 40 m wide ultramafic layers. The ultramafic rocks are unaltered, coarse to medium grained pyroxenite and websterite layers with cumulate textures. These ultramafic layers are partly highly altered and metasomatised to serpentinite. The composition of these ultramafic layers is highly variable (clinopyroxene + orthopyroxene ± amphibole ± plagioclase ± serpentinite ± actinolithe ± chlorite ± garnet ± tremolite ± talc ± olivine ± phlogopite ± sapphirine) and the ultramafic layers show a gradational compositional zonation towards amphibolitic compositions (Fig 4). These dm to m wide amphibolitic layers are in parts penetratively hydrothermal altered with a distinct rusty alteration colour (Fig. 4), but

Figure 4. *Ultramafic cumulate layers in leucogabbro – anorthosite with gradational compositional zoning towards amphibolite. Note the rusty alteration colour of the amphibolites.*

on a macroscopic scale no evidence could be found for distinct mineralisations in these rusty alterated zones.

The area towards the W and SSW of the shear zone comprises an approximately 1000 – 1500 m wide unit of more homogeneous orthogneisses that is tectonically overlain by the Naujat gabbro-anorthosite complex. The contact between the orthogneisses in the foot wall and the leucogabbro/anorthosite in the hanging wall are a series of well defined, dm wide mylonite zones (Fig 5) that are associated with brecciated rocks most likely representing a tectonic breccia. The mylonite contains frequently rotated, up to several cm sized plagioclase blasts (Fig 6 a & b).

Figure 5. *Mylonite zone at the contact between leucogabbro/anorthosite (hanging wall) and dominantly homogeneous orthogneisses (lying wall).*

The medium grained, strongly foliated and folded grey orthogneisses are dominantly of tonalitic composition and are composed of plagioclase + quartz + biotite ± amphibole. The unit has dm to m sized enclaves, leucogabbro/anorthosite and ultramafic rocks as well as dm to m sized pegmatitic and migmatitic leucocratic melt layers and pods parallel to the foliation. Within the orthogneisses, m sized amphibolite layers occur that sometimes can be followed along the strike of the foliation for a couple of hundred m. These amphibolites are showing rusty alteration zones that are dm to m sized and can also be followed along the strike of the foliation (Fig 7).

Figure 6 a upper & b lower. *Cm-sized, rotated plagioclase blast in the mylonite that marks the boundary between leucogabbro/anorthosite (hanging wall) and dominantly homogeneous orthogneisses (foot wall).*

Figure 7. *Dm-sized layer of amphibolite with rusty alteration in homogeneous orthogneisses.*

This leucogabbro/anorthosite sequence is thinning out to the S – SSE; towards the glacier Kangaasarsuup Sermia, only boudinaged m to dm sized blocks of leucogabbro remains and the homogeneous orthogneisses are directly overlain by a sequence of heterogeneous orthogneisses (Fig 8). Directly at the boundary between these two orthogneiss units, a m sized mineralised amphibolitic layer with strong rusty alteration occur. The layer is incorporated into a fold hinge and strikes out into the air. On a macroscopic scale, only pyrite could be identified as mineralisation.

A large, almost N-S striking mafic dyke can be traced through the entire mapping area. The width of the dyke varies between approx. 20 m to just a couple of metres. The dyke has a black to greenish colour and is compositionally very homogeneous (pyroxene + plagioclase). The dyke is homogeneous, generally fine grained and only the central parts of the dyke are slightly more coarse grained and show a weak gabbroic texture. The dyke shows a partly curious granular weathering texture producing peculiar weathering forms (Fig 9). No evidence for mineralisations on a macroscopic scale could be found.

Figure 8. *Boundary between heterogeneous orthogneisses (hanging wall) and homogeneous orthogneisses (lying wall) to the south of camp 1. Note the dm sized boudins of leucogabbro - remains of the thinned-out leucogabbro/anorthosite sequence that overlains the homogeneous orthogneisses to the N.*

Figure 9. *Peculiar weathering forms produced by granular weathering of the large N-S striking mafic dyke.*

Camp 2 and 3 – Lithologically varied unit overlying the Naujat gabbro-anorthosite complex W of Akuliarusersuaq

From Camp 2 (64°15.64' - 50°06.07'; Fig. 1) and Camp 3 (64°13.44' - 49°97.95'; Fig. 1) the lithologically varied unit that structually overlies the Naujat gabbro-anorthosite complex to the W of Akuliarusersuaq was investigated in detail. The lithologically varied units are composed of a thick sequence of strongly folded and foliated, heterogeneous orthogneisses that comprise several layers, homogeneous amphibolites and compositionally very variable ultramafic rocks. The entire unit has been regionally metamorphosed at upper amphibolite facies (or higher) conditions.

The heterogeneous orthogneisses are compositionally very variable, but tonalitic and dioritic compositions dominate, wheras granodioritic and granitic compositions are subordinate. The heterogeneous orthogneisses are medium to coarse grained and of grey to dark grey colour. The mineralogical composition is dominated by plagiclase + quartz + biotite ± amphibole ± garnet ± potassiumfeldspar. All rocks partly show migmatisation and the entire unit can partly contain up to 50 % of leucocratic pegmatites. Especially the contact zones towards the amphibolitic and ultramafic layers are characterised by the frequent occurence of garnet.

Similar to the contact between leucogabbro/anorthosites and the underlying orthogneisses to the E of Akuliarusersuaq, the contact between the leucogabbro/anorthosites (in the lying wall) and the heterogeneous orthogneisses (in the hanging wall) is characterised by a series of well defined, dm wide mylonite zones (Fig 10) that are associated with brecciated rocks (Fig 11) that most likely represent a tectonic breccia. Again, the mylonite contains frequently rotated, up to several cm sized plagioclase blasts (Fig 10).

Figure 10. *Mylonite zone at the contact between leucogabbro/anorthosite (lying wall) and heterogeneous orthogneisses (hanging wall) W of Akuliarusiarssuk. Note the cm sized, rotated plagioclase blasts.*

The amphibolites and ultramafics occur as variably sized layers in the heterogeneous orthogneisses that can be followed along strike or are elongated into the foliation of the gneisses (Fig 12).

The amphibolites are usually homogeneous and form prominent, up to 200 m wide layers that occasionally can be followed for several km along the strike of the foliation, but also occur as several m sized, discontinuous layers. The bluish-grey to dark grey rocks are medium grained and partly distinctively platy breaking. They consist of amphibole + plagioclase ± biotite ± garnet ± pyroxene. All amphibolite layers show rusty alteration zones that are dm to m sized and can also be followed along the strike of the foliation.

Figure 11. *Angular clasts in heterogeneous orthogneiss at the contact between leucogabbro/anorthosite (lying wall) and heterogeneous orthogneisses (hanging wall) W of Akuliarusiarssuk. These clasts are mostly likely tectonic breccias.*

Figure 12. *Layers of homogeneous amphibolites (dark grey) and ultramafic rocks (brownish-green) in heterogeneous orthogneisses.*

Of special interest are the ultramafic rocks that are outcroping in the lithologically varied unit. They usually form discontinuous lenses and layers that are elongated along the strike of the foliation and are several m to 20 m wide and are several tenth of m to a hundred m long. However, one prominent layer occurs that is approximately 75 m wide and several hundred m long. Additionally, small, only m sized pods and lenses occur that are aligned along the strike of the foliation and most likely represent boudinaged layers. The ultramafics consist of orthopyroxene + clinopyroxene + olivine ± garnet ± serpentine ± phlogopite ± sulfides. The ultramafics show a very wide range of compositions comprising pyroxenites, websterites, dunites and harzburgites. Some of the ultramafic layers provide clear evidence for metamorphic recrystallisation and reaction and are best termed ultramafic schists (Fig 13), whereas others show cumulate textures. The degree of alteration is also highly variable, ranging from complete freshness to complete serpentinisation (Fig 14). Metasomatism is widespread and has lead to the formation of spectacularly coarse grained garnet-biotite felses.

The origin (cumulates, ultramafic intrusions or mantle remnants?) and genesis of these mineralogical and textural highly heterogeneous ultramafic rock suites, is unknown and we suggest to carry out further in-depth petrologic and geochemical investigations to clarify the origin and evolution of these rocks.

Figure 13. *Strongly foliated ultramafic schist consisting of elongated olivine + clinopyroxene.*

Figure 14. *Thin weathering crust on serpentinite.*

Concluding remarks

Detailed mapping in the Naujat gabbro-anorthosite complex and its country rocks during the GEUS 2006 field season allows drawing the following conclusions

- The investigated gabbro-anorthosite complex is predominantly composed of relatively homogeneous leucogabbros and anorthosites with minor intercalations of mafic and ultramafic sequences. These intercalations most likely represent mafic and ultramafic cumulate layers and can thus be regarded as formed during the magmatic evolution of the layered mafic intrusion. So far no evidence has been found for the existence of cumulate layers that contain valuable mineral occurrences (e.g. chromite cumulates).
- The extent of the entire gabbro-anorthosite complex exposed at Naujat is smaller than previously believed.
- The Naujat gabbro-anorthosite complex is underlain by a lithological varied series comprising heterogeneous orthogneisses and homogeneous, mainly tonalitic orthogneisses intercalated with amphibolites and ultamafics that have been regionally metamorphosed and deformed at amphibolite facies (and partly higher) conditions.
- The heterogeneous orthogneisses represent a series of multiple intrusions comprising tonalitic, dioritic, granodioritic and granitic rocks that locally contain large proportions of leucocratic pegmatites. The intrusion of both heterogeneous and homogeneous orthogneisses obscured the primary igneous layering.
- The mafic and ultramafic rocks exposed in the lithological varied sequence show a wide compositional and textural range. Origin and genesis, especially of the ultramafic rocks (cumulates, ultramafic intrusions or mantle remnants?), is unkown and should be the focus of further detailed petrological and geochemical investigations.
- The widespread occurrence of tectonic breccias and ultramylonitic zones at the boundary between the Naujat gabbro-anorthosite complex and its country rocks provides evidence for a tectonic juxtaposition of both units, most likely during amphibolite to greenschist facies metamorphism.
- All amphibolitic rocks exposed, regardless of their tectonic position (whether they occur in the gabbro-anorthosite complex or in the lithological varied sequence) show zones of rusty alteration. These zones are generally only m – dm wide and can be traced for long distances along the strike of the amphibolites. The rusty alterated zones are generally mineralised with pyrite.

