DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2003/94

Preliminary evaluation of the economic potential of the greenstone belts in the Nuuk region

General geology and evaluation of compiled geophysical, geochemical and ore geological data

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(1 DVD included)

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MINISTRY OF THE ENVIRONMENT

GEUS

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G E U S

Rusty mid to late Archaean greenstones with promising gold showings on Aappalaartoq mountain on Storø

Contents

Summary

1. This report provides an up-to-date review of known mineral showings in the Nuuk region in southern West Greenland, together with a presentation and interpretation of geophysical and geochemical data and an overview of the region's Archaean and Palaeoproterozoic geological evolution. A large amount of additional geochemical and geophysical data, geological field maps from the archives of the Geological Survey of Denmark and Greenland (GEUS), a large bibliography and many company reports from the region are enclosed in digital form in the accompanying DVD. The report was initiated by the Bureau of Minerals and Petroleum, Nuuk, Greenland, in order to facilitate and promote further mineral prospecting in the region.
2. The mineral potential of the Nuuk region is promising, especially for gold, but has not hitherto been prospected accordingly. There are several generations of Archaean greenstone belts, some of which have close similarities with world class gold- and nickel-producing greenstone belts such as Kalgoorlie in Western Australia and Timmins in Canada (see below). Besides, the Nuuk region has a good infrastructure and is easily accessible. Ocean-going vessels can operate in the large fjords all year round, and Greenland's largest town Nuuk (Fig. 1) with its c. 15 000 inhabitants provides excellent communication, supply and repair facilities. There are frequent flight connections to Denmark and Canada, and helicopters are locally available. In addition there is a large hydropower plant with excess capacity.
3. The Nuuk region, located within the Archaean North Atlantic craton, comprises three different tectono-stratigraphic terranes which had independent geological evolutions until they were tectonically assembled at c. 2.7 Ga (see Fig. 4). The middle, Akulleq terrane contains both the c. 3.8 Ga old Isua greenstone belt, the middle Archaean Ivisârtoq greenstone belt, and several other fragments of greenstone belts, all in amphibolite facies. These are intercalated with c. 3.8, 3.6 and 2.8 Ga old orthogneisses and fragments of layered anorthosite-gabbro complexes. The Akulleq terrane is bounded to the south-east and north-west by mylonitic zones few tens of metres wide (the Qarliit Nunaat thrust and Ivinnguit fault), which were variably reworked in the late Archaean and Palaeoproterozoic. The central part of the terrane, around Qooqqut and on Nunatarsuaq (Figs. 1, 4), hosts several generations of late Archaean granites and pegmatites, including the 2.5 Ga Qôrqut granite complex which postdates the terrane assembly. The granites may have triggered the redistribution of gold, base metals and tungsten into the economically interesting deposits. Palaeoproterozoic orogeny north and south of the Archaean craton resulted in the Nuuk region in minor heating, emplacement of basic and rare granitic dykes, and a conjugate system of ductile to brittle faults. One of these faults, the Ataneq fault, appears to have reworked the Ivinnguit fault along part of its exposure in the north-east.
4. Modelling of regional magnetic and gravity data shows that a NW-dipping boundary in westernmost Godthåbsfjord separates two crustal segments with different petrophysical properties. The boundary is located close to the north-western boundary of the Akulleq terrane and runs parallel to the latter, but its surface expression is displaced about 10 km to the north-west. It is possible that the magnetic boundary represents the south-western continuation of the Palaeoproterozoic Ataneq fault found in the north-east. Another large-scale modelled boundary separates two crustal segments with different pet-

rophysical properties close to the mapped south-eastern boundary of the Akulleq terrane. The modelled boundary strikes approximately east-west and dips north. Aeromagnetic data with high resolution are also available from several small parts of the region and examine a number of greenstone belts in detail. In some of these locations the detailed magnetic data indicate the presence of greenstone units that have not been identified during geological mapping.

5. The Survey's large geochemical data base comprises systematic regional data from stream sediment samples, their heavy mineral concentrates, and from rock samples. In the Nuuk region these data outline a c. 25 km wide, NNE-trending zone that is enriched both in lithophile elements and Ni. The enriched zone extends for some 150 km from Nuuk to the margin of the Inland Ice and overlaps with the north-western part of the Akulleq terrane, the terrane boundary iself, and the Ataneq fault. A somewhat similar pattern is also apparent from a regional airborne gamma spectrometic survey. The latter outlines a large area enriched in K, Th and U, which largely coincides with the zone enriched in lithophile elements and with the mapped extent of the Qôrqut granite complex. The zone enriched in lithophile elements also coincides with the known gold prospects and a series of smaller gold anomalies.
6. Together with the bedrock geology, the geochemical and radiometric data show that the Akulleq terrane preserves a higher crustal level than is exposed in the two neighbouring terranes. It also appears that the central and north-western parts of the former terrane may have experienced an additional enrichment in mobile lithophile and incompatible elements that is not just explained by its higher crustal level and may point to the presence of a hydrothermal mineralising system connected to the high-level granite magmatism and possibly also related to the Ivinnguit fault. However, the detailed relationship between the NE-striking magnetic boundary, the geochemical anomaly, and the Ivinnguit and Ataneq faults remains unclear.
7. On Storø about 40 km from Nuuk along the above mentioned zone enriched in lithophile elements, high grade gold has been found over mineable widths in Archaean greenstones during two drilling campaigns around 1995 by NunaOil A/S. The obtained results are up to 6.1 ppm Au over 18 metres, 32.7 ppm Au over 1.7 metres, and 20 ppm Au over 2 metres. About 150 km from Nuuk along the same zone, grab samples from the Isua greenstone belt yielded up to 106 ppm gold in a shear zone-hosted, sheeted carbonate vein, and 3.1 ppm gold over 3 metres in fuchsite-stained pyrite-rich chert.
8. In addition to the above mentioned gold showings, the Nuuk region is also a tungsten province with stratabound scheelite, and it contains many small volcanic-hosted sulphide deposits with copper, zinc, lead and silver. Lead-zinc occurrences with up to 14% combined Pb and Zn, 6.8 ppm Au and 180 ppm Ag occur in a tonalite sheet intruded into an early Archaean greenstone belt. This occurrence also has up to 50 ppm mercury, the highest value recorded in this part of Greenland.
9. There are several indications that the gold mineralisations in the Nuuk region were deposited from epigenetic, presumably late Archaean mineralising fluids, and some of the showings contain very good intersections. However, the actual genesis of the individual gold mineralisations is far from understood. In order to assess them properly and find more, we believe that it is necessary to acquire an understanding of the interplay between granite emplacement, fluid movements and regional and localised deformation, over time, and along the entire length of the NNE-trending zone that is enriched in

lithophile elements. Accurate dating of granites and pegmatites as well as mylonite zones and faults, coupled with structural and geochemical studies, are important ingredients in such an investigation. It is also recommended that the most promising gold prospect at Storø is carefully mapped and its local structure analysed in detail before diamond drilling is resumed.

Introduction

The present study was initiated by the Bureau of Minerals and Petroleum (BMP) in Nuuk and carried out by staff from Department of Economic Geology and Department of Geological Mapping at the Geological Survey of Denmark and Greenland (GEUS). The study was carried out during the second part of 2003.

The purpose of this project was dual. One part was to compile present knowledge of the general geology, the known mineral occurrences of the greenstone belts and available geochemical data from the Nuuk region. The second part of the project comprised field work with geophysical measurements on prominent rock types on either side of a major terrane boundary, which can be traced from Nuuk to Isukasia. Field work also included collection of rock samples for petrophysical measurements. The results of the geophysical field work and petrophysical measurements are shown in the chapter: Aeromagnetic and gravity data covering the Akulleq terrane, southern West Greenland.

When all these data have been compiled and interpreted they will serve as guidelines for future work in the region which will aim at discovering mineral deposits which can be mined for the benefit of the population of Greenland in general and the population in nearby Nuuk in particular. The presently known mineral ocurrences are scattered throughout the greenstone belts of the Nuuk region but appear to be preferentially located near the northern terrane boundary. It is not known, however, to what extent this regional structure has determined the location of the mineral occurrences. The present report outlines all known mineral occurrences and suggests which paths should be followed in order to determine whether the Nuuk region hosts a gold province or whether the gold only occurs in small showings irregularly distributed throughout the region.

The chapters in this report have been written by different authors, with different degree of detail. Especially detailed and comprehensive is the section on the general geology of the Nuuk region. This depicts that much work has been carried out over the last decades on this section of ancient rocks comprising the oldest rocks on Earth. These detailed and often contradictory studies have resulted in hundreds of articles in various international journals, which are listed in a bibliography on the enclosed DVD. The geophysical sections describe in detail the geophysical anomalies found in different parts of the Nuuk region. The present study also comprises geophysical modelling suggesting Palaeoproterozoic faulting subparallel with Archaean terrane boundaries. The sections on general geology and geophysical investigations contain brief summaries. The sections on geochemistry and the mineral occurrences in the various greenstone belts are not as detailed as the section on general geology. This shows that only limited work has been carried out within these fields and is a clear indication that much more work is warranted in order to get an idea of the mineral potential of the Nuuk region.

The Nuuk region dealt with in this report stretches from Buksefjorden to Isukasia (Fig. 1). Nuuk, the capital of Greenland with a population of ~15.000 is situated at the coast and is accessible by ship the whole year. The deep fjords are also mostly accessible 12 month per year for ocean going vessels. The topography along the fjords is near alpine with steep mountains raising to 1600 m above sea level, whereas it is gentler towards the Inland Ice. Small glaciers are seen on the highest mountains. Nuuk has an international airport with direct connections to Canada and connection to Denmark via Kangerdlussuaq. Nuuk has a shipyard and all necessary infrastructure for future mining operations. Nuuk has fish factories and hydropower with excess capacity.

In most previous reports and articles dealing with the Nuuk region the term supracrustal belts has been used. However, in a recent description of the early Archaean Isua rocks the term Isua greenstone belt was introduced (Appel et al. 1998). The younger supracrustal belts formerly termed Malene supracrustal rocks have all the characteristics of greenstone belts. It has thus been decided in this report to apply the term greenstone belts to these belts.

The report contains a compilation of existing data from the Nuuk region with emphasis on the greenstone belts, most of which have been acquired by geologists from the Geological Survey of Denmark and Greenland (GEUS) (formerly The Geological Survey of Greenland (GGU)). Some airborne geophysical data acquired by exploration companies have been included.

Enclosed in this report is a DVD, which contains this report as well as numerous figures showing the geochemical trends in rock samples, stream sediments and heavy mineral concentrates from stream sediments of the Nuuk region. Instructions for accessing the data on the DVD are given in Appendix A together with descriptions of data acquisition and presentation. The DVD contains analyses of rock samples and heavy mineral concentrates from stream sediments. The DVD has also scanned copies of all relevant company reports, which describe the activities within mineral exploration in the region. Over the years much geological mapping has been carried out in the Nuuk region. Many of the results of this mapping have been published but not the original field maps. All these field maps from the region have been scanned and can be seen on the DVD. A complete bibliography up until year 2000 is also seen on the DVD. On the electronic version of this report, there are links to field maps, to company reports, to geochemical and geophysical maps. Thes links are marked in blue.

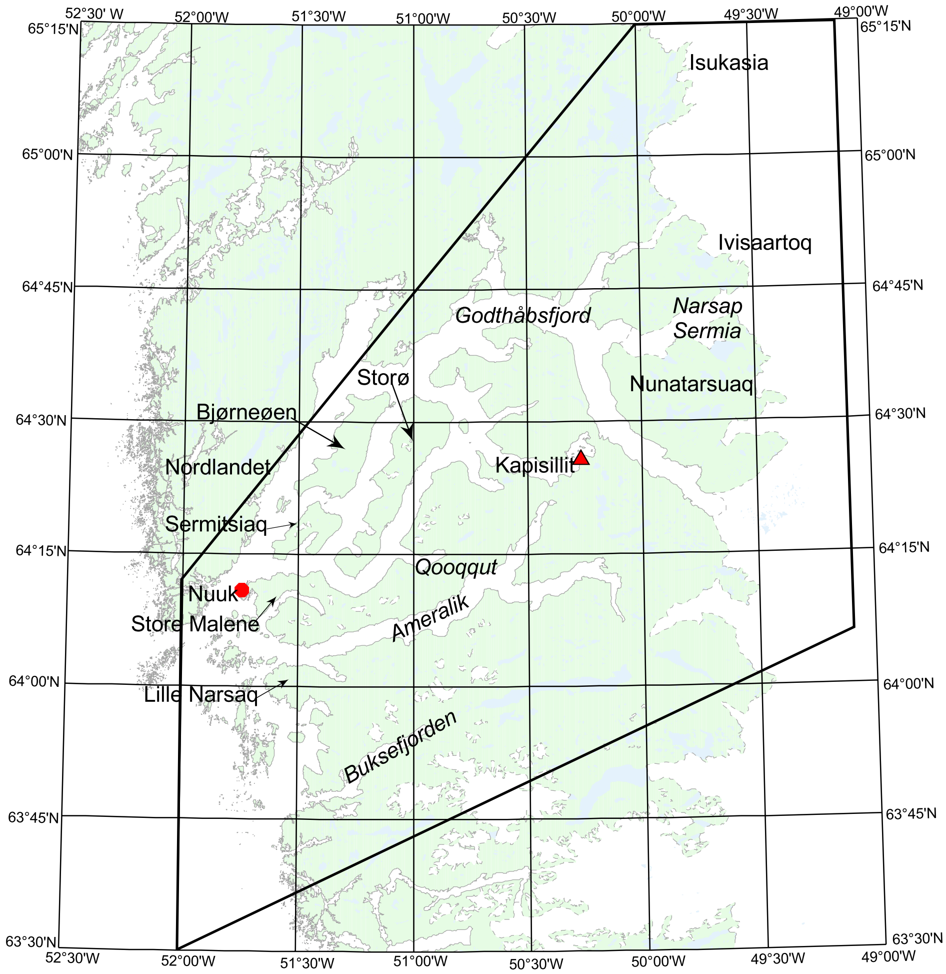

Figure 1: *Location map of the Nuuk region showing the outline of the project area*

Exploration history (Peter W. U. Appel)

Exploration by companies from 1960s to 1990s

The exploration activity of Greenland seems to be reverse proportional with the distance from available infrastructure. In Citronen fjord in Northeast Greenland more than 1000 km from nearest settlement, where no ships ever have been able to go through the ice millions of dollars have been spent in exploration. In the Nuuk region which is accessible by ship 12 months per year and is close to the best infrastructure in Greenland the exploration activities have been very limited. It is not because the geology of the Nuuk region is not favourable; the region has several generations of greenstone belts, regional sized shear zones and numerous gold, base metal and tungsten showings.

On the enclosed DVD is a list of all company reports covering activities in the Nuuk region. Most of these reports have been scanned and can be read on the DVD. References to company reports GEUS Report file in blue are linked to the scanned report. The location of the exploration targets mentioned below can be seen on Fig. 1. An overview of the exploration activities in the Nuuk region is shown in Table 1.

Table 1: *Exploration activities in the Nuuk area. Company reports are listed at the end of this report*

Commodity	Area	Activity	Company	Period
Iron	Isukasia	Geophysics Diamond drilling	Kryolitselskabet Øresund A/S (KØ)	1960s to 1970s
Iron	Isukasia	Diamond drilling	Rio Tinto Ltd.	1990s
Molybdenite	Ivisaartoq	Prospecting	KØ	1970s
Molybdenite	Lille Narsaq	Prospecting	Gemco	1970s
Tungsten	Store Malene to Ivisaartoq	Prospecting	Kidd Creek	1980s
Gold and base metals	Isukasia	Prospecting Geophysics	Nunaoil A/S	1990s
Gold	Ivisaartoq	Prospecting	Nunaoil A/S	1990s
Gold	Storø	Prospecting Diamond drilling	Nunaoil A/S	1990s
Gold and base metals	Bjørneøen Store Malene	Prospecting	Nunaoil A/S	1990s
Gold	Storø	Prospecting	NunaMinerals A/S	2002 to present

Kryolitselskabet A/S (KØ) carried out regional exploration programmes in West Greenland in the 1960s and 1970s. The surveys comprised helicopter reconnaissance and airborne geophysical surveys. In the late 1960s KØ discovered a major geophysical anomaly in the Isukasia area. Ground check revealed a world class magnetite ore body, partly concealed under the Inland Ice (Fig. 2). KØ immediately initiated a large drilling programme and constructed a drill camp at the edge of the ice sheet. Part of the drilling went through the ice. KØ collected bulk samples of magnetite ore for beneficiation tests. The samples were packed in plastic bags and piles of now rather worn plastic bags are still littering the area. Some of the bulk samples were flown down to the head of Godthåbsfjord where mineral collectors now use them (GEUS Report file 21215). KØ furthermore carried out measurements of water flow in the rivers for future hydropower. The company also carried out topographic investigations for construction of a road to the iron mine from the head of Godthåbsfjord. For a short period the American iron ore company Marcona was involved, but Marcona never contributed significantly to the investigations in the area (GEUS Report file 21215).

Figure 2: *Two billion tonnes of iron ore partly burried under the Inland Ice at Isukasia*

After several years of drilling KØ concluded that there are ~2 billion tonnes of iron ore with a grade of about 32% Fe (GEUS Report file 21215). Two thirds of the orebody are concealed under the Inland Ice. KØ also discovered abundant float with high-grade hematite in the area. Tracing a boulder fan and interpretation of the geophysical results led to the conclusion that there is a major hematite orebody under the Inland Ice situated on top of the magnetite orebody. In 1977 KØ realised that the orebody was too low grade to be mined and decided to pull out of the area. KØ did not carry out any mapping or exploration for other metals in the Isukasia area.

In 1996 and 1997 Rio Tinto Ltd. carried out a drilling programme in the Isukasia area through the Inland Ice into the underlying ore body. The company proved that there is indeed a very large hematite orebody under the Inland Ice, overlaying the magnetite ore (GEUS Report file 21551). However, Rio Tinto did not find any high grade hematite ore, so they pulled out.

KØ carried out minor programmes in other parts of Nuuk region. In Ivisaartoq area they found a molybdenite showing which was prospected by shallow drilling in the 1960'ies (GEUS Report file 20062). The prospect was quickly abandoned.

In Lille Narsaq about 20 km south of Nuuk molybdenite occurrences are found in diopside skarn bands up to 30 m. wide in a mid to late Archaean greenstone belt. This showing was prospected by GEMCO in 1972 (GEUS Report file 20268). Bands of semimassive pyrrhotite with minor chalcopyrite were extensively prospected by trenching by an American prospector. When that took place is not known.

The Geological Survey of Greenland (GGU) worked on the greenstone belts of the Godthåbsfjord region in the 1980s (Appel 1990a). During these campaigns numerous stratabound tungsten (scheelite) occurrences were discovered in mid to late Archaean greenstone belts. The most promising area seems to be the Ivisaartoq area, where three extensive (>10km long) intrusive, carbonate-altered peridotites proved to contain appreciable amounts of tungsten (channel sampling revealed up to 0.44% WO_3 over 2.5 m) (Appel 1990a). The GGU campaign also discovered numerous small VMS occurrences with pyrrhotite and chalcopyrite together with zinc minerals sphalerite and/or gahnite (Appel 2000). Many of the VMS prospects also contain molybdenite.

The discovery of a tungsten province in the Nuuk region prompted Kidd Creek Ltd. to obtain an exploration licence (GEUS Report file 20036). After one year Kidd Creek Ltd. was sold and its interest in Greenland ceased. At the same time China dumped the tungsten market. Thus all interest in tungsten in the Western World vanished for the time being.

Recent exploration by NunaMinerals A/S

This chapter presents a brief outline of exploration carried out in the Nuuk region by NunaMinerals A/S. The company which started as Nunaoil A/S was owned jointly by the Danish and Greenlandic government. Late 1998 it was split into two companies Nunaoil A/S and NunaMinerals A/S. The latter is now owned by the Greenlandic government (91%), and by the public (9%). For a matter of simplicaity the name NunaMinerals will be used in the text below.

NunaMinerals A/S has carried out exploration in the Nuuk region since 1990. Most of their work was devoted to the areas of Storø, Isukasia and Ivisaartoq. The exploration targets described below are seen on Fig. 1.

Storø

In the early 1990s scree and stream sediment sampling together with grab sampling of promising outcrops on the two prominent mountains Qingaaq and Aappalaartoq on central Storø drilling was carried out (Fig. 3). In 1995 diamond drilling, detailed geological and structure mapping was done on Qingaaq. Eleven holes were drilled on Qingaaq with a total length of 2000 m. and one hole was drilled on Aappalaartoq with a length of 500 m. Best intersections were 10.1 ppm Au over 10 m, another with 37 ppm Au over 1.5 m and 1.9 ppm over 8.5 m (GEUS Report file 21823). Unfortunately the report has no core log, neither are there detailed assay results. Unfortunately there was neither a proper geological map available nor a structural interpretation available to direct the drilling programme. There were furthermore major problems with location in relation to the topography. This was realised by NunaMinerals A/S already in 1996 where they wrote the following comment to the 1995 year drilling programme: *- an unacceptable uncertainty regarding location of samples, grids, geology and quality in relation to the topographic maps has been discovered.*

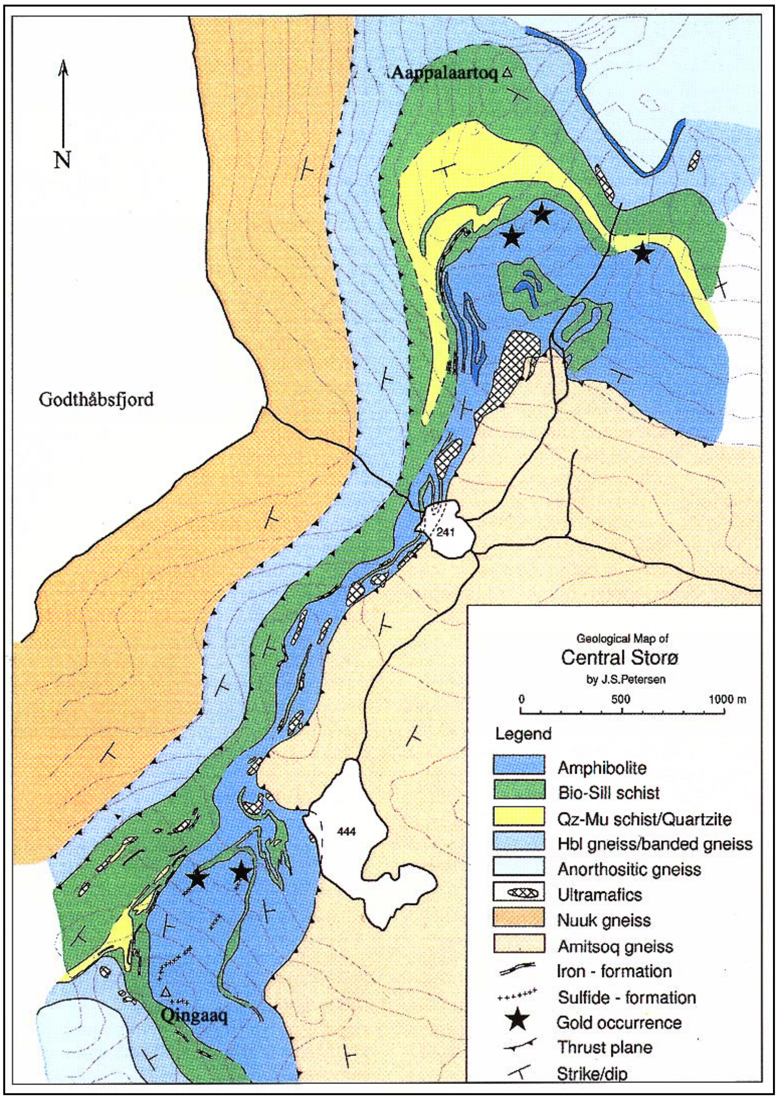

Figure 3: *Geological sketch map of central Storø (from Appel et al. 2000).*

Fortunately some structural investigations were made contemporaneously with the NunaMinerals drilling (GEUS Report file 21452). Later NunaMinerals A/S initiated another short structural investigation of the mineralised areas on Storø, but only very little fieldwork was done (GEUS Report file 21602).

In 1996 diamond drilling was carried on the two mountains. 2128 metres of NQ-size were drilled from 9 holes (3 from Aappalaartoq and 6 from Qingaaq). Dip tests was planned for each hole but the necessary acid never arrived from Canada. 195 sections from drill cores representing 487 m were analysed after logging and splitting. A small magnetometer survey was carried out and 7 geological maps and several field sketches were produced. Furthermore 349 rock samples and 24 sediments were collected. The drill cores recovered have very good intersections such as: 6.1 ppm Au over 18 metres, 32.7 ppm Au over 1.7 metres, 20 ppm Au over 2 metres and 18.9 ppm Au over 2 metres. For further information consult the report from 1996 (GEUS Report file 21565).