SAMPLES					
locality	**sample_number**	**type of**	**description**	**Latitude**	**Longitude**
2006DF013	**496601**	RS/RSC	rusty alterated ultramafic boudin in heterogenous amphibolite	64.16501	-49.938880
2006DF013	**496602**	RS/RSC	rusty alterated ultramafic boudin in heterogenous amphibolite	64.16501	-49.938880
2006DF015	**496603**	RS	heterogeneous amphibolite	64.16544	-49.941450
2006DF015	**496604**	RS/RSC	pyroxenite (cumulate layer in amphibolite)	64.16544	-49.941450
2006DF015	**496605**	RS	leucocratic, heterogeneous, gt-bearing amphibolite	64.16544	-49.941450
2006DF006	**496606**	RS/RSC	coarse grained, partly metasomatised pyroxenite	64.16804	-49.939920
2006DF001	**496607**	RS	coarse grained, gt-cpx-bio-gneiss	64.15864	-49.945930
2006DF027	**496608**	RSC	highly alterated, mineralised layer in metagabbro	64.14727	-49.968580
2006DF027	**496609**	RS	highly alterated, mineralised layer in metagabbro	64.14727	-49.968580
2006DF027	**496610**	RS	highly alterated, mineralised layer in metagabbro	64.14727	-49.968580
2006DF028	**496611**	RS/RSC	fine-grained basaltic dyke	64.16122	-49.950470
2006DF028	**496612**	RS	coarse-grained, pyroxenitic dyke	64.16122	-49.950470
2006DF028	**496613**	RS	coarse-grained, mafic dyke	64.16122	-49.950470
2006DF028	**496614**	RS/RSC	medium- to fine grained mafic dyke, partly mineralised	64.16122	-49.950470
2006DF034	**496615**	RS/RSC	rusty alterated zone in amphibolite	64.16336	-50.011540
2006DF035	**496616**	RS	quartzite with fsp-clasts	64.16302	-50.009090
2006DF039	**496617**	RS	olivine-bearing ultramafic rock	64.15992	-49.999610
2006DF039	**496618**	RS/RSC	rusty alterated, partly mineralised, gt-amphibolite	64.15992	-49.999610
2006DF042	**496619**	RS/RSC	olivine-bearing ultramafic rock	64.15745	-50.006600
2006DF045	**496620**	RS/RSC	rusty alterated zone in amphibolite	64.15826	-50.076750
2006DF052	**496621**	RS/RSC	ol-sp-bearing ultramafic body in amphibolite	64.15557	-50.088100
2006DF052	**496622**	RS/RSC	coarse-grained, bio-rich ultramafic rock	64.15234	-50.026690
2006DF068	**496623**	RS/RSC	metasomatic reaction rim around coarse-grained, ol-cpx-bearing ultramafic rock	64.15234	-50.026690
2006DF068	**496624**	RS/RSC	coarse grained, ol-cpx-bearing ultramafic rock	64.15234	-50.026690
2006DF087	**496625**	RS/RSC	felsic clast in heterogeneous tonalitic-dioritic gneiss	64.15937	-50.068800
2006DF093	**496626**	RS/RSC	tonalitic gneiss with relictic magmatic structures	64.16172	-50.093920
2006DF094	**496627**	RS/RSC	heterogeneous, gt-bearing tonalitic gneiss	64.15983	-50.098740
2006DF099	**496628**	RS/RSC	mineralised, ol-bearing ultramafic rock	64.15490	-50.095810
2006DF102	**496629**	RS/RSC	mineralised, gt-bearing amphibolite	64.15854	-50.076400
2006DF103	**496630**	RS	gt-bearing amphibolite	64.15848	-50.076780
2006DF105	**496631**	RS	ol-cpx-opx-trem-act-bearing ultramafic rock	64.15789	-50.075940
2006DF105	**496632**	RS	ol-cpx-mag-bearing ultramafic rock	64.15789	-50.075940
2006DF106	**496633**	RS	ol-bearing ultramafic gneiss	64.15778	-50.076410
2006DF107	**496634**	RS	massive, coarse-grained amphibolite	64.15756	-50.076610
2006DF109	**496635**	RS	heterogeneous amphibolite	64.15686	-50.078980
2006DF110	**496636**	RS	highly altered, ol-bearing ultramafic rock % olivine sand	64.15680	-50.080630
2006DF111	**496637**	RS/RSC	phlogopite-garnet-fels	64.15649	-50.082010
2006DF111	**496638**	RS	ultramafic gneiss	64.15649	-50.082010
2006DF112	**496639**	RS	dunitic ultramafic gneiss	64.15609	-50.082870
2006DF112	**496640**	RS	ultramafic gneiss	64.15609	-50.082870
2006DF112	**496641**	RS	dunitic ultramafic gneiss	64.15609	-50.082870
2006DF113	**496642**	RS	gt-amphibolite	64.15561	-50.082480
2006DF115	**496643**	RS	serpentinised, sulfide-bearing, massive ultramafic rock	64.15562	-50.087890
2006DF115	**496644**	RS	tonalitic gneiss	64.15562	-50.087890
2006DF115	**496645**	RS	mafic-dense gt-amphibolite	64.15562	-50.087890
2006DF121	**496646**	RS/RSC	gt-ms-bio-fsp-qtz.bearing gneiss	64.09349	-50.062000
2006DF123	**496647**	RS	impure quartzite	64.09731	-50.014700
2006DF144	**496648**	RS	ultramafic schist	64.14996	-49.992570
2006DF131	**496649**	RS/RSC	impure quartzite	64.13913	-49.985800
2006DF131	**496650**	RS/RSC	massive amphibolite	64.13913	-49.985800
2006DF154	**496651**	RS/RSC	coarse-grained, granitic gneiss	64.16457	-49.992520
2006DF161	**496652**	RS	serpentinite with sulfide mineralisations	64.13420	-49.982560
2006DF161	**496653**	RSC	serpentinite with sulfide mineralisations	64.13420	-49.982560
2006DF161	**496654**	RS/RSC	bio-act-fels	64.13420	-49.982560
2006DF162	**496655**	RS	ultramafic rock	64.13423	-49.983730
2006DF163	**496656**	RS	amphibolite	64.13374	-49.983230
2006DF166	**496657**	RS/RSC	massive greenish fels		
2006JKM272	**496658**	RS	ultramafic xenolith in amphibolite	64.13133	-49.980033

Table 1.

References

Allaart, J.H. 1982: Geologisk kort over Grønland, 1:500 000, Sheet 2 Frederikshåb Isblink - Søndre Strømfjord. Copenhagen: Grønlands Geologiske Undersøgelse.

Escher, J.C. & Myers, J.S. 1975: New evidence concerning the original relationships of early Precambrian volcanics and anorthosites in the Fiskenæsset region, southern West Greenland. Rapport Grønlands Geologiske Undersøgelse, **75**, 72–76.

Escher, J.C. & Pidgeon, R.T. 1976: Field mapping of nunatak 1390 m, east of Alángordlia, southern West Greenland. Rapport Grønlands Geologiske Undersøgelse, **80**, 84–87.

Friend, C.R.L. & Nutman, A.P. 2001: U - Pb zircon study of tectonically bounded blocks of 2940 - 2840 Ma crust with different metamorphic histories, Paamiut region, South-West Greenland: implications for the tectonic assembly of the North Atlantic craton. Precambrian Research **105**, 143 - 164.

Friend, C.R.L. & Nutman, A.P. 2005: New pieces to the Archaean terrane jigsaw puzzle in the Nuuk region, southern West Greenland: steps in transforming a simple insight into a complex regional tectonothermal model. Journal of the Geological Society, London **162**, 147 - 162.

Hollis, J.A., Schmid, S., Stendal, H., van Gool, J.A.M. & Weng, W.L. 2006: Supracrustal belts in Godthåbsfjord region, southern West Greenland. Progree report on 2005 field work: geological mapping, regional hydrothermal alteration and tectonic sections, 171 pp plus 1 DVD, Geological Survey of Denmark and Greenland, Copenhagen, 2006/7).

Kalsbeek, F. & Garde, A.A. 1989: Geologisk kort over Grønland, 1:500 000, Sheet 2 Frederikshåb Isblink - Søndre Strømfjord. Descriptive text, 36p. Copenhagen: Grønlands Geologiske Undersøgelse.

Geological Environments: Oceanic crust and hydrothermal alterations - Field report 2006

By Henrik Stendal & Anders Schérsten

Geological Survey of Denmark and Greenland (GEUS)

Nunatak 1390 in the background. All black rocks are mafic volcanic rocks (greenstones).

Introduction

During the field campaign in the Nuuk region, one of the objectives was to describe Archaean primary geological environments (Hollis *et al.* 2006). The investigations were carried out in the northern part of the Tasiusarsuaq terrane (Fig. 1, 2). At Nunatak 1390 a well preserves bimodal volcanic succession was interpreted as a former ocean floor environment. The investigation comprised geological mapping of a volcanic sequence of mafic- to ultramafic rocks, acid volcanic rocks and granite intrusions.

Available published GEUS/GGU 1:500 000 Frederikshåb Isblink - Søndre Strømfjord geological map sheet (Allaart 1982), four 1:100 000 map sheets (Qorqut 64 V.1 Syd (1983), Buksefjorden 63 V.1 Nord (Chadwick & Coe 1983), Kangiata Nuna 63 V2 Nord (1981), and an unpublished sketch of the Kapisillit map sheet form the basis for the selection of work areas. Further descriptions and references of the involved areas can be found in Appel *et al.* (2003, 2005), Chadwick & Coe (1983), Eilu *et al.* (2006), Garde (1997), Hollis *et al.* (2004, 2006), Hollis (2005), McGregor (1993), Nielsen *et al.* (2004), and Stensgaard *et al.* (2006).

Detailed mapping was made on 1:10.000 scale topographic map sheets (Isortuarsuup) produced by the Geological Mapping Department at GEUS. The maps used are Isortuarsuup map sheets # 4, 6 and 11. These maps lie within the 1:100.000 Geological map Kangiata Nuna 63 V2 Nord (1981). Detailed geological field maps from the GEUS archives (1:20.000 scale geological field maps) from the GGU campaign 1973 – 1975 were used for background data.

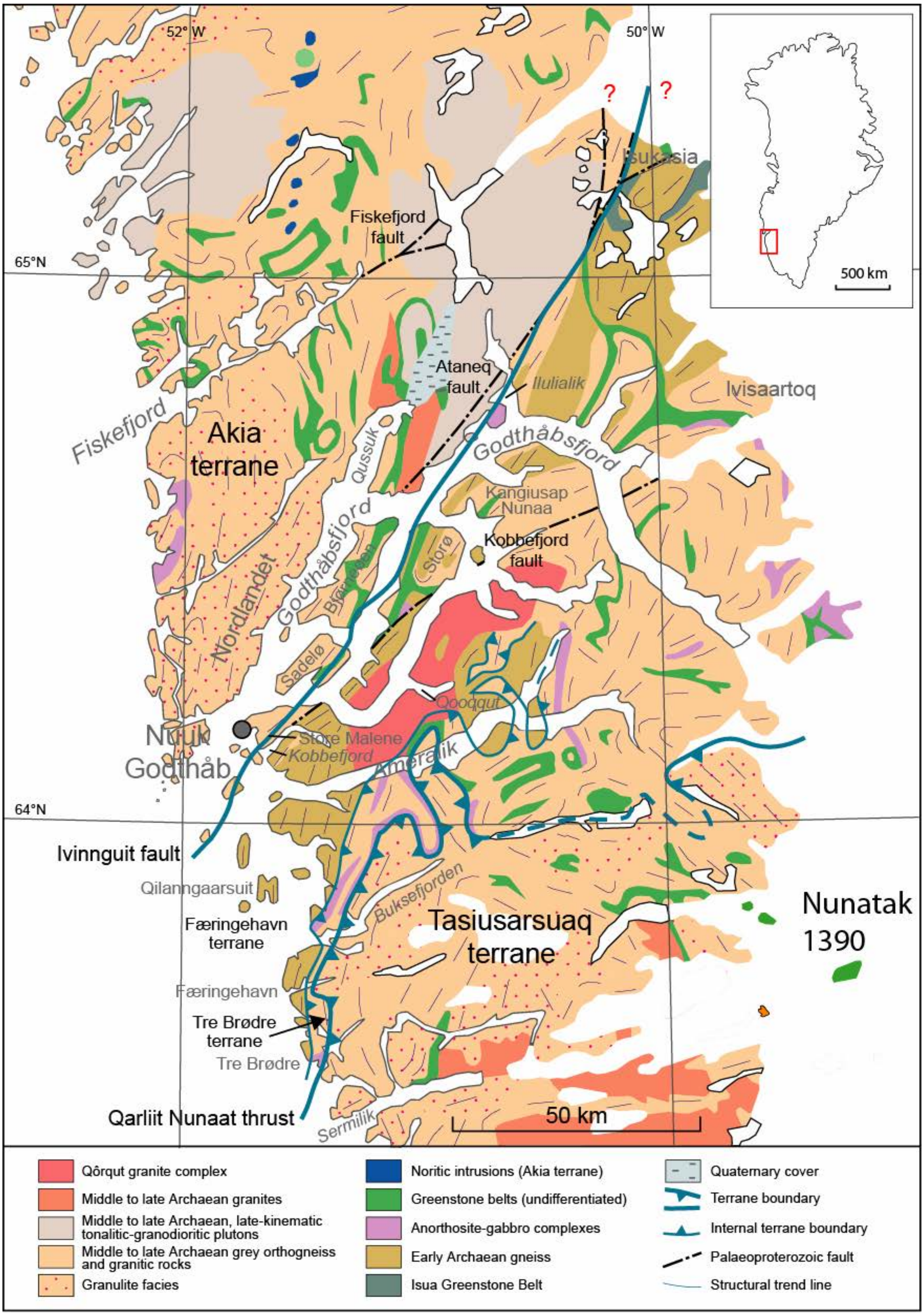

Figure 1. *Geological map of the Nuuk region and location of the Nunatak 1390 study are modified after Escher & Pulvertaft (1995). The Tasiusarsuaq terrane in the southern part of the map.*