In 2000 NunaMinerals released the area. However, in 2002 the company decided to continue their work on Storø and obtained a new exploration licence on Storø and Bjørneøen.

Bjørneøen and Sermitsiaq

These areas have been explored by NunaMinerals A/S from 1994 to 1996. The company found very promising showings of gold, lead and zinc. The best value of gold was 2.4 ppm in a galena-bearing quartz vein on Bjørneøen. Sulphide-rich quartzites (?) in amphibolites up to 10 m thick traceable for more than 4 km, locally fuchsite stained contain up to 284 ppb Au, 0.3% Pb and 0,4% Zn. Sulphide-rich zones with 1.4% Zn, 0.7% Cu and 13.5 ppm Ag are found in amphibolites on Bjørneøen and Sermitsiaq. These occurrences are probably small VMS deposits. For further details see NunaMinerals A/S report from 1995 (GEUS Report file 21457).
In 1996 NunaMinerals found further encouraging occurrences. On Bjørneøen sulphide-rich lenses and bands with up to 3.55 % Zn, 1.33% Pb, 33 ppm Ag and 0.153 ppm Au (GEUS Report file 21514).

Ivisaartoq

The Ivisaartoq area has been prospected by NunaMinerals A/S 1990-1997. The company released the area in 1999. During that period much fieldwork was carried out on the greenstone belt and a granite-related molybdenite showing. A large soil sampling programme was carried out over the greenstone belt in 1995 with a line spacing of 1 km and sample spacing of 50 m on each line (GEUS Report file 21458). Unfortunately the co-ordinates for these lines have been lost. A total of 208 rock samples and 718 soil and scree sediment samples were collected. The best sediment sample yielded 1.5 ppm Au, and the best rock sample yielded 3.2 ppm Au.

Isukasia

In 1993 Nunaoil A/S initiated an exploration programme in the Isua Greenstone Belt (IGB). After some reconnaissance they carried out a detailed geophysical survey on ground and helicopterborne (see chapter on geophysical investigations). Channel and chip sampling was carried out over many of the mineralised zones.

The company found an interesting lead-zinc showing with assay results up to 10.4% Zn, 4.3% Pb, 44 ppm Ag and 0.7 ppm Au (Appel 2000). The zone is up to a metre wide and traceable for several tens of metres along strike in a tonalite sheet intruded into the greenstones. A careful field check by the company did not reveal any extension of the showing. For further description see chapter on early Archaean greenstone belts.

The company also discovered a number of gold occurrences associated with pyrite-rich fuchsite stained cherts. Gold contents up to 3.1 ppm over 3 metres were found (GEUS Report file 21453 and 21513). An interesting carbonate vein in a shear zone cutting a package of mafic and ultramafic volcanic rocks was found by the company. The vein is sheeted and consists of carbonate, tourmaline, visible gold, arsenopyrite, pentlandite, magnetite and chromite. Grab samples with up to 100 ppm Au were found. For further details see chapter on early Greenstone belts.

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 (Adam A. Garde)

Summary

The Nuuk region in southern West Greenland (Fig. 4) is part of the Archaean North Atlantic (or Nain) craton in southern Greenland and eastern Labrador. The region consists of three different tectono-stratigraphic terranes. From south-east to north-west these are the Tasiusarsuaq, Akulleq and Akia terrane (Fig. 4). Together the three terranes comprise (1) the c. 3.8 Ga Isua greenstone belt which is the largest coherent segment of early Archaean supracrustal rocks known on Earth, (2) a group of c. 3.8-3.6 Ga orthogneisses (formerly the Amîtsoq gneisses), (3) middle to late Archaean supracrustal rocks holding the Ivisârtoq greenstone belt and the greenstones on Storø, (4) fragments of layered anorthosite-gabbro complexes, (5) voluminous 3.2-2.8 Ga orthogneisses (including those formerly called Nûk gneisses), and (6) the 2.5 Ga Qôrqut granite complex. A simplified overview of the main geological components in the three terranes is shown in Table 2.

In all three terranes, greenstone belts and smaller enclaves of supracrustal rocks in upper amphibolite and locally granulite facies are magmatically and tectonically intercalated with orthogneisses. The greenstone belts are dominated by metamorphosed tholeiitic pillow lavas and sills and lesser mica-garnet schists and may have been formed in oceanic or island arc environments. Magnesium-rich siliceous units are also locally important and have been interpreted as weathered or hydrothermally altered and then metamorphosed acid volcanic rocks. Quartzitic metasediments are rare but have been found e.g. south of Nuuk. All the middle to late Archaean supracrustal sequences were formerly collectively known as the Malene supracrustal rocks, but subsequent work has documented that they comprise several different, middle to late Archaean groups.

There are also several large fragments of metamorphosed anorthosite-gabbro complexes, which may represent the deeper plutonic counterparts of the metamorphosed pillow lavas and sills in an original layered oceanic crust that is now totally disrupted by magmatic and tectonic intercalation with grey gneisses and granitic rocks.

Both the early and middle to late Archaean grey orthogneisses are predominantly of tonalitic to trondhjemitic composition, with smaller volumes of dioritic, quartz-dioritic, and iron-rich augen gneiss. Two large, late-kinematic, dome-shaped, tonalitic-granodioritic plutons, the Finnefjeld gneiss and Taserssuaq tonalite complex, occur in the north-western part of the region (Fig. 4), and late Archaean (c. 2.97-2.75 Ga) granodioritic and granitic intrusions are common in the central and eastern parts of the region and are thought to have formed by partial melting of the orthogneisses. They commonly form flat-lying to steeply inclined sheets with thicknesses ranging from metres to several hundred metres.

The major and trace element compositions of the tonalitic to trondhjemitic orthogneisses suggest they were derived from partial melting of hydrated basaltic crust. The most likely geotectonic scenario for the partial melting of the latter and generation of the grey gneiss precursor magmas is plate-tectonic subduction, not least because several distinct, late Archaean microcontinents or terranes have been identified in the Nuuk region.

Table 2: *Overview of the main components of the Akia, Akulleq and Tasiusarsuaq terranes and their approximate ages.*

Ma			
2530	Qôrqut granite complex Localised shearing Pegmatites		
2720	Qârusuk granitic dykes (stitching of terranes)		
	Terrane assembly and deformation of terrane boundaries		
	Akia terrane	**Akulleq terrane** (incl. Tre Brødre and Færingehavn terranes)	**Tasiusarsuaq terrane**
2800			Granulite facies metamorphism Ilivertalik granite
		Ikkatooq gneisses	
	Assembly of Akia and Akulleq terranes???		TTG gneisses and granites
~3000	Qugssuk granite Static retrogression Granulite facies metamorphism TTG gneisses (incl. Nûk gneiss)		
?	Greenstone belts and basic intrusive complexes	Greenstone belts and basic intrusive complexes (formerly Malene supracrustal rocks)	Greenstone belts and basic intrusive complexes
3200	Dioritic gneiss		
		Ameralik dykes	
3500			
3600		(Itsaq gneiss complex) White and Fe-rich gneisses	
3700		Grey gneisses (incl. Âmitsoq gneiss)	
3800		Isua greenstone belt	
~3850		Akilia association	

The Akia, Akulleq and Tasiusarsuaq terranes had geological evolutions that were independent of each other until they were assembled along two tectonic boundaries in the south-eastern and north-western parts of the Nuuk region, namely the Qarliit Nunaat thrust and the Ivinnguit fault (Fig. 4). There is some debate concerning when the terrane assembly began, but all the terranes were 'stitched' by granitic dykes that have been dated at 2720 Ma.

The c. 2.5 Ga Qôrqut granite complex was emplaced after the terrane assembly, apparently contemporaneously with the development of local steep shear zones. It forms a dense swarm of inclined and undeformed granite sheets and related pegmatites that occupy an area of c. 20 by 50 km along the eastern part of Godthåbsfjord.

Swarms of N-S, E-W and NE-SW trending basic dykes of Palaeoproterozoic age are related to the early rifting stages of two contemporaneous orogenies to the north and south of the Archaean craton. A system of conjugate, WNW- and ENE-trending faults are presumed to reflect the brittle response of the craton to the subsequent contractional phases of these events, and rare granitic dykes up to a few metres thick and Palaeoproterozoic biotite ages show that the Archaean crust was mildly reheated.

The Akulleq terrane in the central part of the Nuuk region preserves a higher crustal level than the two adjacent terranes. This can be seen both from the inverse distributions of granitic rocks and granulite facies areas in the three terranes (Fig. 4), and from the higher concentration of large-ion lithophile elements in the Akulleq terrane revealed by airborne gamma spectrometry (Fig. 25) and stream sediment geochemistry (Fig. 23) also presented in this report. Furthermore, this conclusion is also consistent with the distribution of known gold anomalies in the Nuuk region, which are concentrated within the Akulleq terrane (Fig. 23).

The higher crustal exposure within the Akulleq terrane - or a geographical area that largely overlaps with it - shows that it has experienced a major downthrow relative to the neighbouring areas. The downthrow may have occurred during the late Archaean terrane assembly, or in the Palaeoproterozoic. The major aeromagnetic boundary visible on Fig. 28 along the northwestern margin of Godthåbsfjord may represent a major NW-dipping thrust fault that could account for part of the downthrow.

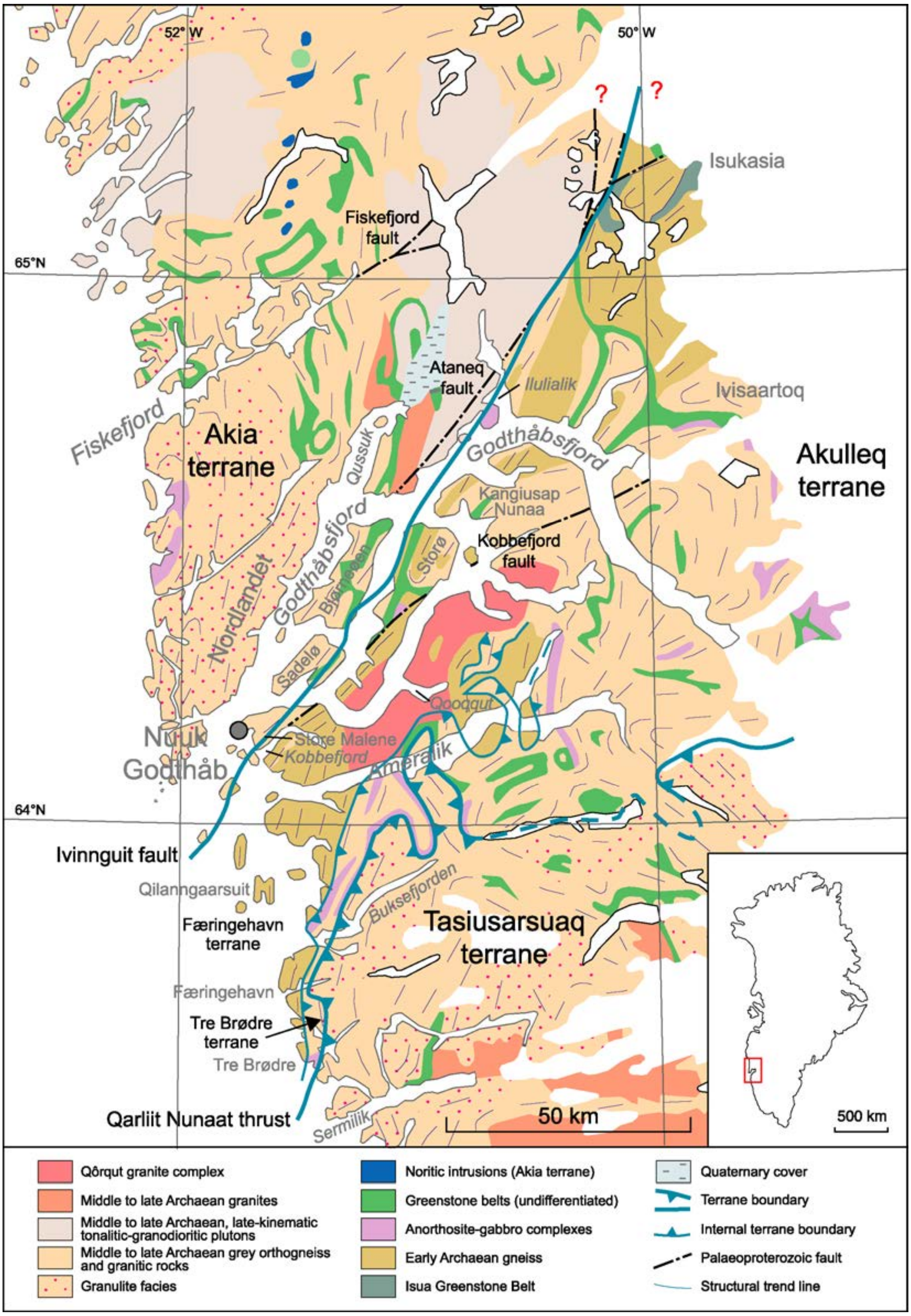

Figure 4. *Simplified geological map of the Nuuk region with terrane boundaries and Palaeoproterozoic brittle faults. The extent of early Archaean orthogneiss is uncertain in some areas, especially in the eastern part of the Akulleq terrane. Index map shows position in Greenland. Modified from Escher & Pulvertaft (1995).*

Introduction

General

The Nuuk region (Fig. 4) comprises probably the world's most intensely studied segment of early Archaean crust. This is a consequence of two major discoveries within the past c. 30 years, which have made the Nuuk region famous among Precambrian geologists: (1) the detection of early Archaean orthogneisses and supracrustal rocks in the beginning of the 1970s, and (2) the establishment of the concept of Archaean lithotectonic terranes in the late 1980s (a terrane in this sense (Coney et al. 1980) is a piece of crust with its own magmatic, tectonic and thermal history, different from a geographic terrain). However, despite the international focus on the geological history of the Nuuk region, only small parts have been explored for economic mineral deposits.

The aim of this chapter is to provide a coherent overview of the Archaean geological evolution of the region and provide an entry into the very extensive and sometimes confusing literature. It is also intended as a basis for the descriptions of individual greenstone belts and regional geochemical and geophysical data in this report. In addition, it may help the reader to establish an overview of the tectonic framework of the Nuuk region, and put older descriptions of rocks and processes into an updated local and regional geological context.

The following sections of this chapter describe the geological setting of the Nuuk region in West Greenland (section 2), an outline of the geological evolution as it was perceived in the 1970s and 1980s, accompanied by the then prevailing terminology and reference to ideas and conclusions that are still appropriate (section 3), an account of the now prevailing interpretation, incorporating the terrane concept and its revised terminology (section 4), short outlines of late Archaean terrane assembly (section 5) and Palaeoproterozoic events (section 6), and finally a few notes about recent scientific developments (section 7).

Terminology and spelling

The terminology first established in the Nuuk region underwent major changes when the terrane concept was introduced in the late 1980s. However, modern readers also need to make themselves familiar with the older terminology, as it is found not only in numerous papers but also in several M.Sc. and Ph.D. theses which contain valuable primary descriptions, for instance those from the Ivisaartoq region (Hall 1981; Brewer 1985; Robertson 1985; Crewe 1986; Park 1986).

This report employs the newer of two ways to spell Greenlandic place names recommended by the place name commission under the Home Rule government. However, many geological units were named when the older spelling was prevailing, and these remain unchanged. Thus, both Nuuk (new spelling) and Nûk (old spelling, as in Nûk gneiss) refer to the same town ('Godthåb' in Danish). Most place names on the printed geological maps, except for towns, also employ the old Greenlandic spelling, along with Danish names where the latter exist. The name 'Nuukfjord' for Godthåbsfjord is widely used locally and found in recent company reports, but it is not an official place name and is not used in this report.

Geological setting of the Nuuk region in southern West Greenland

The Nuuk region forms the central part of the Archaean craton of southern West Greenland, which was contiguous with the Nain craton in eastern Labrador in the late Archaean and early Palaeoproterozoic (Fig. 4). It is largely composed of early and middle to late Archaean grey orthogneisses of tonalitic-trondhjemitic-granodioritic (TTG) affinity sensu Martin (1994). Granitic gneisses formed by partial melting from the TTG suite are also very common in the eastern part of the Nuuk region, and a late Archaean swarm of inclined, undeformed granite sheets occurs in its central part (e.g. Brown et al. 1981).

The orthogneisses and granodioritic-granitic rocks derived from the TTG suite are intercalated with fragments of an anorthosite-gabbro association and belts of metamorphosed supracrustal rocks, which (besides small volumes of sedimentary and acid volcanic rocks) predominantly consist of tholeiitic metavolcanic rocks. In West Greenland the latter are generally referred to as amphibolites (e.g. Kalsbeek & Garde 1989) irrespective of their metamorphic grade, which is generally upper amphibolite to granulite facies. However, these belts are termed greenstone belts in this report because of obvious similarities with the slightly lower grade, but likewise pillow-lava dominated greenstone belts that are common in the Archaean parts of central and eastern Canada.

The Nuuk region contains a number of narrow, late Archaean shear zones that separate terranes with different prior histories. Both the early Archaean components and most of the granitic rocks in the Nuuk region are concentrated in the central (Akulleq) terrane, which is exposed at a higher crustal level than the neighbouring terranes. Swarms of Palaeoproterozoic basic dykes trending N-S, E-W and NE-SW are related to early rifting stages of the contemporaneous Nagssugtoqidian and Ketilidian orogens to the north and south of the Archaean craton (van Gool et al. 2002; Garde et al. 2002), and a system of conjugate, WNW- and ENE-trending faults such as the Ivinnguit and Kobbefjord faults (Smith & Dymek 1983; Park 1986) are presumed to reflect the brittle response of the craton to the later contractional phases of these events.

The early view of two major Archaean accretionary cycles in the Nuuk region

Amîtsoq gneisses, Ameralik dykes and Nûk gneisses

Between the discovery in the early 1970s of the early Archaean rocks and the introduction of the terrane concept in the late 1980s, the Archaean crust of the Nuuk region was considered to have evolved during two major cycles of long-lived continental crustal accretion, maturation, and stabilisation of early and middle to late Archaean age. The latter cycle was believed to have covered the entire region (a "sea of orthogneisses", Nutman et al. 1989) and lasted several hundred million years, and a description of this scenario formed the core of the classic, but now outdated account of the Archaean of West Greenland by Bridgwater et al. (1976). The first regional coastal reconnaissance that included the Nuuk region had been published by Noe-Nygaard & Ramberg already in 1961. Their work is rarely cited but was of a high quality and formed the basis for the subsequent, more detailed studies.

The early Archaean gneisses were first recognised along the coasts of Ameralik fjord east of Nuuk (Fig. 5) because they were cut by basic dykes that were absent from other, neighbouring gneisses in the same region (McGregor 1966). The dykes, generally only preserved as folded and metamorphosed fragments, were named **Ameralik dykes** (McGregor 1968). Whole-rock Pb-Pb and Rb-Sr age determinations revealed that the older gneisses with dyke fragments were early Archaean (c. 3.7 Ga) in age, and they were termed **Amîtsoq gneisses**.

Figure 5. *Early Archaean orthogneiss with folded relicts of Ameralik dykes. The exposure is ca. 2.5 m high. North coast of outer Ameralik, the original type area for Amîtsoq gneiss.*

The younger gneisses that were devoid of such dykes and which are common in the vicinity of Nuuk, were called **Nûk gneisses** (Black et al. 1971; Moorbath et al. 1972; McGregor 1973). The whole-rock geochronology cited above showed that the Nûk gneisses were about 3.0 Ga old. Subsequent bulk zircon ages of typical Amîtsoq gneisses by Baadsgaard (1973) confirmed that they were indeed early Archaean, and orthogneisses without remnants of basic dykes both in Nuuk town and south-western Godthåbsfjord were repeatedly shown to be around 3.0 Ga old (Taylor et al. 1980; Baadsgaard & McGregor 1981).

In the early publications coauthored by V.R. McGregor (e.g. Moorbath et al. 1973) the Amîtsoq gneisses were defined as rocks that were cut by or contained fragments of Ameralik dykes and considered to be older than neighbouring rocks from which such dykes were absent. However, the early Archaean age itself was not part of the definition, and this led to considerable confusion in the following years. Gill & Bridgwater (1976, 1979) and Chadwick (1981) studied the Ameralik dykes, and it was shown that there were not only several generations and compositions of Ameralik dykes, but also several generations of so-called intra-Nûk dykes, i.e. synplutonic dykes that were emplaced simultaneously with the middleArchaean magmatic crustal accretion. Nevertheless some gneisses cut by deformed basic dykes were still regarded as Amîtsoq gneisses and depicted as such on geological maps (e.g. McGregor 1983), although they were shown by other workers to be middleArchaean in age (e.g. Moorbath et al. 1986; Nutman & Friend 1989). Recent geochemical, isotopic and geochronological work by e.g. White (2001), Nielsen et al. (2002) and Bernstein (2003) has confirmed Chadwick's (1981) observation that there are several generations of Ameralik dykes which may not be related to each other.

The Isua greenstone belt, Malene supracrustal rocks, and the Akilia association

Soon after it was discovered that the Amîtsoq gneisses were early Archaean it was realised that the **Isua greenstone belt** north-east of Godthåbsfjord (Fig. 4) is also early Archaean, since it is cut by orthogneisses containing Tarssartôq dykes equivalent to Ameralik dykes (Gill & Bridgwater 1979; Nutman 1986). The Isua greenstone belt had been found in the 1960s by geologists from Kryolitselskabet Øresund A/S and was initially considered to be of Proterozoic age. A Rb/Sr whole-rock age from orthogneisses intruding the Isua greenstone belt and a Pb/Pb age from banded iron formation within the belt confirmed its early Archaean age (Moorbath et al. 1972).

Other sequences of supracrustal rocks occur e.g. in the vicinity of Nuuk. McGregor (1969) coined the term **Malene supracrustal rocks** for a "sequence of supracrustal rocks, younger than the Ameralik dykes, that crops out in the area around Godthåb and is well exposed on the western slopes of the mountain Store Malene, east of Godthåb" (McGregor 1973). Figure 6 shows supracrustal rocks and orthogneisses on a nearby mountain south-east of Nuuk, from the area where the Malene unit was first defined.

Figure 6: *Middle Archaean supracrustal rocks, orthogneisses and granitic veins at the mountain of Hjortetakken (914 m, 10 km south-east of Nuuk), where the Malene supracrustal rocks were first defined. View towards north-east.*

The Malene unit was subsequently extended and became widely used to cover other greenstone belts in the region that were thought to be younger than the Amîtsoq gneisses (e.g. Hall & Friend 1979). However, the Malene supracrustal rocks were subsequently shown e.g. by Nutman et al. (1989) and Schiøtte et al. (1988) to comprise rocks of different ages, with different provenance, and within different tectono-stratigraphic terranes, and the term is no longer in use.

Yet another term, **Akilia association,** also to be abandoned later by some authors (Nutman et al. 1996), was introduced by McGregor & Mason (1977) for enclaves of rocks intruded by Amîtsoq gneisses (and thus implying that they were older than the Malene supracrustal rocks). The largest known enclave, that of the Isua greenstone belt, was for some reason not included. The Akilia association was described as comprising supracrustal rocks including banded iron formation, ultrabasic and metabasic rocks, and rocks of unknown origin which are common on the islands of Akilia, Qilanngaarsuit and other islands in the archipelago south-west of Nuuk, and within Amîtsoq gneisses south of the Isua belt (e.g. Crewe 1986; Nutman et al. 1996). The term gradually became less precise with the introduction of the terrane model and the realisation that the early Archaean of the Godthåbsfjord is not an association of genetically related rocks but comprises several unrelated sequences.

The Qôrqut granite complex

The only of the old rock unit names surviving unchanged to date is the Qôrqut granite complex, a dense swarm of inclined, c. 2530 Ma old, post-kinematic granite sheets that crops out on south-eastern Storø and between Ameralik and Kangiusap Nunaa in central Godthåbsfjord (Baadsgaard 1976; Brown et al. 1981; Moorbath et al. 1981; Friend et al. 1985; McGregor 1993). The granite complex is generally post-kinematic but was probably contemporaneous with local late, upright shear zones (McGregor 1993, discussed in a later section). The individual sheets are generally up to some 10-50 m thick (Fig. 7), and the granite sheets commonly form around 50 per cent of the local rock volume. A series of detailed field maps of the granite complex, drawn from aerial photographs, are included in the DVD accompanying this report (**Clark Friend field map**). In some places successive granite sheets have been emplaced into their immediate predecessors to form an almost solid, sheeted body that excludes any host rocks. There is a good apparent correlation between the mapped extent of the Qôrqut granite complex and a weak aeromagnetic high (see Rasmussen & Garde, this report). If this correlation is valid, it indicates that the granite does not continue far from the Qooqqut area towards the west under the western, gold mineralised part of Storø, contrary to the interpretation of NunaMinerals A/S (2003) reported in the chapter on economic potential of the greenstone belts in this report.