Ocean floor environment

The aim of the fieldwork was to improve the understanding of the relationships and evolution of mafic rocks (greenstone belts) with respect to their genesis and their mineral potential, especially precious metals. The field work focussed on the area southeast of Kangerdluarssenguup taserssua (Fig. 1). The investigations comprised geological mapping of selected areas and investigations of hydrothermal alterations for possible gold-bearing rocks. The detailed studies included mafic- to ultramafic sequences and granitoids in the Tasiuarsuaq terrane southeast of Kangerdluarssenguup taserssua.

The sampling of rock samples of representative lithologies and mineralised rocks (Table 3) was carried out to obtain analyses of both major and minor elements. Some of the samples will be used for age dating.

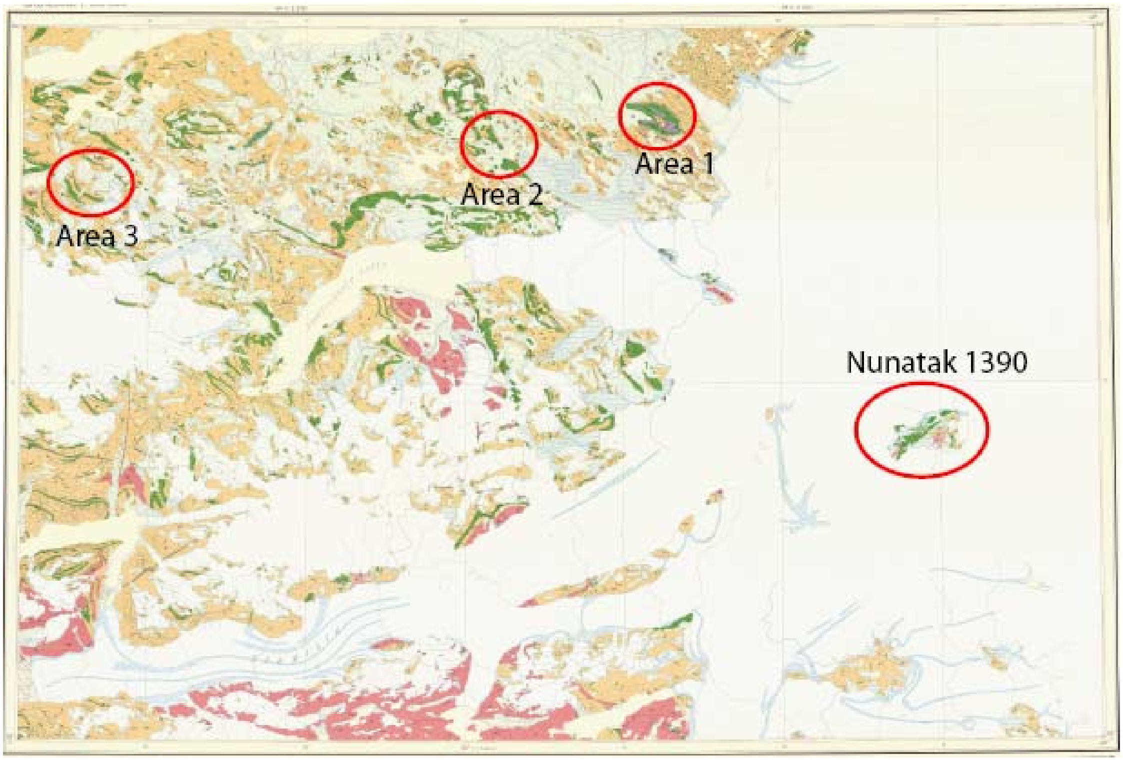

Figure 2. *The Kangiata Nunamap sheet63 V2N. Index of study areas.*

Tasiuarsuaq terrane

The Tasiuarsuaq terrane (e.g. Friend & Nutman 2001, 2005) southeast of Kangerdluarssenguup taserssua (Kang) is dominated by mafic rocks (amphibolite), tonalitic to granodioritic gneisses. The mafic rocks comprise pillowed amphibolite (calc-silicate alteration), massive amphibolite (gabbroic), and ultramafic pods and dykes. Dimensions of these mafic complexes ranges from 50 up to more than 1000 m, and they are intruded by the country rock granitoid gneisses and cross-cut by brown-weathered dolerite dykes (up to 30 m wide) with well developed chilled margins and generally strike E-W. Alterations are common within the amphibolites such as calc-silicate formation within pillowed lava sequences. The pillowed mafic sequences have intercalations of 1 – 2 m wide rusty, sulphide-bearing layers (exhalites), which consist of pyrite, pyrrhotite, chalcopyrite and occasional arsenopyrite. Occurrences of garnet-sillimanite-biotite-sulphide rocks represent another prominent alteration type in the area, post-dating the granitoid formation.

Mapping area 1

The mapping area 1 (Figs. 1, 2, 3) is located 20 km NE of Isortuarssuup tasia (63°56.29' - 49°40.62') and the main lithologies are given in the Table below.

Lithology	Thickness (m)	Comments
Mafic dyke	1 - 30	Undeformed Palaeoproterozoic brown dykes
Alteration(rusty rocks)	5 – 50	Alteration along fault/shear zones and sulphide formation
Granitoids		Tonalite (gneiss) and granodiorite/pegmatite (two generations)
Ultramafic pillows	1 – 10	10 – 30 cm large pillows with magnetite
Ultramafic dykes	1 – 30	Feeder dykes (peridotites) for the ultramafic pillows
Mafic volcanic flows/ash	>200	Gabbro flows dominate but intercalated with mafic pillows (see below)
Mafic volcanic pillows	50 – 100	5 – 50 cm large pillows, pillow breccias and calc-silicate alterations
Pyroxenites/harzburgite	>500	Pyroxenites dominate

Table 1. *Lithostratigraphy of area 1.*

The lowest part of the sequence consists of ultramafic cumulates (>500 m) that are dominated by pyroxenites and minor harzburgites. The pyroxenites comprise coarse-grained orthopyroxene with minor fine-grained clinopyroxene, phlogopite and olivine. The mafic volcanic pillow sequence has some well preserved but deformed pillows, which are 5 – 50 cm large (Fig. 4) and the sequence has pronounced calc-silicate alteration with epidote, diopside and actinolite. Minor rusty layers (exhalites) occur within the pillow sequence and carry a few volume % of iron sulphides. The pillowed mafic rocks are overlain by gabbro and amphibolite. The gabbroic rocks are mafic coarse-grained volcanic flows (1 – 10 m thick) with m-thick finegrained amphibolites (ash layers) between the flows.

The pyroxenites/harzburgites and the mafic volcanic extrusions are all cut by an ultramafic dyke swarm (1 – 30 m thick) with nicely developed chilled margins. The rocks are called peridotite as a field term. These dykes are feeder dykes for ultramafic pillows (10 – 30 cm; Fig. 5) and often have a dark chilled margin and matrix between the pillows. The composition of the peridotite is dominated by olivine and coarser grained orthopyroxene. Both the dykes and the pillows have several volume percentage of magnetite.

All the mafic to ultramafic rocks are intruded by granitoids. The first intrusion event is the tonalite which appears as gneiss around and as intrusive part in the centre of the mafic-ultramafic complex. A later intrusive rock is granodiorite that preserves intrusive relationships with the mafic-ultramafic complex. The granodiorite is deformed but not as much as the tonalite. Pegmatites formed contemporaneously with the granodiorite, both as irregular bodies (~10 m^2) and as veins.

Rust zones along fault/shear zones occur very pronounced in the middle part of the mafic complex. This is a biotite alteration zone where the amphibolite is altered with some Fe sulphides. One specific zone is up to 50 m wide but other rust zones are 1 – 10 m wide. The rust zones contain/are intruded by minor veins of granodiorite and pegmatite.

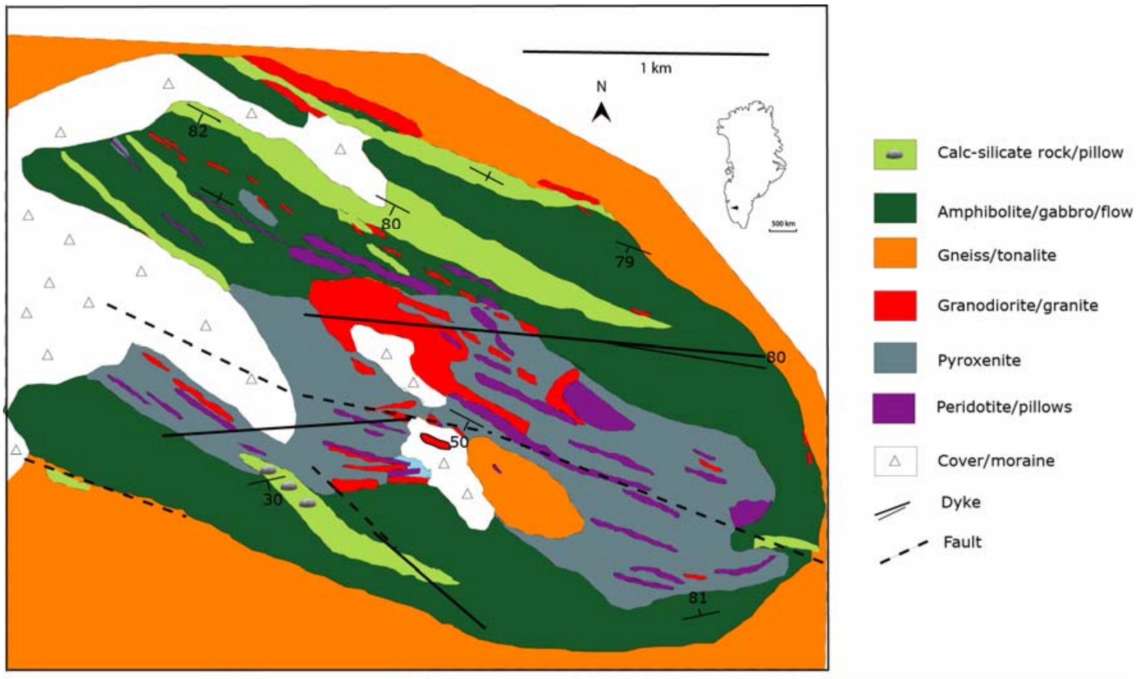

Figure 3. *Geological map of Area 1.*

Figure 4. *Deformed pillow lava from Area 1.*

Figure 5. *Ultramafic pillow lava from Area 1. The pillows contain olivine and coarser grained orthopyroxenes.*

Mapping area 2

The mapping area 2 was visited in 2005 (Hollis *et al*. 2006). It was revisited because of the indication of gold and arsenic in the region. The study area contains amphibolite deduced to have originated as a pillowed mafic volcanic sequence. The mafic sequence has a similar ultramafic pillow sequence and magnetite-bearing amphibolite as observed in ‘Mapping area 1’, but the rocks here are generally more deformed and at higher metamorphic grade. The amphibolites have plenty calc-silicate minerals (diopside, epidote and ±garnet) and intercalations of 1 – 2 m wide rusty, sulphide-bearing layers (exhalites; Fig. 6). The sulphides are pyrite, pyrrhotite, chalcopyrite and arsenopyrite. It is worth noting that this area is the only place outside Storø, which carries arsenic in considerable amounts. Analytical results from 2005 (Hollis *et al*. 2006) yielded gold in one sample with 456 ppb Au and 1.48% As. The mafic rocks have some Cu up to 0.16%. The arsenopyrite-bearing rusty amphibolite is either an exhalite or an altered amphibolite layer with some garnet formation. It was not possible to follow the mineralised layer over long distances due to coverage with mainly talus material.