Figure 7. *Early Archaean orthogneiss with a relict of an Ameralik dyke, cut by a sheet of Qôrqut granite. Note the plagioclase phenocrysts in the Ameralik dyke, lower left. The exposure is c. 3 m high. South coast of Storø, within the area where the Amîtsoq gneiss and Qôrqut granite complex were first defined.*

The Qôrqut magmas consisted of numerous small melt batches derived from rocks with a chemical composition similar to the locally exposed grey TTG gneisses (Friend et al. 1985). Its chemistry and mineralogy show that the magma was hydrated, had an approximate minimum melt composition at less than 5 kbar total pressure, and was emplaced at a moderate temperature. However, no convincing explanation of the heat source and timing of the granite emplacement has been published. McGregor (1993) speculated that it was due to local radioactive crustal heating following terrane assembly (see below). However, the granite-forming event is so much younger than the original magmatic and tectonic continental crustal accretion that it is unlikely to have been triggered by heat accumulated in the crust during these processes. Furthermore, the granite emplacement as numerous thin sheets and the total absence of rapakivi-like textures do not suggest that a large, long-lived magma existed in the deep crust prior to the intrusion.

The north-eastern extent of the Qôrqut granite complex within the Ivisârtoq map sheet area has not been determined with certainty. The research group from University of Exeter, U.K., who mapped the Ivisârtoq map sheet for the Survey in the early 1980s, found that much of the ground was covered by leucocratic and weakly deformed granitic rocks of presumed or proven late Archaean age. Limited whole-rock geochronology suggested that the majority of the granitic rocks were around 2.6 Ga in age (Brewer 1985; Robertson 1985, 1986), but the group did not have access to precise zircon dating. More recent, unpublished age data indicate that the Qôrqut granite complex is more widespread than shown on the published geological maps (A.P. Nutman, personal communication, 2003).

Early views on the magmatic, tectonic and thermal accretion of the Nuuk region

Already from the onset of the detailed study of the Nuuk region it was clear that the quartzo-feldspathic grey gneisses were largely of magmatic origin (Fig. 8) and not transformed metasedimentary rocks, as was proposed at around that time for orthogneisses e.g. in South Greenland.

Several of the early conclusions are still valid, although some studies were carried out on suites of rocks that have later been shown not to be cogenetic (e.g. Compton 1978). REE studies by O'Nions & Pankhurst (1974) and Pillar (1985) showed that hornblende and garnet were present in the source of the Nûk gneisses. McGregor (1979) noted their predominantly tonalitic-trondhjemitic and granodioritic compositions (besides minor dioritic and Fe-rich phases), suggesting that the main source of the orthogneisses was via partial melting of basaltic rocks. This was later supported by melting experiments (Winther & Newton 1991; van der Laan & Wyllie 1992) and corroborated by Garde (1997) from a detailed geochemical study of Nûk-type orthogneisses north-west of Godthåbsfjord. The most likely origin of the TTG gneisses thus seems to be slab melting of hydrous basaltic rocks. Nutman et al. (1984) studied iron-rich, early Archaean augen gneisses and argued that their relatively mafic compositions required a component of mantle melts in their genesis.

Figure 8. *Polyphase middle Archaean orthogneiss, with compass for scale. South coast of Bjørneøen (in the original type area of the Nûk gneisses).*

It was also quickly recognised that horizontal tectonic interleaving was an important component of the continental crustal accretion in the Nuuk region. Bridgwater et al. (1974) suggested that the Amîtsoq gneisses and Malene supracrustal rocks were tectonically interleaved during an early phase of crustal shortening, then injected by the magmatic precursors of the Nûk gneisses, and finally isoclinally folded. The idea of horizontal crustal shortening was correct, although Friend et al. (1987) showed that the tectonic intercalation postdated the magmatic emplacement of the Nûk gneiss precursors.

Wells (1976a, 1979, 1980) investigated the thermal evolution of the middle continental crust during magmatic crustal accretion in the south-eastern part of the Nuuk region. He modelled both over-accretion where successive tonalitic magmas were emplaced on top of the previous ones, and under-accretion where they were emplaced at the bottom, and then compared the predicted heat distributions with the distribution of amphibolite and granulite facies rocks. He interpreted the amphibolite-granulite facies transitions as essentially prograde, and concluded that the granulite facies metamorphism was the result of magmatic over-accretion and thus followed quickly after the magmatic accretion of the grey gneisses. According to his interpretation the amphibolite and granulite facies metamorphism in the southern part of the Nuuk region took place at different crustal levels during a single, c. 2800 Ma thermal event, followed by crustal stabilisation. Chadwick & Coe (1983) considered that the 2800 Ma granulite facies metamorphism outlasted the regional deformation and was part of a regional cratonisation process. However, both Bridgwater et al. (1976) and McGregor et al. (1983; 1986) showed that post-granulite facies deformation had occurred in some areas, and Dymek (1984) documented polymetamorphism.

In hindsight Wells' thermal modelling was a highly relevant exercise that demonstrated how granulite facies conditions can be a natural and rapid consequence of the continued injection of hydrated tonalitic magmas into the middle crust. His findings have important consequences for the understanding of partial melting of newly accreted orthogneisses to form leucocratic granites, fluid movements in the middle crust, and auto-retrogression under middle to upper amphibolite facies conditions (e.g. Nutman et al. 1986; Garde 1990, 1997). However, most of Wells' regional geological conclusions were incorrect because he was comparing rocks that were later shown to belong to different terranes with separate crustal histories.

The tectono-stratigraphic terrane model

Introduction

In the late 1980s it was recognised that the Nuuk region consists of several individual tectono-stratigraphic terranes, i.e., crustal blocks that had evolved independently of each other until they were tectonically juxtaposed in the late Archaean (Friend et al. 1987, 1988; Nutman et al. 1989. Key aspects of the terrane model in the Buksefjorden area were recently tested by Crowley (2002) who showed that the previous conclusions by the above mentioned authors were essentially correct.

Prior to this recognition it had already been noted that the early Archaean Akilia supracrustal rocks and Amîtsoq gneisses appeared to be confined to the central part of the Nuuk region. Also, the increasing number of precise age determinations that became available from several parts of the region gradually revealed that the middleArchaean orthogneisses belonged to (at least) two different, geographically separate age groups of around 3.0 and 2.8 Ga, and that the granulite facies events in the north-western and south-eastern part of the Nuuk region were not contemporaneous. A final step towards the recognition of the terranes was a puzzling observation in the eastern part of the Godthåbsfjord area that amphibolite facies gneisses were overlain by granulite facies gneisses, and that they were separated from each other by a flat-lying, mylonitic shear zone.

The terrane model led to a complete revision of the interpretation of the magmatic and tectonic continental crustal accretion in the Nuuk region, for the first time suggesting that plate-tectonic processes were operating in the late Archaean, although some of the 'plates' appear to have been no more than tectonic panels a few kilometres wide. Another effect of the new model was that most of the previously defined, and by then widely used and famous lithological units such as the Amîtsoq gneisses, Nûk gneisses and Malene supra-crustal rocks had to be restricted to one terrane or became redundant. The map sheet description by McGregor (1993) provides a good overview of the geology in the Nuuk area as it was perceived soon after the introduction of the terrane concept. However, along with the appearance of new field and geochronological data the new terranes themselves and their boundaries have been undergoing continuous revision, and new units have been defined.

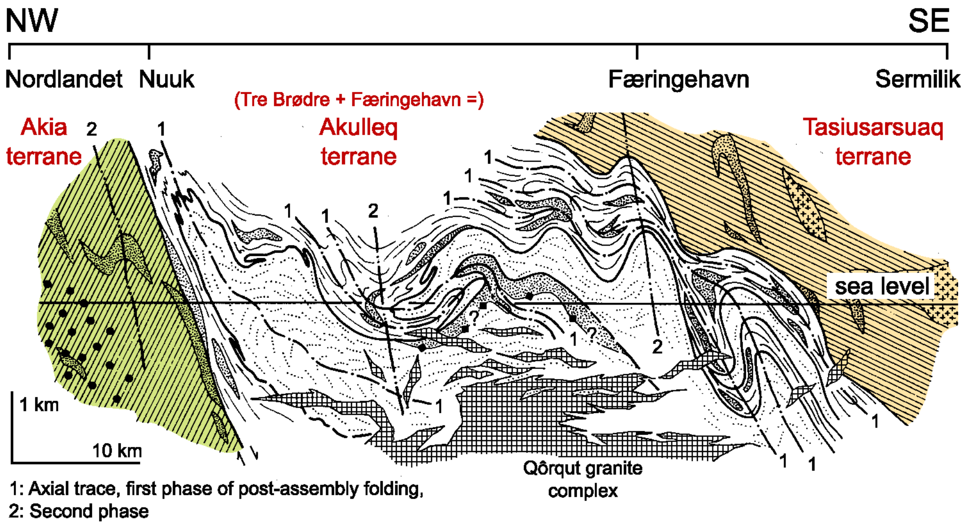

Figure 9: *Schematic cross section of the stacked and folded Tasiusarsuaq and Akulleq (= Tre Brødre + Færingehavn) terranes overlying the Akia terrane, modified from Nutman et al. (1989). The Akia-Akulleq terrane boundary is shown here as SE-dipping, whereas the (?) NW-dipping magnetic boundary along Nordlandet is not shown. Note the large vertical exaggeration.*

Two small crustal blocks, the **Tre Brødre and Færingehavn terranes**, were first identified in the south of the Nuuk region, bounded by the larger **Tasiusarsuaq terrane** in the south-east and the **Akia terrane** in the north-west; the Færingehavn and Tre Brødre terranes were subsequently extended northwards and combined into a unit called the **Akulleq terrane**. The south-eastern terranes were described as forming a SE-dipping, folded tectonic stack with the Tasiusarsuaq terrane on top in the south-east and successively underlain by the Tre Brødre and Færingehavn terranes towards the north-west (Fig. 9). The terrane boundaries themselves were described as inclined and commonly folded flaggy zones, 10-50 m wide, with mylonitic to ultramylonitic or blasto-mylonitic textures and consisting of finely layered quartzo-feldspathic and quartz-rich rocks, mica- and amphibolite-rich schistose rocks, seams of coarse-grained fuchsitic rocks, and centimetre-thin disrupted pegmatite veins (Friend et al. 1987).

The Tasiusarsuaq terrane

General features

The Tasiusarsuaq terrane largely consists of late Archaean (2920-2860 Ma, Friend et al. 1996) tonalitic to dioritic orthogneisses, and is characterised by a 2.8 Ga granulite facies metamorphic event that has not been recognised elsewhere in the Nuuk region. No early Archaean rocks have been identified. The folded, SE-dipping boundary between the Tasiusarsuaq terrane and the Tre Brødre (viz. Akulleq) terrane was named the Qarliit Nunaat thrust; the assembly obviously postdated the 2.8 Ga granulite facies metamorphism but predated the last phase of folding.

Grey orthogneisses in the northern part of the Tasiusarsuaq terrane were first described as Nûk gneisses (Compton 1978; Coe 1980), i.e. quartzo-feldspathic gneisses not containing Ameralik dykes. However, later geochronological work has shown that they are 2.9-2.8 Ga old and thus significantly younger than the type Nûk gneisses. The north-western part of the terrane also includes nebulitic gneisses with thin rafts of amphibolite resembling Ameralik dykes. It was first suggested that these were strongly reworked Amîtsoq gneisses (Chadwick et al. 1974; McGregor et al. 1986; Collerson et al. 1986; Nutman et al. 1986). However, both Rb-Sr and Sm-Nd whole-rock studies and U-Pb zircon geochronology yielded middle to late Archaean ages and preclude that the protoliths are early Archaean (e.g. Moorbath et al. 1986; Nutman & Friend 1989).

Wells (1976b) and Vines (1979) mapped isoclinal folds that were originally isoclinal or overturned and which predated the granulite facies metamorphism and Ilivertalik granite, and Chadwick & Coe (1973, 1983) described upright folds and shear zones that postdate the recumbent folding but were probably established prior to the granulite facies metamorphism.

The Ilivertalik granite in the south of the Tasiusarsuaq terrane (Bridgwater et al. 1976; Chadwick & Coe 1983) consists of up to 2 km thick, flat-lying granite sheets and subordinate dioritic and basic rocks. It was emplaced during the granulite facies event, and was dated by Pidgeon et al. (1976) and Pidgeon & Kalsbeek (1978) at c. 2795 Ma using the conventional U-Pb zircon method.

The 2.8 Ga granulite facies metamorphism in the Tasiusarsuaq terrane

As already mentioned the Tasiusarsuaq terrane underwent a granulite facies thermal episode that is not recognised elsewhere in the Nuuk region. In the northern part of the Tasiusarsuaq terrane the distribution of granulite facies rocks is patchy, becoming more widespread southwards. Wells (1976a, 1979), Nutman et al. (1989) and Riciputi et al. (1990) investigated the granulite facies metamorphism and found peak conditions around 750-800 °C, 7-8.5 kbar. Garnet overgrowths in granulites from the Sermilik area, probably formed by the reaction opx + plag + water = gnt + qtz, suggested to Wells (1979) that the granulite facies event was followed by near-isobaric cooling.

Both Wells (1979), Coe (1980), and Chadwick & Coe (1983) described the amphibolite-granulite facies transition as essentially prograde. However, the common observation in the grey gneisses of blebby textures, i.e., the replacement of hypersthene by cm-sized, rounded aggregates of sheaf-like biotite and spongy actinolitic hornblende with quartz intergrowths (besides epidote and locally garnet) strongly suggest that large parts or all of the amphibolite facies areas have been retrogressed from granulite facies (Nutman et al. 1989). Using the reaction opx + plag + water = hbl + gnt + qtz, they calculated retrogressive metamorphic P-T conditions of c. 650-740 °C, 6-7 kbar. Furthermore, the deformation of some of the blebby textures also suggested that some deformation outlasted the granulite facies metamorphism, in accordance with the fact that the post-granulite facies Qarliit Nunaat thrust is folded.

The retrogression and hydration in the hanging wall suggest that significant fluid movement occurred during the terrane assembly when the Tasiusarsuaq terrane was thrust over the Tre Brødre and Færingehavn terranes. Continued, but more localised retrogression and fluid movement took place at c. 530-580 °C and 5-5.5 kbar during the subsequent formation of steep linear shear zones (hornblende-plagioclase thermobarometry, Nutman et al. 1989).

The Tre Brødre and Færingehavn terranes in the southern Nuuk region

The Tre Brødre terrane and Ikkattoq gneisses

The Tre Brødre terrane tectonically underlies the north-western boundary of the Tasiusarsuaq terrane along the Qarliit Nunaat thrust (Fig. 4) and is dominated by uniform, c. 2.8 Ga grey gneisses with a simple crustal history, the Ikkattoq gneisses of Friend et al. (1988). The Ikkattoq gneisses are mostly granodioritic rocks with pegmatitic banding; there are also small volumes of older diorite. As for the grey gneisses in the northern Tasiusarsuaq terrane, the Ikkattoq gneisses were previously thought to be part of the c. 3.0 Ga Nûk gneisses because no dyke relics were observed within them (e.g. Compton 1978; Coe 1980). The oldest deformation that has been observed in the Ikkattoq gneiss seems to be related to the juxtaposition of the Tre Brødre and Færingehavn terranes. The previous model (Stainforth 1977; Chadwick et al. 1980) of heterogeneous deformation of a gabbro-anorthosite sheet north of Buksefjorden during syntectonic intrusion of grey gneiss precursors is not sustainable with the terrane model.

The Ikkattoq gneisses have intruded or are in tectonic contacts with several different belts of supracrustal and basic plutonic rocks. These greenstone belts mainly consist of amphibolite associated with gabbro-anorthosite, metapelite, and quartz-cordierite (±anthophyllite-sillimanite-garnet) gneiss; such quartz-cordierite rocks also occur e.g. on Store Malene and Sadelø (Beech & Chadwick 1980; Dymek & Smith 1990; Smith et al. 1992). The latter unusual, siliceous and magnesium-rich metasedimentary associations have been interpreted as weathered or hydrothermally altered and metamorphosed acid volcanic rocks. The hydrothermal alteration is thought to have taken place by percolating sea water during diagenesis (Smith et al. 1992).

At the same time as the terrane model was introduced by Friend et al. (1987) it was shown by other workers that the Malene supracrustal rocks as defined by McGregor (1973) were an artificial unit of unrelated rocks. Ion probe dating of detrital zircons from metasedimentary rocks in the south-western part of the Tre Brødre and Færingehavn terranes demonstrated that the supracrustal sequences in these areas have a range of middle to late Archaean depositional ages, and that some also contain early Archaean detrital zircons (Kinny et al. 1988; Schiøtte et al. 1988).

The Færingehavn terrane

The Færingehavn terrane north-west of the Tre Brødre terrane was only defined in the coastal area around Færingehavn, and the proponents noted themselves that there might be more than one allochthonous tectonic slice (Fig. 9; Friend et al. 1987). This terrane comprises a large range of early and late Archaean lithologies including (a) early Archaean orthogneisses thought to be continuous with the original Amîtsoq gneisses around inner Ameralik; (b) early Archaean iron-rich augen gneisses that cut previously deformed Amîtsoq gneisses (Chadwick & Nutman 1979; Nutman et al. 1984); (c) Akilia association supracrustal rocks in the archipelago south of Nuuk with e.g. banded iron formation, quartzite and ultrabasic rocks (Fig. 10; McGregor & Mason 1977); (d) younger supracrustal rocks (originally part of the Malene supracrustal rocks); and (e) late Archaean aplitic, pegmatitic and granitic intrusive sheets (the Sâtut gneiss of Friend et al. 1987).

Figure 10: *Early Archaean garnet-rich metasediment of possible chemical sedimentary origin, belonging to the Akilia association. Granatø, Qilanngaarsuit area. Diary for scale.*

Some of the early Archaean rocks in the Færingehavn terrane contain textures indicating retrogression from granulite facies. Such textures are, however, absent from the late Archaean rocks, and the granulite facies event in the Færingehavn terrane is therefore correlated with the 3.6 Ga event described from nearby Qilanngaarsuit by Griffin et al. (1980) and dated more accurately by Nutman et al. (1996).

The Akulleq terrane, Itsaq gneiss complex and Ivinnguit fault

The Akulleq terrane

The **Akulleq terrane** of McGregor et al. (1991), was probably established for two reasons: first of all, the Tre Brødre and Færingehavn terranes in the south-west could not be identified as individual blocks as the detailed investigation moved from the coastal areas into the inland region north-east of the Qarliit Nunaat thrust, and it was therefore convenient to combine them into one common unit that comprised both early and late Archaean rocks. Secondly, another tectonic boundary, the **Ivinnguit fault**, had been identified in several parts of western Godthåbsfjord. This structure separates the central Nuuk region (characterised by large component of early Archaean gneisses) from the north-western part (containing the c. 3.0 Ga Nûk gneisses and related granitic rocks around Nuuk, western Sadelø, Bjørneøen, and most of the peninsula east of Qussuk). The region to the north-west of the Ivinnguit fault was called the Akia terrane (Friend et al. 1988). The Akia terrane and not least the Ivinnguit fault itself are discussed in a separate section below.

The new terrane in central Godthåbsfjord (Akulleq: "the one that lies in the middle" in Greenlandic, McGregor et al. 1991) was established as a composite tectonic block that contained all the early Archaean rocks known in southern West Greenland, bounded in the south-east by the Qarliit Nunaat thrust separating it from the Tasiusarsuaq terrane, and in the north-west by the Ivinnguit fault that separates it from the Akia terrane (Fig. 4). In the south it comprises the previously established Tre Brødre and Færingehavn terranes, which were redefined by McGregor et al. (1991) as local rather than regional features. Its central part contains large areas of early Archaean gneisses (including the original Amîtsoq gneisses), as well as the late Archaean Ikkattoq gneisses which underwent prograde amphibolite facies metamorphism between 2740 and 2700 Ma (Crowley 2002). In the north it also comprises the Isua greenstone belt and the adjacent c. 3.8 and 3.6 Ga grey and white, respectively tonalitic and granodioritic-trondhjemitic orthogneisses that intrude it.

Nutman et al. (1996) have more recently described the Akulleq terrane as a pile of complexly folded tectonic slices of supra- and infracrustal rocks with different ages and origins that include early Archaean orthogneisses, early and late Archaean supracrustal units and layered intrusive basic rocks, and intruded by large volumes of the 2.8 Ga Ikkattoq gneisses (Fig. 9). The eastern, inland parts of the terrane between 64° and 64°30' are poorly known, and a large triangular magnetic high in this area (discussed elsewhere in this report) cannot be correlated with the ground geology as it is known today. Furthermore, there might also be problems with the presently defined north-western boundary along the Ivinnguit fault (see below). Therefore the Akulleq terrane as it is currently defined may not hold up to further investigations.

The Akulleq terrane preserves a higher crustal level than the adjacent Tasiusarsuaq terranes. This can be seen both from the inverse distributions of granitic rocks and granulite facies areas in the three terranes (Fig. 4) and from the higher concentration of large-ion lithophile elements in the Akulleq terrane revealed by airborne gamma spectrometry (Fig. 25) and stream sediment geochemistry (Fig. 23) also presented in this report. This conclusion is also consistent with the distribution of known gold anomalies in the Nuuk region (Fig. 22; Steenfelt 1987, 1994, 1990; Steenfelt et al. 1990).

The higher crustal exposure within the Akulleq terrane - or a geographical area that largely overlaps with it - shows that this area has experienced a major downthrow relative to the neighbouring terranes. The downthrow may have occurred during the late Archaean terrane assembly or in the Palaeoproterozoic. The major aeromagnetic boundary visible on Fig. 27 west of the terrane boundary along the northwestern margin of Godthåbsfjord may represent a major NW-dipping thrust fault that could account for part of the downthrow.

The Itsaq gneiss complex

Realising that the Akulleq terrane was not a single geological unit, Nutman et al. (1996) introduced a new term, the **Itsaq Gneiss Complex,** as a collective name for <u>all</u> early Archaean (3.8-3.6 Ga) rocks in the Nuuk region irrespective of their genetic relationship (Itsaq: 'ancient thing' in Greenlandic). Their Table 6 gives an overview of the main early Archaean lithologies in the Nuuk region, supported by zircon age data. The Itsaq gneiss complex includes both the former Amîtsoq gneisses, the Isua greenstone belt in the north, and the numerous smaller areas and enclaves of early Archaean supra- and infracrustal rocks in the central and southern Nuuk region that were previously collectively called the Akilia association. Thus, the Itsaq gneiss complex does not replace the terms Amîtsoq gneiss or Akilia association, although the authors recommend that the terms 'Amîtsoq gneiss' and 'Akilia association' are abandoned because they "include unrelated rocks". Nutman et al. (1996) further recommended that the Isua greenstone belt is only used as a geographical entity. In conclusion, the term 'Itsaq gneiss complex' can be equalled to 'the early Archaean rocks of the Nuuk region'; in fact, the latter entity is so concise that the new term 'Itsaq gneiss complex' seems superfluous and likely to cause confusion.

The Ivinnguit fault

Unlike the Qarliit Nunaat thrust, the Ivinnguit fault (Figs. 4, 9) is a straight, steeply dipping structure. According to Friend et al. (1988) it separates the Akia terrane in the mainland to the north-west from the Akulleq terrane around central Godthåbsfjord, but there may also be other interpretations which are addressed in the following.

The south-western part of the Ivinnguit fault is parallel to a major magnetic boundary along the east coast of Nordlandet (see below and Rasmusssen & Garde, this report), but the fault is not itself represented in the regional aeromagnetic data. On the south coast of Bjørneøen the Ivinnguit fault is cut by thin, weakly deformed Qârusuk granitic dykes dated at 2712 ±9 Ma (Fig. 13; Friend et al. 1996), which provide a minimum age for the assembly of the Akia and Akulleq terranes.

The Ivinnguit fault is generally exposed as a thin (only 10-15 m) zone of chlorite-rich mylonite and ultramylonite, which coincides along part of its length with the Palaeoproterozoic Ataneq fault (Fig. 4; Friend & Nutman 1991; McGregor et al. 1991). The Ivinnguit fault is generally parallel to the tectonic fabric in its host rocks and only locally discordant to lithological layering. The fault locally dips moderately NW and in this area contains a SW-plunging linear tectonic fabric, which may indicate that the terrane juxtaposition occurred by both strike-slip movement and uplift of the Akia terrane. Accordingly it has been suggested that the overall steepness of the Ivinnguit fault may not be a primary feature but is due to later shearing at around 2550 Ma that also affected the host rocks (see below).

Hanmer et al. (2002) have recently questioned the significance of the Ivinnguit fault in the area west of the Isua greenstone belt (Fig. 4). Based on field observations and U-Pb zircon geochronology they contend that a flat-lying early Archaean thrust stack in this area is cut by a 2948 ± 8 Ma pegmatite, and that a nearby 2991 ± 2 Ma old tonalite sheet is post-kinematic with respect to the thrusting. They argue that the Akia and Akulleq terranes were stitched by this tonalite sheet and that the thrusting was directed towards the Akia terrane contrary to the earlier interpretation. They furthermore suggest that the Akia-Akulleq interface was not an important late Archaean tectonic structure and question its identification as an accretionary boundary. More work is needed to prove or disprove these statements.