The granitoids in the area comprise tonalitic gneiss and a later intrusive granodiorite. Both granite phases are intrusive into the mafic package. The region is crosscut by brown-weathered dykes (up to 30 m wide), which generally strikes roughly E-W and probably are Palaeoproterozoic in age.

Figure 6. *Rusty sulphide-bearing layers in amphibolite*

Nunatak 1390

The mapping area 3 is called ‘Nunatak 1390 m East of Alangordlia’ by (Escher & Pidgeon (1976) and is located 63°42.96’ - 49°16.89’ (Figs. 1, 2, 7). The main rock types are greenschist facies mafic and acid volcanic rocks and granitoids. The main rock units are given in the Table 2 and parts of the stratigraphy in shown in Fig. 8.

Rock type	Thickness (m)		Comments
Mafic dyke	1 – 20		Undeformed Palaeoproterozoic brown dykes
Granite(s)		B	Porphyritic granite, altered granite and pegmatite
Tuff	700 - 800		Finely laminated ash layers intruded by granitoids
Hydrothermally altered zone	50	D	Altered mafic ash – silicified and epidotised rocks
Mafic volcanic flows/ash	120		Basaltic-komatiitic/mafic-ultramafic flows and ashes, intercalated with ultramafic sills, mafic rusty layers, sulphides (exhalites) and tourmalinites
Acid flows and pyroclastites	80		Acid lava flows and ignimbrites
Upper mafic volcanic pillows	~200	C	25 – 100 cm large pillows, pillow breccias and calc-silicate alterations
Ultramafic greenstone	10 – 50	A	Ultramafic sill between lower and upper pillow sequence
Lower mafic pillow sequence	>500		Deformed pillow lavas with extensive calc-silicate alterations that are cut by mafic dikes

Table 2. *Lithostratigraphy of Nunatak 1390.*

The lower mafic pillow sequence consists of 50 – 100 cm large deformed pillows and pillow breccias with calc-silicate alteration in the matrix between the pillows and in the centre of the pillow. The calc-silicate minerals are epidote, diopside and carbonates and comprise up to 20 vol% of the rock. The pillowed sequence is cut but by a slightly deformed mafic dyke swarm (1 – 5 m in thickness) striking more or less E-W. The dykes are fine- to middle-grained gabbroic or noritic rocks.

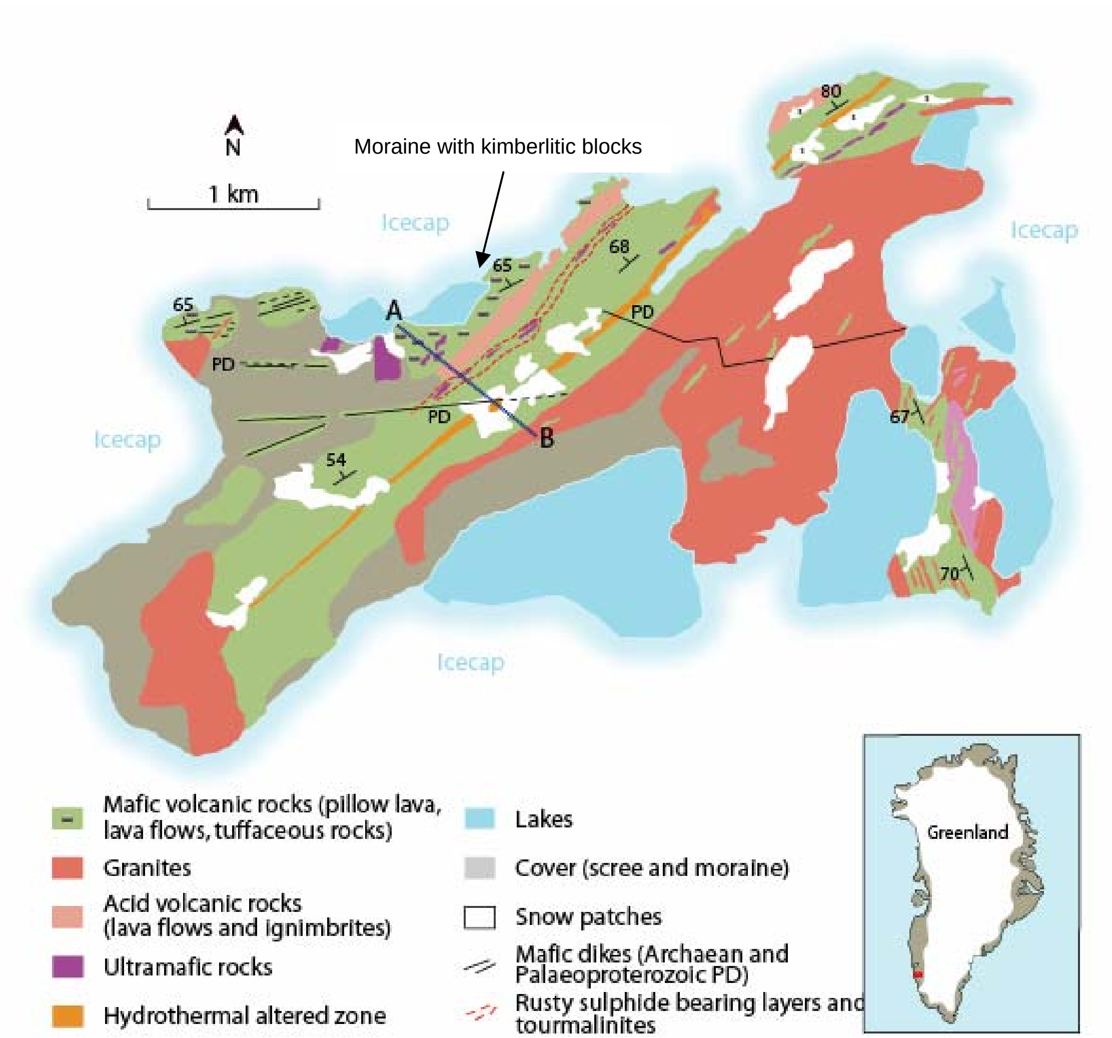

Figure 7. *Geological map of Nunatak 1390.*

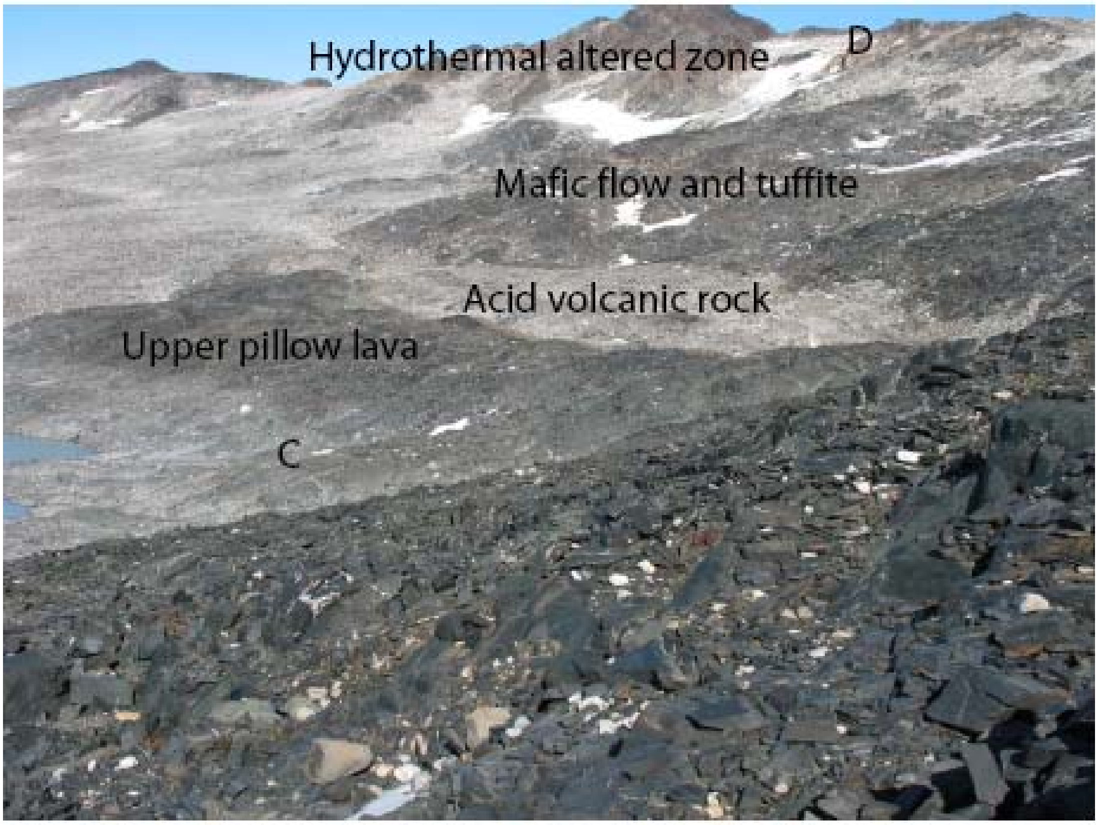

Figure 8. *Central part of the stratigraphy of profile A–B on Nunatak 1390.*

Figure 9. *Pillow lava structures in the upper pillow lava sequence.*

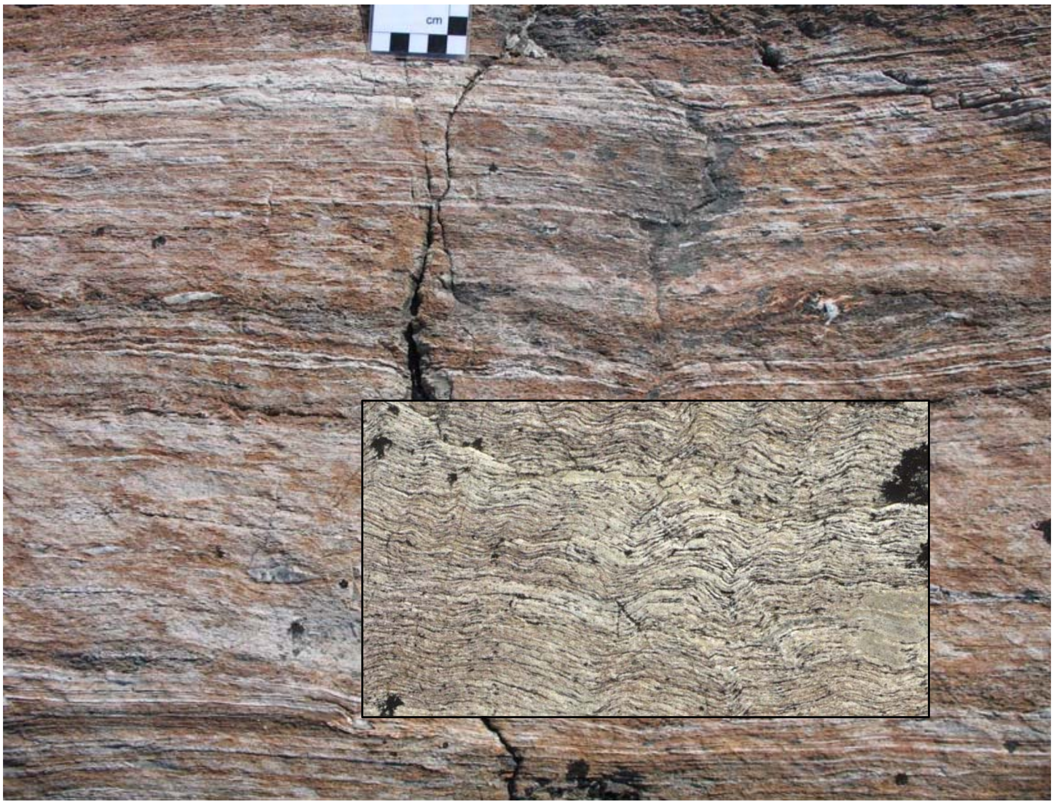

Figure 10. *Laminated acid volcanic rock (ignimbrite). Insert lower right is an enlargement (insert is about 5 cm wide).*