Park (1986) also analysed part of the Ivinnguit fault in the Ilulialik area, where it has been reactivated by the Ataneq fault (see below).

The Akia terrane

Location and bounding structures

The Akia terrane, as currently defined north-west of the Ivinnguit fault (Friend et al. 1988), comprises the original type area of the 3.0 Ga Nûk gneisses around Nuuk (Fig. 11), most of Sadelø and Bjørneøen, and the mainland north-west of Godthåbsfjord stretching from Nordlandet to the Inland Ice in the area north-west of the Isua greenstone belt (Fig. 4). The location of the Akia terrane boundary in the vicinity of the Isua greenstone belt is uncertain; it has previously been described as a splay zone of several small faults (Friend et al. 1988) and was recently discussed by Hanmer et al. (2002). The position of the north-western boundary of the Akia terrane, north of 65°N, was addressed by Garde et al. (2000) but has not been established with certainty.

Figure 11: *Polyphase middle Archaean orthogneiss with folded granitic veins. Compass for scale. South coast of Bjørneøen, within the original type area of the Nûk gneiss.*

As mentioned elsewhere in this report the presumed south-eastern boundary of the Akia terrane (the Ivinnguit fault) is not a feature that is visible on aeromagnetic maps. However, between 5 and 15 km to the north-west of the Ivinnguit fault there is a sharp magnetic boundary along north-western Godthåbsfjord itself (Fig. 4; Rasmussen & Garde, this report). This structure separates the 3.2 Ga granulite facies dioritic gneisses of Nordlandet from the 3.0 Ga Nûk gneisses around Nuuk, which have not undergone granulite facies metamorphism. The magnetic boundary is presumably a major, inclined fault with a significant vertical component. It is generally presumed to be of late Archaean or Palaeoproterozoic age, but no unequivocal continuation of this structure has been established onshore north-east of Nordlandet: the N-S trending high-strain tract around the head of Fiskefjord on strike with the magnetic anomaly is a 3.0 Ga old, granulite facies structure (Garde 1997). Alternatively, the magnetic boundary may continue in the Ataneq fault on the peninsula east of Qussuk. However, the Ataneq fault only appears to host a minor offset in the order of 4 km in this area (Park 1986; Garde 1997). As mentioned above, also the terrane boundary in the area adjacent to the Isua greenstone belt may be in need of revision.

In conclusion, the south-eastern boundary of the Akia terrane, viz., north-western boundary of the Akulleq terrane, is not fully understood. As noted above there is a major change in the exposed crustal level between Nordlandet and western Godthåbsfjord that may or may not be related to the terrane boundary itself. It is possible that the amphibolite facies area with the type Nûk gneisses around Nuuk, between the Ivinnguit fault and the magnetic boundary in Godthåbsfjord, forms a small independent tectonic panel that does not belong to the Akia terrane. Another, previously mentioned but not fully proven possibility (suggested by Hanmer et al. 2002) is that the stitching of the Akia and Akulleq terranes took place before 2720 Ma ago.

Lithological components, granulite facies metamorphism and structural evolution of the Akia terrane

The Akia terrane largely consists of 3.0 Ga tonalitic, trondhjemitic and granodioritic orthogneisses metamorphosed to upper amphibolite to granulite facies (McGregor 1993; Garde 1997), and a 3.2 Ga old quartz-dioritic core on the peninsula of Nordlandet (Fig. 12; MacDonald 1973; Reed 1980). The magmatic precursors of the orthogneisses were intruded into an older supracrustal complex of mainly basic metavolcanic and associated intrusive rocks which include a large layered complex in central Fiskefjord (Garde 1997).

Figure 12: *Granulite facies dioritic gneiss with diffuse partial melt veins. East coast of Nordlandet opposite Sadelø.*

The southern and central parts of the terrane underwent thermal granulite facies metamorphism at 2980 Ma (Dymek 1984; Riciputi et al. 1990; Garde et al. 2000). This was followed by almost simultaneous metasomatism and retrogression under amphibolite facies conditions, controlled by metamorphic fluids escaping from deeper parts of the orthogneisses. The orthogneisses in the east underwent partial melting to form granodioritic and granitic intrusions such as the c. 2975 Ma Qûgssuk granite north and east of Qussuk (Garde et al. 1986; Garde 1997; Garde et al. 2000). The Akia terrane also contains a suite of post-kinematic, circular to sheet-like 2975 Ma noritic to dioritic intrusions with Au-Pt mineralisationThese were probably derived from crustally contaminated ultrabasic magmas (Garde 1991; Garde et al. 2000).

Berthelsen (1960) and Garde (1997) described the structural evolution of the southern part of the Akia terrane, beginning with magmatic and tectonic intercalation of amphibolites (viz., greenstone belts) and orthogneisses by crustal shortening and formation of two generations of recumbent isoclinal folds. These were subsequently refolded by upright dome and basin structures and finally affected by steep ductile shear zones during continued NW-SE crustal shortening prior to 2975 Ma. The easternmost, marginal part of the Akia terrane in the Nuuk area is strongly affected by late Archaean 'straight belt' deformation (e.g. McGregor 1993), but no late Archaean magmatic or tectonic events have so far been documented elsewhere in this terrane.

Late Archaean terrane assembly, structural reworking and late granitic rocks

The Tasiusarsuaq, Akulleq and Akia terranes in the Nuuk region were assembled at around 2720 Ma, around which time the first common events in all three terranes occurred (Friend et al. 1996). An upper age limit of the assembly is the emplacement of the youngest Ikkattoq gneisses in the Akulleq terrane at c. 2750 Ma (Nutman et al. 1989), and all three terranes contain members of the Qârusuk granitic dykes dated at c. 2720 Ma (Fig. 13; Friend et al. 1996). Contemporaneous metamorphic zircons have been found within the Akulleq terrane but not in the other two terranes, and Friend et al. (op. cit.) also reported several other zircon ages around 2.7 Ga from various localities within the Akulleq terrane, and younger episodic recrystallisation at upper greenschist to amphibolite facies conditions between c. 2.6 and 2.5 Ga.

Figure 13. *2720 Ma Qârusuk granitic dyke under the compass, intruding middle Archaean tonalitic gneiss to the right. South coast of Bjørneøen. The Qârusuk dykes represent the first common event in the Akia, Akulleq and Tasiusarsuaq terranes.*

Crustal thickening during the initial stacking of the southern terranes is possibly recorded in metamorphic parageneses that locally indicate higher than normal metamorphic pressures, and according to Friend et al. (1987, 1996) by the observation that the Tre Brødre - Færingehavn terrane boundary is folded by large, tight to isoclinal folds. During the isoclinal folding the metamorphic conditions were middle to upper amphibolite facies, with only local partial melting (Wells 1976a, 1979; Dymek 1984). The Tre Brødre - Tasiusarsuaq terrane boundary is straight and younger than the isoclinal folds, and Nutman et al. (1989) suggested that the isoclinal folds in the Tre Brødre - Færingehavn terrane boundary were developed during the subsequent overthrusting of the Tasiusarsuaq terrane.

The juxtaposition of the southern terranes and the isoclinal folding in the lower two panels were succeeded by en echelon dome and basin F2 folding during continued shortening (Fig. 9; Chadwick & Nutman 1979; McGregor 1979; Chadwick & Coe 1983; McGregor et al. 1986). In the east the folds are very large with wavelengths up to c. 20 km, and generally open. Further west the folding was more intense, developing tight domes and basins with wavelengths about 10 km. The limbs of the upright folds, and locally whole folds, are replaced by straight belts up to 2 km thick steep shear zones.

As mentioned in a previous section, the south-western part of the Akia terrane also appears to have been affected by localised reworking that has not to date been reported from the mainland within this terrane - possibly because it has been overlooked. Granitic dykes belonging to the 2720 Ma Qârusuk dykes are folded and sheared e.g. on Bjørneøen, and several large pegmatite bodies on the ridge of Store Malene east of Nuuk (Appel & Garde 1987) have been affected by ductile deformation along a steep mylonite zone, which McGregor (1993) considered to be equivalent to the Ivinnguit fault.

The Qôrqut granite complex has already been discussed in a previous section. A recent unpublished report by NunaMinerals A/S (2003 p. 30) reports a U-Pb zircon and monazite age of 2530 Ma from one of these pegmatites, suggesting that the pegmatite injection and reworking are contemporaneous with the emplacement of the Qôrqut granite complex. However, the latter complex itself (which was discussed at some length in a previous section) has generally been considered to be post-kinematic.

Palaeoproterozoic events

In the Palaeoproterozoic the Archaean block of southern Greenland was located between the Nagssugtoqidian and Ketilidian orogens already mentioned in the introduction, but the Godthåbsfjord was only mildly affected by these events. A detailed account is outside the scope of this review. Several generations of basic dykes were emplaced (e.g. Hall & Hughes 1990), and the region is cut by a few major faults such as the Kobbefjord fault in the Akulleq and Akia terranes and the Ataneq and Fiskefjord faults in the Akia terrane. The Ataneq fault was studied in detail in the Ilulialik area by Park (1986). She concluded that it is a dextral strike-slip fault with an offset of about 4 km, that it is a reactivated structure from an earlier thrust along part of its length (the Ivinnguit fault), and that certain sections contain considerable amounts of quartz rock deposited from fluids moving through the fault zone. The major magnetic boundary along the east coast of Nordlandet, which may represent the continuation of the Ataneq fault, is discussed in the chapter on geophysical data (Rasmussen & Garde, this report).

The crust was also mildly heated, and small granitic dykes have been found in the Isukasia and Qussuk areas. The former dykes have yielded Rb-Sr and Pb-Pb whole-rock ages of around 1700-1600 Ma (Kalsbeek & Taylor 1983), whereas U-Pb zircon data from the latter suggests an age of c. 2085 Ma (Garde 1997). The chemical compositions of the granitic dykes suggested to these authors that they were formed by very small amounts of partial melting of continental crustal material. In addition, biotite ages of around 1700 Ma have been reported from various parts of the Nuuk region by several authors.

Recent developments in the study of the Nuuk region

Archaean continental masses, terranes and blocks in West Greenland

When the Akulleq terrane was proposed by McGregor et al. (1991), it was seen as a unique, heterogeneous zone of small crustal blocks caught between two larger continental masses of the Akia and Tasiusarsuaq terranes to the north and south. There may still be some truth in this observation, however, it has recently been documented that the latter terranes also have limited extents, and that small tectonic collages were the rule rather than the exception in the middle to late Archaean. Rosing et al. (2001) identified a new early Archaean terrane, the Aasivik terrane, bounded by late Archaean orthogneisses to the south, only about 100 km north of the northernmost exposure of the Akulleq terrane. Likewise, several different crustal blocks have also recently been discovered in the Paamiut region about 100 km south of the Akulleq terrane (Friend & Nutman 2001).

Early Archaean processes

A large amount of the most recent literature from the Nuuk region deals with the early Archaean history of the region itself, the crust-mantle differentiation of the early Earth, and early life; topics that are not much in focus in this report. Much effort has been put into identifying the region's oldest rocks, zircons, and fractions of zircons (e.g. Myers & Crowley 2000; Nutman et al. 2000). Also the significance of these oldest zircons has been hotly debated: do they date the rocks in which they are found, or the early Archaean differentiation of continental crust from the mantle? (e.g. Moorbath & Kamber 1998).

The origin of life and possible evidence for this early life in the Isua greenstone belt has been intensely debated for decades. Some of the most recent discussion has centred around alleged remnants of early Archaean sea water as fluid inclusions in minerals and organic carbon inside an apatite crystal (e.g. Mojzsis et al. 1996; Whitehouse & Fedo 2003). Probably the most robust, but perhaps least spectacular evidence of early life consists of finely disseminated graphite with a likely biogenic carbon isotopic composition, which was reported from a fine-grained clastic metasedimentary rock by Rosing (1999, building on ideas put forward by Schidlowski et al. (1979).

Greenstone belts and their mineral occurrences

(Peter W. U. Appel)

In most reports from GEUS (formerly the Geological Survey of Greenland GGU) and articles dealing with the Nuuk region the term supracrustal belt has been used (see bibliography on the DVD). However, since most of these belts have all the characteristics of greenstone belts, and since the term greenstone belt is used in most parts of the world by geological surveys, mining and exploration companies it has been decided to use the term greenstone belt in this report.