Figure 11. *Intrusive granite into amphibolite.*

Ultramafic greenstones/soapstones occur between the upper and lower pillow lava sequences. These magnetite bearing greenstones/soapstones are interpreted as sills. The upper pillow sequence has very well preserved primary structures such as pillows (Fig. 9), lava flows and ash layers. The least deformed pillow lavas and flows contain relic/preserved vesicles. Way-up criteria of the mafic sequence (is easy to determine) from the pillow structures and consistently point to the south. Interbedded in the mafic flows and pyroclastics is 80 m of acid volcanic rocks. The rocks are acid flows and and pyroclastic rocks (Fig. 10) and fine laminated ignimbrites. Fine-grained grey to light porphyritic dykes 0.3 – 0.8 m wide) cut the mafic and the volcanics and are interpreted as feeder dykes to the acid rocks. Superimposed on the acid volcanics consists of gabbroic flows and ashes with intercalation of ultramafic sills, mafic rusty layers with sulphides (exhalites) and tourmalinites. The latter is an up to one metre thick layer located between the ultramafic bodies and fine laminated ash layers. The sulphides in the rusty layers are iron sulphides with minor chalcopyrite.

A prominent strike parallel hydrothermal zone strongly silicified and epidotised mafic ash layers, which appears like hornfels. The hydrothermal altered zone is up to 50 m wide and light brownish in colour on the surface. The hydrothermal zone follows a fault lineament. The hanging wall of the hydrothermal zone comprises a thick sequence of finely laminated tuff layers. Granite intrusion abundance increases upwards and eventually dominates with tuff xenoliths.

Two phases of granite occur, one porphyritic with K-feldspar phenocrysts up to several cm in length and nearly isotropic. The other granite phase is more homogeneous, medium-grained, foliated and muscovite-bearing (Fig. 11). Parts of the granites especially in the western part are altered and have a distinct pink colouration probably due to hematite formation in the granite.

Geochemistry

Twenty samples representing most rock types found on Nunatak 1390 were analysed by Actlabs, Canada. The data fall into three subsets in MgO variation diagrams. One subset represents mafic pillow sequence, where the samples plot within the Mg- and Fe-tholeiite basalt fields (4.5–10 wt% MgO) in a Jensen cation classification diagram, which is used instead of the TAS diagram to avoid the effects of disturbed alkali element contents. The interbedded acid volcanic rocks constitute dacites (63.8–72.8 wt% SiO_2) and an andesite (55.1 wt% SiO_2) and forms the second subset. The mafic-ultramafic sills and ash layers form the third subset and classify as komatiite, komatiitic basalt and Mg- and Fe-tholeiitic basalt. The komatiitic affinities have 16–21 wt% MgO, TiO_2 <0.65 wt% and 47.4–50.4 wt% SiO_2, and are compositionally distinct from the basalts with an SiO_2 concentration gap between 10–16 wt%. Collectively, the mafic-ultramafic rocks plot along a single tholeiitic trend, while the acid rocks plot along a loosely defined calc-alkaline trend (Fig. 12). Bivariate plots against MgO illustrate a number of contrasting features between the tholeiites and calc-alkaline series. For instance, the tholeiites are invariant with respect to iron, while the calc-alkaline rocks yield a strong positive correlation.

Trace element abundances corroborate the differences between the tholeiites and calc-alkaline rocks, but also show similarities that may be important as tectonic discriminators. Ce/Pb ratios do not appear to vary with Ce (Fig. 13A), and have an average of 3 ±1 (1σ; n=11), which is considerably lower than Primitive Mantle (PM; ~10), modern Mid Ocean Ridge Basalt (MORB; ~25) or modern Ocean Island Basalt (OIB, ~25). In fact, this mode of Pb-enrichment is typical for supra-subduction rocks (Chauvel *et al.*, 1995), and may be indicative of modern style arc processes. It should be noted that the pillow lavas have Pb below detection limit for all samples but one, which straddles the detection limit. The Ce/Pb ratio for this sample is associated with great analytical error and the Ce/Pb ratio may be underestimated. It thus remains uncertain whether the pillow lavas share the arc signature or whether they formed as oceanic volcanic crust upon which the arc rocks were deposited. Overall, immobile trace elements in the pillow basalts are relatively similar to MORB. The tholeiites are characterised by flat REE profiles (median La/Yb_N = 1.8) while the dacites have steeper REE profiles with La/Yb_N ranging from 15–47 (Fig. 13B). By analogy with modern arc systems, this may reflect input from trench-side and back arc-side volcanoes respectively, or temporal shifts in the petrogenetic processes.

Interpretation

The volcanic rocks on Nunatak 1390 consist of a bimodal succession, which was metamorphosed in greenshist facies.The overall preservation of primary textures and structures is unusually good for West Greenland. While the age of the complex remains unknown, it is assumed to be within the range of the Tasiuarsuaq terrane (2.92–2.86 Ga). Preserved tholeiitic pillow basalts and calc-alkaline associations resembles modern arc systems. Bimodal volcanism might reflect input from trench side and back arc side volcanoes respectively. On a regional scale, it should be noted that western and southern parts of the Tasiusarsuaq terrane preserve remnants of volcanic rocks at several localities, probably of similar age to that on Nunatak 1390 (Escher & Myers 1975).

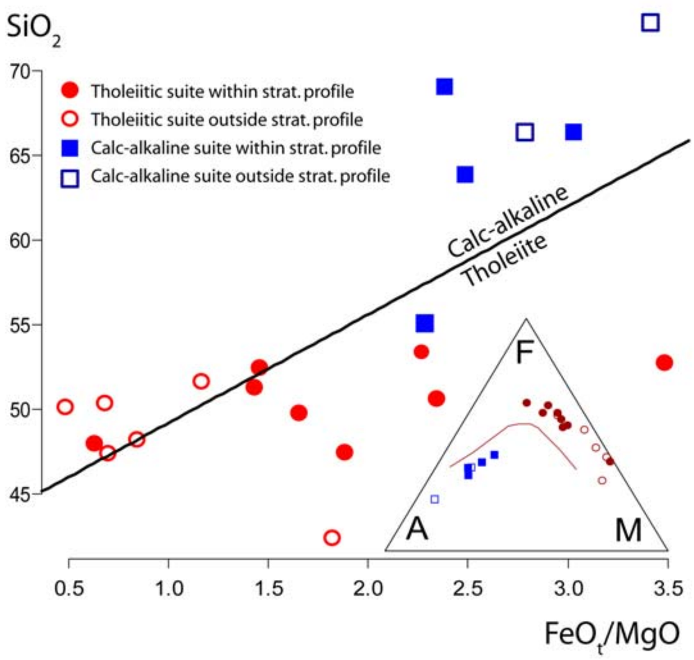

Figure 12. *FeO_t/MgO versus SiO_2 variation diagram, and an AFM diagram.*

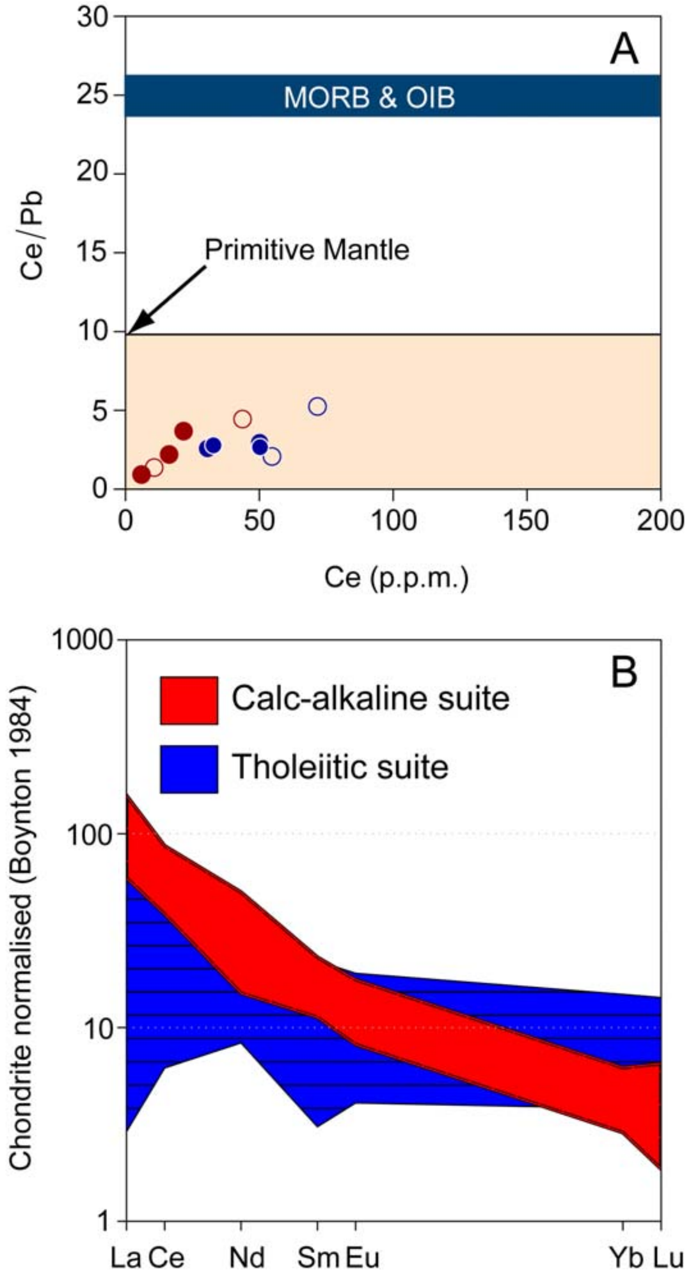

Figure 13 *A: Ce/Pb ratios variation versus Ce. Red symbols = tholeiitic suite. Blue symbols = calc-alkaline suite. B: REE distribution of the tholeiitic suite and calc-alkaline suite.*

The entire volcanic package is generally striking north-east and steeply dipping towards NW. The rocks at the nunatak are the lowest grade of our study areas and metamorphosed in greenschist facies. Despites all the primary textures the rocks are slightly to moderately deformed with lineations, folding, faulting and shearing.

Other areas

The mapping areas 1, 2 and Nunatak 1390 above are all located on the Kangiata Nuna map sheet. Reconnaissance by helicopter was carried out with the aim to investigate the amphibolites on a regional scale and to cover the map sheet (Fig. 14). The overall impression is that all the mafic sequences originated as extrusive mafic volcanic rocks as described above. Samples of amphibolite, ultramafic rocks and granitoids have been collected for geochemical comparison of the different rock types and age determinations.

Area 3 (63°53.82’ and 50°32.58’; Fig. 2) illustrates a nice example of intrusive relationships of both tonalite and granodiorite into the mafic volcanic package (Fig. 15). Hydrothermal alterations prior to regional metamorphism of amphibolite to rusty garnet-biotite±sillimanite rocks ± sulphides occurred in zones up to a couple of metres wide and continued along strike (Fig. 16). The garnets are 1 – 5 mm in size and have a light pink colour (grossular?). Sulphides are common, especially in the biotite zones. The sulphides are mostly fine-grained pyrite and pyrrhotite placed in a matrix of biotite and quartz but not more than a few volume percent.

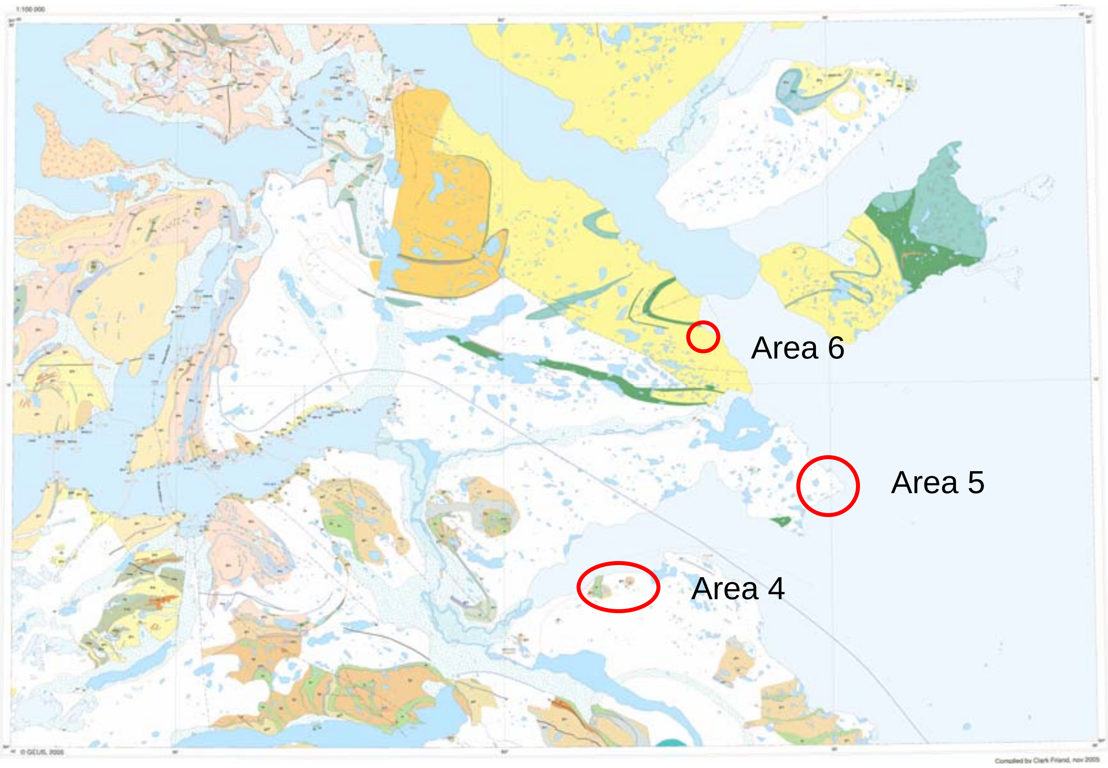

Figure 14. *Prelimanary Kapisillit map sheet with indication of field work areas.*

Figure 15. *Granite intrusion into amphibolite – Area 3.*

Figure 16. *Garnet-sillimanite-biotite alteration with iron sulphides. The white rocs is grano-diorite/pegmatite – in Area 3.*

Figure 17. *Hydrothermal alteration of gneiss, granitoid and amphibolite – in the area south of Ameralik.*

Qorqut 64 V. 1 Syd map sheet

South of Ameralik

One locality was investigated in the area south of Ameralik in 2004 (Appel *et al*. 2005), where one big loose block (~1 m^3) was albitized and disseminated with sulphides (pyrite and chalcopyrite). The analyses gave nearly 2% copper and 200 ppb gold. This area was revisited during a reconnaissance together with Bo Møller Stensgaard. The area is located in the vicinity of the transition between the Tasiusarsuaq and Tre Brødre terranes. The quartzo-feldspatic gneisses of the area have been strongly deformed, migmatised and intruded by Ikkattoq gneisses and granite veins of the Qorqut granite complex. Younger supracrustal rocks are intercalated with the Amitsoq gneisses. The supracrustal rocks are amphibolite facies pillow lavas, minor bodies of metagabbros and metadolerite with minor exhalites (quartz-garnet rocks). Magnetite is common in ultramafic and amphibolite rocks. The rusty layers (exhalites) have varying amounts of sulphides, most commonly pyrrhotite with minor pyrite and chalcopyrite.

Extensive hydrothermal alteration occurs along fault/shear zones. The alteration products are garnet-sillimanite-biotite rocks with varying amounts of iron sulphides (e.g. 64°02.67' and 50°48.75'). The alteration zones are found in up to 200 m wide zones and all rock types (gneiss, granites, and amphibolites) are more or less altered (Fig. 17). The altered rocks might be the source for the Cu-Au mineralised loose block reported in 2004.

Kapisillit 64 V. 2 Syd map sheet (Fig. 14)

Qarliit Nunaat – Area 4

Area 4 (64°06.81' and 49°49.12'; Fig 14) was located just south of an east-west striking glacier the area is part of the Kapisillit terrane. It consists of gneiss, amphibolite (gabbro), ultramafic rocks and anorthosite and granitoids (tonalite, granodiorite and pegmatite). The mafic and ultramafic rocks are part of a layered gabbro-anorthosite complex, which is intruded by granitoids. Extensive garnet-bearing rocks occur along an E-W fault zone (parallel with the south side of the glacier) and conjugated fault systems. Garnets are up to 5 cm in diameter and are in some places nearly massive garnet rocks or garnet amphibolites. The garnet has a light pink colour (grossular?). The conjugated fault zones strike ~130° where the extensive alterations of ultramafic to mafic rocks took place (Fig. 18). The size of the area with pronounced alteration is approximately 2.5 km E-W and 0.5 km N-S.

A 0.5 – 2 m thick layer of coarse-grained massive pyrrhotite with minor fine-grained pyrite and chalcopyrite occurs along the steep north facing wall towards the glacier. The mineralised layer occurs at several places approximately 200 m along strike. The ore and host rock are brecciated (Fig. 19) along the E-W fault zone. Veinlets of quartz crosscut the ore zone. The ore zone is thought to consist of primary ore in gabbroic host rock. The garnet rock is in some places accompanied by biotite and iron sulphides. Red to yellow rusty soils is associated with weathering biotite and sulphide rich rocks.

The granite and pegmatite make up ~5 vol. % of the rocks in the hydrothermally altered zone. They occur as 5-10 m wide bands that strike 60° and are discordant to the alteration systems and appears to be unaffected by the alteration event. A few 1 – 2 m thick quartz veins are found in the area.

Figure 18. *Rusty alteration along fault zones.*

Figure 19. *Brecciated massive pyrrhotite ore.*

Nunataaraq – Area 5

Area 5 (64°11.39' - 49°31.78'; Fig. 14) is another area with extensive alteration of the country rock, which is altered to garnet-sillimanite-biotite ±sulphides. The area comprises Amitsoq gneisses and intrusions of tonalite and granodiorite. The granitoids are foliated but clearly intrusive into the Amitsoq gneisses with discordant contacts. The hydrothermally altered area is approximately 1000x200 m and shows pervasive alteration of all rock types but the most altered rock is grey gneiss (granodiorite) and the least altered are pegmatites. The alteration occur in many stages from faint, partly to complete alteration. The main rock type is a garnet-sillimanite rock with up to 20 – 30 volume % of each mineral. In mylonite and shear zones (Fig. 20) biotite and Fe sulphides are added to the garnet-sillimanite together with some silicification. The sulphide content does normally not exceed a few volume % of the rock. The sulphide bearing biotite shear zones are 0.5 – 1 m wide and vary in strike but a NNE-NE trend is common.

Figure 20. *Alteration in a mylonite zone to rusty garnet-sillimanite-biotite rock.*

Kangersuneq SW shore

This site (64°21.38' and 49°50.75') comprises an amphibolite-gabbro-anorthosite complex with abundant garnet-sillimanite-biotite ±sulphide formation in alteration zones. The alteration is similar to the description of several other hydrothermal altered localities above. The most intense rust layers are 2 – 5 m wide and often occur along rock types e.g. between gabbro and anorthosite (Fig. 21). Biotite and sulphide alteration often occurs in narrower bands (0.5 – 1 m) together with silicification within the alteration zone.

Figure 21. *Hydrothermal alteration zones in anorthosites, Kangersuneq SW. To the left the contact is between anorthosite and gabbro. To the right the alteration pattern is more patchy.*

Kimberlitic rocks

A completely new and exciting discovery of kimberlititic rocks was made during investigations of supracrustal rocks on the 10 km^2 large Nunatak 1390 (Fig. 7) in the Inland Ice, *c*. 140 km south-east of Nuuk. We discovered a large number of kimberlitic boulders in a side moraine along the northern side of the Nunatak 1390. The kimberlite erratics occur over a distance of 300 m and are from one cubic centimetre up to 0.5 cubic metres in size (Fig. 22). They have a greyish-greenish appearance with abundant fragments/nodules of crustal, mantle and eclogitic origin such as gabbro, granite, eclogite, pyrope, Cr-diopside etc. The source of the boulders is unknown, as no in situ kimberlititic rocks have yet been seen on the Nunatak 1390.

Figure 22. *One of the kimberlite boulders in the side moraine of Nunatak 1390.*

Tabel 3

Locality	Sample #	Type of sample	Latitude	Longitude	UTM Zone	UTM Easting	UTM Northig	Elevation
2006HST283	499101	Quartz-mica-hbl exhalite with disseminated iron sul-phides	63.914390	-49.935313	22V	552233	7087909	1080
2006HST284	499102	Quartz-mica-hbl exhalite with disseminated iron sul-phides	63.913880	-49.935833	22V	552209	7087852	1058
2006HST286	499103	Rusty amphibolite with disseminated iron sulphides	63.922680	-49.955880	22V	551209	7088817	1400
2006HST286	499104	Amphibolite/hornblende gneiss	-	-	-	-		1400
2006HST287	499105	Dense, fine-grained amphibolite	63.865960	-49.953262	22V	551441	7082499	956
2006HST288	499106	Peridotite with magnetite	63.839210	-49.673787	22V	565236	7079775	938
2006HST289	499107	Fine-grained biotite-amphibole schist	63.840440	-49.677982	22V	565027	7079907	965
2006HST293	499108	Gabbro	63.925370	-49.685873	22V	564444	7089362	1003
2006HST297	499109	Ultramafic pillow with magnetite	63.929150	-49.684569	22V	564499	7089784	1023
2006HST297	499110	Ultramafic pillow with magnetite	-	-	-	-	-	1023
2006HST297	499111	Quartz-feldspar granite	-	-	-	-	-	1023
2006HST297	499112	Ultramafic pillow with magnetite	-	-	-	-	-	1023
2006HST298	499113	Pyroxenite with olivine	63.930610	-49.687085	22V	564373	7089944	1050
2006HST300	499114	Diorite layer in mafic volcanic sequence	63.939380	-49.675031	22V	564943	7090934	1027
2006HST300	499115	Banded amphibolite	-	-	-	-	-	1027
2006HST302	499116	Grey, finegrained granodiorite	63.943510	-49.693335	22V	564037	7091375	872
2006HST303	499117	Coarse-grained gabbro	63.943300	-49.695454	22V	563934	7091349	912
2006HST305	499118	Coarse-grained granite	63.935730	-49.678272	22V	564793	7090523	1083
2006HST306	499119	Mafic dike	63.934640	-49.676271	22V	564894	7090403	1116
2006HST307	499120	Homogene, middle-grained granodiorite	63.934160	-49.677885	22V	564816	7090349	1112
2006HST308	499121	Black pyroxenite with olivine	63.931380	-49.685583	22V	564445	7090031	1063
2006HST309	499122	Peridotite with magnetite/chromite	63.931470	-49.688968	22V	564278	7090037	1046
2006HST310	499123	Pyrrrotite-bearing UM rock	63.931216	-49.689233	22V	564261	7090021	1032

Locality	Sample #	Type of sample	Latitude	Longitude	UTM Zone	UTM Easting	UTM Northig	Elevation
2006HST310	499124	Altered pyrrhotite	-	-	-	-	-	1032
2006HST313	499125	Homogene, fine-grained amphibolite	63.927670	-49.687262	22V	564371	7089617	1054
2006HST315	499126	Granodiorite	63.939220	-49.669163	22V	565231	7090921	1045
2006HST322	499127	Gabbro	63.934030	-49.670794	22V	565164	7090342	1158
2006HST324	499128	Fine-grained leuco-gabbro	63.925650	-49.669924	22V	565226	7089409	1090
2006asch022	499129	Xenolith of peridotite in granite	63.929320	-49.675117	22V	564962	7089812	1079
2006HST326	499130	Dense, fine-grained amphibolite	63.923160	-49.665762	22V	565436	7089136	1095
2006HST331	499131	Mafic pillow with pyrite	63.937770	-49.681753	22V	564618	7090748	1036
2006HST332	499132	Pillow lava	63.937540	-49.685342	22V	564442	7090718	1034
2006HST333	499133	Olivine basalt/amphibolite	63.938770	-49.688426	22V	564288	7090851	1037
2006HST337	499134	Spotted gabbro/lava flow	63.941380	-49.706140	22V	563414	7091125	964
2006HST338	499135	Hornblende-mica schist (rusty)	63.938650	-49.706504	22V	563403	7090821	972
2006HST339	499136	UM pillow lava with chromite/magnetite	63.938130	-49.701853	22V	563632	7090767	986
2006HST342	499137	UM pillow lava with chromite/magnetite	63.936450	-49.683427	22V	564539	7090598	1034
2006HST347	499138	Gabbro	63.930280	-49.704611	22V	563514	7089890	986
2006HST348	499139	Grey amphibolite	63.929260	-49.711558	22V	563176	7089769	933
2006HST348	499140	Calc-silicate rock - amphibolite	-	-	-	-	-	933
2006HST351	499141	Calc-silicate rock - amphibolite	63.929180	-49.692959	22V	564088	7089779	1022
2006HST351	499142	Calc-silicate rock - amphibolite with pyrite						1022
2006HST354	499143	UM pillow lava	63.899640	-49.912343	22V	553388	7086285	917
2006HST357	499144	Exhalite with arsenopyrite and pyrrhotite	63.913880	-49.935753	22V	552212	7087853	1060
2006HST361	499145	Exhalite with arsenopyrite and pyrrhotite	63.916010	-49.942104	22V	551897	7088085	1181
2006HST362	499146	Coarse-granined garnet amphibolite	63.915380	-49.941557	22V	551925	7088015	1170
2006HST363	499147	Rusty mica-schist with disseminated iron sulphides	63.916060	-49.944379	22V	551785	7088088	1160
2006HST364	499148	Quartz-garnet exhalite with disseminated pyrite	63.916380	-49.945972	22V	551707	7088122	1173
2006HST367	499149	Grey tonalite	63.909540	-49.940715	22V	551977	7087365	1016
2006HST370	499150	Amphibolite from lense in tonalite	63.919200	-49.911683	22V	553383	7088466	804
2006HST370	499151	Grey tonalite	63.919000	-49.914220	22V	553259	7088441	805
2006HST375	499152	Grey granodiorite	63.913090	-49.913560	22V	553303	7087783	817

Locality	Sample #	Type of sample	Latitude	Longitude	UTM Zone	UTM Easting	UTM Northig	Elevation
2006HST379	499153	Kimberlite	63.720370	-49.278005	22V	585059	7067000	1102
2006HST379	499154	Kimberlite	-	-	-	-	-	1102
2006HST379	499155	Kimberlite	-	-	-	-	-	1102
2006HST380	499156	Kimberlite	63.721770	-49.275345	22V	585186	7067160	1162
2006HST381	499157	Kimberlite	63.725670	-49.269197	22V	585478	7067602	1223
2006HST382	499158	Lamproite	63.726200	-49.265716	22V	585648	7067666	1213
2006HST383	499159	Ignimbrite with disseminated Fe-sulphides	63.726350	-49.261129	22V	585874	7067689	1217
2006HST384	499160	UM rock	63.728840	-49.238920	22V	586963	7067997	1221
2006HST388	499161	Feldspar porphyric tuff	63.722220	-49.245368	22V	586665	7067251	1319
2006HST392	499162	Kimberlite	63.721080	-49.275967	22V	585157	7067083	1172
2006HST395	499163	Kimberlite	63.719840	-49.278724	22V	585025	7066941	1162
2006HST395	499164	Kimberlite	-	-	-	-	-	1162
2006HST395	499165	Kimberlite	-	-	-	-	-	1162
2006HST396	499166	Kimberlite	63.719160	-49.280119	22V	584958	7066863	1151
2006HST397	499167	Kimberlite	63.718590	-49.281439	22V	584895	7066798	1156
2006HST399	499168	Soapstone	63.715820	-49.291760	22V	584393	7066475	1141
2006HST400	499169	UM dike/sill	63.715740	-49.292849	22V	584340	7066465	1140
2006HST401	499170	Dark, homogene gabbro - dike?	63.718020	-49.302258	22V	583868	7066707	1150
2006HST408	499171	Greenstone - UM rock	63.719400	-49.260957	22V	585904	7066916	1338
2006HST410	499172	Greenstone - UM rock with magnetite	63.721810	-49.257739	22V	586055	7067188	1343
2006HST411	499173	Porhyritic granite	63.717950	-49.256231	22V	586142	7066760	1406
2006HST418	499174	Banded chlorite schist/tuff	63.709380	-49.225558	22V	587683	7065848	1225
2006HST418	499175	Greenstone - UM rock	-	-	-	-	-	1225
2006HST425	499176	Banded chlorite schist/tuff	63.711530	-49.275704	22V	585199	7066019	1330
2006HST426	499177	Hydrothermal altered rock - epidote-quartz bearing horn-fels	63.713120	-49.277582	22V	585102	7066194	1289
2006HST426	499178	Diabas	-	-	-	-	-	1289
2006HST427	499179	Rusty greenstone with disseminated iron sulphides	63.713760	-49.279803	22V	584990	7066261	1242
2006HST428	499180	Exhalite (chert) with pyrite	63.714410	-49.279507	22V	585003	7066335	1212

Locality	Sample #	Type of sample	Latitude	Longitude	UTM Zone	UTM Easting	UTM Northig	Elevation
2006HST430	499181	Mafic pillow lava	63.715400	-49.285054	22V	584726	7066437	1153
2006HST431	499182	Inner part of mafic pillow lava	63.715260	-49.284539	22V	584752	7066422	1153
2006HST432	499183	Fine-grained intermediary lava flow	63.715970	-49.286562	22V	584649	7066499	1140
2006HST433	499184	Pillow lava	63.715010	-49.284266	22V	584766	7066395	1165
2006HST434	499185	Acid lava flow - phyllite	63.714860	-49.283804	22V	584789	7066379	1170
2006HST435	499186	Acid lava flow - phyllite	63.714430	-49.283010	22V	584830	7066332	1170
2006HST435	499187	Grey, intermediary lava flow	-	-	-	-	-	1170
2006HST437	499188	Chlorite schist - UM rock	63.714240	-49.282560	22V	584852	7066312	1181
2006HST437	499189	Phyllitic mafic flow	-	-	-	-	-	1181
2006HST438	499190	Tourmalinite	63.714100	-49.282345	22V	584863	7066296	1183
2006HST438	499191	Asbestos phyllite	-	-	-	-	-	1183
2006HST439	499192	Mafic lava flow	63.714890	-49.283853	22V	584787	7066383	1168
2006HST441	499193	Massive pyrrhotite breccia	64.116110	-49.822939	22W	557331	7110483	862
2006HST441	499194	Massive pyrrhotite ore with pyrite	-	-	-	-	-	862
2006HST441	499195	Quartz-rich rock with disseminated pyrite	-	-	-	-	-	862
2006HST441	499196	Garnet amphibolite	64.116540	-49.825670	22W	557197	7110528	844
2006HST441	499197	Quartz vein	-	-	-	-	-	844
2006HST441	499198	Dark, quartz-rich breccia	-	-	-	-	-	844
2006HST442	499199	Coarse-granined granite - feldspar alteration	-	-	-	-	-	844
2006HST443	499201	Garnet amphibolite (UM composition)	-	-	-	-	-	844
2006HST444	499202	Altered UM rock to garnet gneiss	-	-	-	-	-	844
2006HST440	499203	Pyrrhotite ore	64.115810	-49.828856	22W	557043	7110444	872
2006HST440	499204	Pyrrhotite ore	64.116010	-49.828169	22W	557076	7110466	877
2006HST440	499205	Brecciated pyrrhotite ore	64.115900	-49.826313	22W	557167	7110456	873
2006HST450	499206	Felsic porphyritic dike	64.112540	-49.796208	22W	558640	7110108	775
2006HST452	499207	UM block with olivine and opx	64.109830	-49.822387	22W	557370	7109783	858
2006HST455	499208	Garnet fels with calc-silicate minerals	64.115510	-49.830133	22W	556981	7110409	865
2006HST456	499209	Amphibolite (gabbro)	64.115770	-49.829328	22W	557020	7110439	867
2006HST459	499210	Bleached amphibolite with little garnets	64.115600	-49.824945	22W	557234	7110424	879

Locality	Sample #	Type of sample	Latitude	Longitude	UTM Zone	UTM Easting	UTM Northig	Elevation
2006HST461	499211	Sheared quartz vein - 10 cm wide in altered amphibolite	64.113870	-49.841886	22W	556412	7110216	824
2006HST461	499212	Altered amphibolite with little Fe-sulphide	-	-	-	-	-	624
2006HST462	499213	Garnetite	64.112400	-49.845759	22W	556227	7110049	835
2006HST462	499214	Peridotite	-	-	-	-	-	835
2006HST463	499215	Quartz-garnet gneiss with disseminated sulphides	64.113490	-49.847074	22W	556160	7110168	817
2006HST463	499216	Garnet amphibolite	-	-	-	-	-	817
2006HST466	499217	Diabas	64.111760	-49.852127	22W	555918	7109972	809
2006HST467	499218	Dark amphibolite	63.959270	-50.515148	22V	523749	7092565	569
2006HST468	499219	Dark amphibolite	63.933100	-50.443951	22V	527262	7089677	1011
2006HST468	499220	Granodiorite						1011
2006HST469	499221	Granite	63.968480	-50.209563	22V	538704	7093741	942
2006HST469	499222	Olivine-rich peridotite	-	-	-	-	-	942
2006HST469	499223	Banded amphibolite and little calc-silicates	-	-	-	-	-	942
2006HST470	499224	Homogeneous dark amphibolite with biotite alteration	63.959250	-50.041630	22V	546942	7092826	1148
2006HST471	499225	Garnet-bearing altered amphibolite	63.878420	-50.158516	22V	541336	7083738	1225
2006HST471	499226	Banded amphibolite with calc-silicates	-	-	-	-	-	1225
2006HST472	499227	Grey granodiorite	63.895590	-50.542227	22V	522474	7085460	883
2006HST472	499228	Laminated gneiss	-	-	-	-	-	883
2006HST473	499229	Quartz-garnet-biotite schist	63.896210	-50.548058	22V	522187	7085526	880
2006HST473	499230	Garnetite with biotite and quartz	-	-	-	-	-	880
2006HST474	499231	Amphibolite with calc-silicates	63.897070	-50.551513	22V	522017	7085621	871
2006HST474	499232	Dotted amphibolite (gabbro)	-	-	-	-	-	671
2006HST479	499233	Silicified and biotite altered amphibolite with disseminated Fe-sulphides	63.889930	-50.528424	22V	523156	7084834	1010
2006HST480	499234	Quartz-biotite-hornblende gneiss with disseminated Fe-sulphides	63.890050	-50.527148	22V	523218	7084847	1023
2006HST483	499235	Altered UM rock with aegirine	63.911620	-50.570004	22V	521098	7087237	1000
2006HST485	499236	Altered amphibolite with little Fe-sulphide	63.916130	-50.557821	22V	521692	7087743	876
2006HST488	499237	Garnetite, biotite and disseminated sulphides	63.905040	-50.555837	22V	521798	7086508	906

Locality	Sample #	Type of sample	Latitude	Longitude	UTM Zone	UTM Easting	UTM Northig	Elevation
2006HST490	499238	Gneiss with disseminated Fe-sulphides	63.880370	-50.494151	22V	524847	7083782	1014
2006HST490	499239	Garnet amphibolite with disseminated Fe-sulphides	-	-	-	-	-	1014
2006HST490	499240	Grey amphibolite with disseminated Fe-sulphides	-	-	-	-	-	1014
2006HST491	499241	Quartz-garnet-sillimanite-biotite schist with disseminated Fe-sulphides	64.191610	-49.530181	22W	571394	7119190	644
2006HST492	499242	Biotite-garnet-sillimanite-quartz schist with disseminated Fe-sulphides	64.191390	-49.530981	22W	571356	7119164	641
2006HST493	499243	Sillimanite (20-30 vol%) schist with disseminated Fe-sulphides	64.191350	-49.532225	22W	571295	7119159	645
2006HST494	499244	Sillimanite-biotite-quartz schist with disseminated Fe-sulphides	64.190860	-49.532858	22W	571266	7119104	650
2006HST495	499245	Garnet-sillimanite-biotite schist	64.190960	-49.534189	22W	571201	7119114	645
2006HST497	499246	Biotite-sillimanite-quartz schist	64.187750	-49.523031	22W	571751	7118768	497
2006HST499	499247	Garnet amphibolite	64.189720	-49.524592	22W	571670	7118986	634
2006HST500	499248	Biotite-sillimanite schist	64.192000	-49.532413	22W	571285	7119232	653
2006HST501	499249	Grey biotite gneiss (tonalite)	64.192550	-49.529581	22W	571421	7119295	667
2006HST502	499250	Garnet-biotite-quartz gneiss	64.193220	-49.519254	22W	571920	7119382	629
2006HST503	499251	Light, banded gneiss - Amitsoq gneiss	64.189420	-49.532880	22W	571269	7118943	619
2006HST504	499252	Biotite-sillimanite schist	64.362280	-49.845754	22W	555722	7137891	226
2006HST505	499253	Silicified anorthosite	64.361960	-49.847213	22W	555652	7137854	238
2006HST505	499254	Fine-grai ned garnet amphibolite with disseminated Fe-sulphides	-	-	-	-	-	238
2006HST506	499255	Amphibolite with disseminated sulphides	64.361740	-49.847331	22W	555647	7137829	234
2006HST506	499256	Garne-biotite bearing amphibolite with disseminated sulphides	-	-	-	-	-	234
2006HST507	499257	Biotite amphibolite - silicified	64.361660	-49.846242	22W	555699	7137821	226

Concluding remarks

- Investigated mafic complexes are dominated by amphibolite to upper amphibolite facies metamorphic rocks, although greenshist facies rocks are present at Nunatak 1390. Gradations between rocks that more or less preserve primary textures enables correlation of spatially separated mafic-ultramafic units, and lead us to believe that greenstones in the region were derived in a similar geo-tectonic environment. Preserved pillow basalts and a calc-silicate associations, which are typical for marine volcanic environments make us conclude that the studied rocks constitute remnants of Archaean ocean crust.
- The Nunatak 1390 consists of a bimodal succession or mostly volcanic rocks, which were metamorphosed in greenschist facies. The overall preservation of primary textures and structures is unusually good for West Greenland. The age of the complex remains unknown, but is assumed to be within the range of the Tasiuarsuaq terrane of 2.92–2.86 Ga. Preserved tholeiitic pillow basalts and calc-alkaline associations resembles modern arc systems. Bimodal volcanism might reflect input from trench side and back arc side volcanoes respectively. On a larger scale the Tasiusarsuaq terrane west–and southwards has preserved remnants of volcanic rocks at several localities probably of similar age as the Nunatak 1390 (Escher & Myers 1975).
- The Kangiata Nuna 1:100.000 geological map sheet consists of a large greenstone granite belt with 20 – 30% of greenstones and at least two generations of tonalite and granodiorite (Tasiursuaq terrane). The greenstone granite belt is estimated to make up more than 1200 km^2 and with possible extension towards south.
- Mafic sequences and exhalites (greenstones) in the Tasiuarsuaq terrane south and southeast of Kangerdluarssenguup taserssua with may become economically interesting due to elevated gold and arsenic contents.
- The area south of Ameralik affected from extensive hydrothermal alteration especially along fault/mylonite zones. The source of the albitised Cu-Au bearing rock found in 2004 has probably now been found in a large alteration zone (200 m wide) with garnet-sillimanite-biotite ±sulphides.
- Garnet-sillimanite-biotite ±sulphide rocks seems to record a regional phenomenon. The alterations are pervasive and independent of rock types or geological terrane boundaries. The alteration must have occured after the amalgamation of micro continents in the Nuuk region if it assumed to represent one event. The timing of alteration event(s) is highly significant for the understanding of metallogenesis in southwest Greenland as mineralisations tend to be closely associated with garnetiferous peraluminous bitotie rich rocks. Important time constraints can be obtained by combining sulphide (e.g. Re-Os or Pb*-Pb*) and garnet-biotite (e.g. Sm-Nd or Lu-Hf) geochronology.
- Kimberlites have not previously been recorded in this part of Greenland, thus the discovery at Nunatak 1390 opens a completely new area for diamond exploration.

References

Allaart, J.H. 1982: Geologisk kort over Grønland, 1:500 000, Sheet 2 Frederikshåb Isblink - Søndre Strømfjord. Copenhagen: Grønlands Geologiske Undersøgelse.

Appel, P.W.U., Garde, A.A., Jørgensen, M.S., Moberg, E.D., Rasmussen, T.M., Schjødt, F. & Steenfelt, A. 2003: Preliminary evaluation of the economic potential of the greensone belts in the Nuuk region. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2003/94, 147pp.

Appel, P.W.U., Coller, D., Coller, V., Heijlen, W., Moberg, E.D., Polat, A., Raith, J., Schjødt, F., Stendal, H. & Thomassen, B. 2005: Is there a gold province in the Nuuk region? Report from field work carried out in 2004. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/27**, 79pp.

Chadwick, B. & Coe, K. 1983: Buksefjorden 63 V.1 Nord. Descriptive text. Geological map of Greenland 1:100 000. The regional geology of a segment of the Archaean block of southern West Greenland., 70. Copenhagen: Grønlands Geologiske Undersøgelse.

Eilu, P., Garofalo, P., Appel, P.W.U. & Heijlen, W. 2006: Alteration patterns in Au-mineralised zones of Storø, Nuuk region - West Greenland, 73 pp Geological Survey of Denmark and Greenland, Copenhagen, 2006/30).

Escher, J.C. & Myers, J.S. 1975: New evidence concerning the original relationships of early Precambrian volcanics and anorthosites in the Fiskenæsset region, southern West Greenland. Rapport Grønlands Geologiske Undersøgelse, **75**, 72–76.

Escher, J.C. & Pidgeon, R.T. 1976: Field mapping of nunatak 1390 m, east of Alángordlia, southern West Greenland. Rapport Grønlands Geologiske Undersøgelse, **80**, 84–87.

Friend, C.R.L. & Nutman, A.P. 2001: U - Pb zircon study of tectonically bounded blocks of 2940 - 2840 Ma crust with different metamorphic histories, Paamiut region, South-West Greenland: implications for the tectonic assembnly of the North Atlantic craton. Precambrian Research **105**, 143 - 164.

Friend, C.R.L. & Nutman, A.P. 2005: New pieces to the Archaean terrane jigsaw puzzle in the Nuuk region, southern West Greenland: steps in transforming a simple insight into a complex regional tectonothermal model. Journal of the Geological Society, London **162**, 147 - 162.

Garde, A.A. 1989: Geologisk kort over Grønland, 1:100 000, Fiskefjord, 64 V. 1 Nord. Copenhagen: Grønlands Geologiske Undersøgelse.

Hollis, J.A., van Gool, J.A.M., Steenfelt, A. & Garde, A.A. 2004: Greenstone belts in the central Godthåbsfjord region, southern West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2004/110, 110 pp.

Hollis, J.A.(ed.) 2005: Greenstone belts in the central Godthåbsfjord region, southern West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/42**, 215pp.

Hollis, J.A., Schmid, S., Stendal, H., van Gool, J.A.M. & Weng, W.L. 2006: Supracrustal belts in Godthåbsfjord region, southern West Greenland. Progree report on 2005 field work: geological mapping, regional hydrothermal alteration and tectonic sections, 171 pp plus 1 DVD, Geological Survey of Denmark and Greenland, Copenhagen, 2006/7).

McGregor, V.R. 1993: Geological map of Greenland 1:100 000. Descriptive text. Qôrqut 64 V.1 Syd. The regional geology of part of the Archaean block of southern West Greenland, including a segment of the late Archaean mobile belt through Godthåbsfjord., 40. Copenhagen: Grønlands Geologiske Undersøgelse.

Nielsen, B.M., Rasmussen, T.M. & Steenfelt, A. 2004: Gold potential of the Nuuk region based on multiparameter spatial modelling of known gold showings. Interim report 2004. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2004/121**, 155pp.

Stensgaard, B.M., Steenfelt, A. & Rasmussen, T.M. 2006: Gold potential of the Nuuk region based on multiparameter spatial modelling, 207 pp Geological Survey of Denmark and Greenland, Copenhagen, 2006/27).