The present chapter describes greenstone belts in the Akulleq terrane only (see chapter on regional geology for description of the terranes). Early Archaean greenstone belts occurring in 3.8 to 3.6 Ga gneisses are found on the islands south of Nuuk to Isukasia in the northeast (Fig. 1). Mid to late Archaean greenstone belts occur in younger gneisses and tonalites from the islands south of Nuuk to the Ivisaartoq area in the northeast (Fig. 1).

There are significant lithological differences between the early and the mid to late Archaean greenstone belts as listed in below.

	Iron formation	Chert	Metasediments
Early Archaean	Very common	Very common	Rare
Mid to late Archaean	Very rare	Rare	Very common

Early Archaean greenstone belts

The largest enclave of early Archaean greenstones occurs in the Isukasia area ~150 km northeast of Nuuk (Fig. 1). This belt is crescent shaped about 40 km long and up to 4 km wide. Enclaves of greenstones up to several kilometres long and a few hundred metres wide occur in the area between Isukasia and Ivisaartoq. These greenstone belts are dominated by large ultrabasic bodies with lesser amount of mafic volcanic rocks and banded iron formation. Even in the smallest early Archaean greenstone enclaves there are mostly nice examplea of banded iron formation. Small early Archaean greenstone enclaves are found in gneisses and tonalites on the island of Storø and on the islands south of Nuuk. The contacts between the early Archaean greenstones and the gneisses are either structural or the gneisses intruded into the greenstone belts. The early Archaean greenstone enclave at Isukasia and another much smaller on an island south of Nuuk have been studied studied in great detail, whereas other enclaves of similar ages have not been investigated in much detail. The present description will focus on the greenstone belt at Isukasia.

It has been known for 30 years that the Isua Greenstone Belt (IGB) rocks at Isukasia are at least 3.7 Ga old (Moorbath et al. 1973) and this has not been changed much, but debate persists whether deposition occurred closer to 3.7 or 3.8 or even whether there are two separate periods of deposition within this time range (e.g. Nutman et al. 1997). Measured dates depend on rock type, isotopic method used, and interpretation of field evidence in different sectors of the IGB. There is no convincing evidence for in situ rocks older than ca.

3.8 Ga, but recent Pb-isotope data on IGB metasediments and Pb-ores (Kamber et al. 2001; Kamber et al. 2003) suggest that important geochemical features pertaining to pre-4.0 Ga mantle and crust can be recognised. Such work follows on from previous modelling of the age of the least radiogenic Pb-isotopic composition so far found on Earth, namely in small lead occurrences in the IGB (Appel et al. 1978; Richards & Appel 1987; Frei & Rosing 2001).

Since the first realisation of the scientific importance of the IGB for early Archaic studies in 1971, many research papers have discussed varied aspects of the belt, whilst a geological map of the Isua region was published by the Geological Survey of Greenland in 1986. Later it became evident that the published map needed major revisions and a major re-interpretation of the geology of the IBG was called for. In addition, it was time for the application of new research techniques. In 1996 the broad scale Isua Multidisciplinary Research Project (IMRP) was initiated and was carried out over a period of 5 years (Appel et al. 2003).

The IGB consists of high and low strain domains (Fig. 14), some of which appear to be of slightly different age. The dominating rock types are pillow-structured tholeiitic and high Mg-basaltic rocks. Intercalated in the lavas are extensive bands of chert and banded iron formation, a turbidite as well as garnet-mica schists occasionally with staurolite representing metamorphosed fine-grained sediments. Abundant ultramafic bands of various compositions but of unknown origin are seen. The IGB has suffered several metamorphic events with the first event at ca. 3.7 Ga. Later events took place at 3 Ga and 2.5 Ga. The area has also been repeatedly deformed (Nutman 1986). Carbonate alteration of the IGB took place during several events (Rosing et al. 1996). The first alteration event took place at and immediately below the sea floor at ~3.8 Ga. Later events are coeval with the metamorphic events. Carbonate alteration apparently was most penetrative in the western part of the IGB.

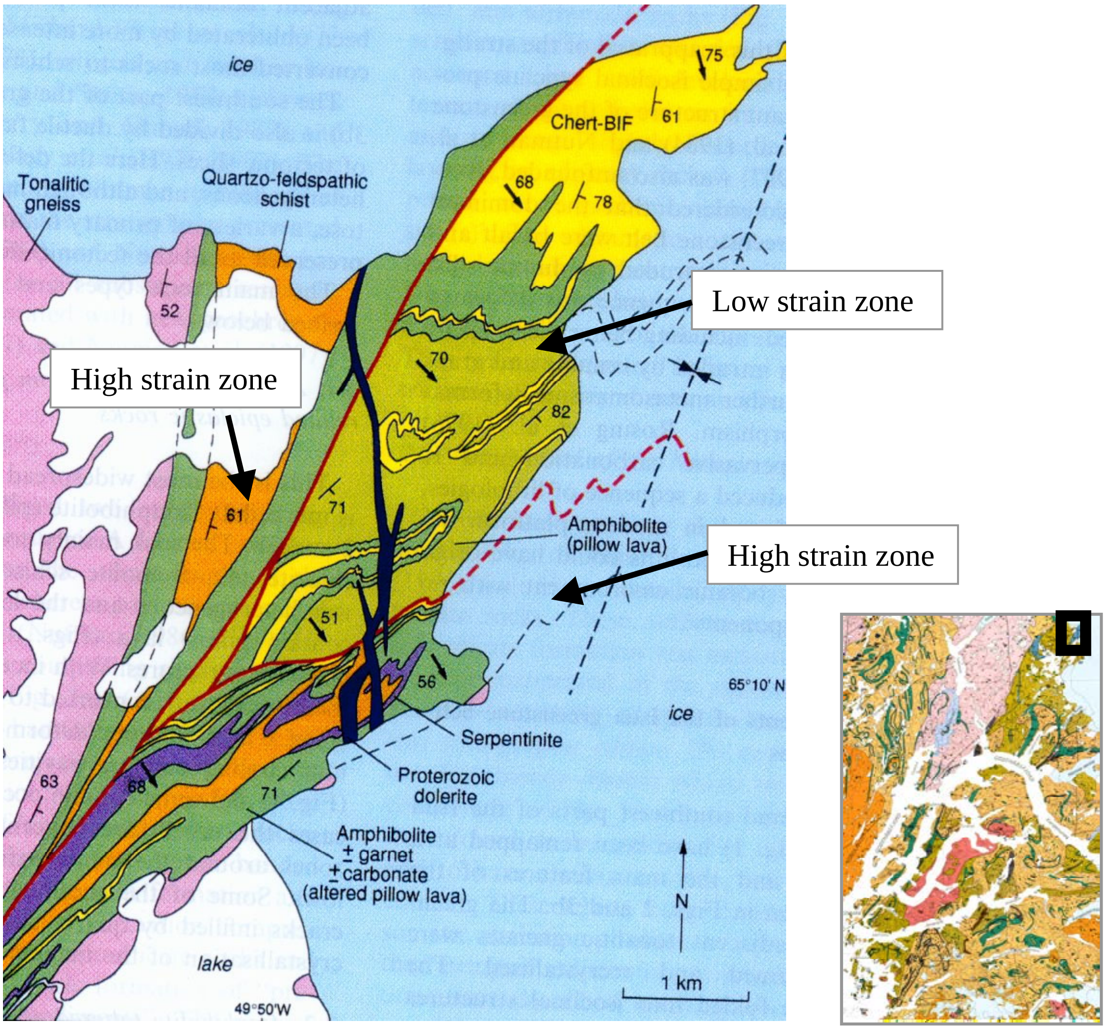

Figure 14: *Eastern part of the Isua Greenstone Belt showing a low strain domain bordered by high strain domains. Red lines show the tectonic contacts between the high and low strain domains (Appel et al. 1998)*

Several post ~3 Ga events have been recorded at the IGB. In the eastern part two intrusive granite sheets up to ten metres wide and traceable for a few hundred metres are seen. These sheets have not been deformed. The granites have not been dated, but a heating event at about 2550 Ma has been recorded in the IGB (Nutman pers. comm.). It is thus possible that the sheets intruded contemporaneously with the Qôrqut granite further south. Late shear zone hosted quartz veins are recorded from different parts of the IGB. They are up to a couple of metres wide and can be traced in zones for up to 150 m. They contain angular fragments of highly sheared pillow lavas. Chalcopyrite is found disseminated to semimassive in these late veins. Gold values up to a few ppm have been recorded.

Highly conflicting geological interpretations of the IGB have been published over the years. In one extreme case it was suggested that all primary structures have been obliterated and all rocks have been carbonate altered beyond recognition and only rock types such as banded iron formation could be recognised (Rosing et al. 1996). At the other extreme end some workers claimed that the preservation of primary depositional features allow detailed stratigraphical and structural mapping (Komiya et al. 1999). The truth is probably somewhere in between. Certain areas are highly strained and no primary features can be recognised whereas several low strain domains host exceptionally well preserved primary features (Myers 2001; Fedo et al. 2001). Prior to the discovery of pillow structures by a M. Masuda from a Japanese research group in the early 1990s, all mafic rock units were regarded as being intrusive (Nutman 1986). After the initial discovery pillow structures, often very well preserved were found in all major mafic rock units in the IGB. In certain parts of the IGB rare volcanic debris flows and pillow breccias were discovered (Appel et al. 1998). The pillow fragments appeared to contain quartz-filled amygdules in which completely unstrained quartz contains tiny inclusions filled with methane and water. This water is interpreted as remnants of a sea-floor hydrothermal system (Appel, et al. 2001; Touret 2003).

Possible biogenic carbon particles have been reported from samples of iron formation from IGB and Akilia rocks (Mojzsis et al. 1996). The biogenicity of this carbon has been seriously challenged by Fedo & Whitehouse (2002), Myers & Crowley (2000), van Zuilen et al. (2003). Rosing (1999) report to have found carbon particles with a biogenic carbon isotopic ratio in a turbidite in the IGB. This claim has not been questioned yet.

Mineral occurrences in the early Archaean greenstone belts

Iron formation

The early Archaean greenstone belts throughout the Nuuk region are characterised by an abundance of banded iron formation (BIF). BIF occurs mostly as quartz magnetite banded iron formation (oxide facies), but silicate facies consisting of alternating bands of grunerite and magnetite is also common. Carbonate facies iron formation consisting of alternating bands of siderite and magnetite is only found in one band in the Isua Greenstone belt (IGB). This band is up to 10 m wide and can be traced for several kilometres. Minor minerals in carbonate facies are graphite, colourless amphibole, pyrrhotite and chalcopyrite. In oxide facies iron formation small amounts of actinolite and pyrite occur. Silicate facies with grunerite contain pyrrhotite, chalcopyrite and locally small amounts of gold (Appel 1982).

In the easternmost part of the IGB a major body of oxide facies iron formation occurs. Two thirds are concealed under the Inland Ice. The iron ore consists of up to 30 cm wide magnetite bands alternating with quartz bands. The ore body is strongly deformed and occurs in a fold hinge. Many pre-deformational dykes cut the iron ore body, which significantly reduces the overall grade. Kryolitselskabet Øresund A/S carried out drilling for several years and estimated the grade to 32% Fe with a tonnage of about 1.5 billion iron ore (GEUS Report file 21270). On top of the quartz magnetite ore is an estimated 500 million tonnes of quartz hematite banded iron ore. High-grade hematite ore is not exposed, but abundant high-grade hematite float is seen in the area. Rio Tinto Ltd. has drilled this hematite orebody in the late 1990s (GEUS Report file 21551). The origin of the hematite is debated.

Gold

The following description of gold occurrences refer to gold found within the IGB. In silicate facies iron formation up to 1.2 ppm of gold has been found. No follow-up has been done on this type of gold occurrence. Gold is frequently found in fuchsite-stained sheared quartz-rich rocks (cherts?) (up to 3.1 ppm over 3 m) (GEUS Report file 21453). The gold is associated with disseminated or semimassive pyrite in quartz. These shear zones are invariably found in close vicinity to sheared ultrabasites. Some of the fuchsite-stained shear zones contain small amounts of galena. Associated with or enclosed in galena are small grains of ullmannite, which in turn has inclusions of greenockite, acanthite and argentian tetrahedrite. Grains of breithauptite together with native antimony and dyscrasite have been found in galena. Within chalcopyrite, inclusions of an argentian bravoite were identified (Appel 1982). No visible gold was found in this type of mineral occurrence. These zones can be traced for several kilometres along strike in poorly exposed parts of the IGB.

Visible gold is found in carbonate altered ultrabasic rocks (Fig. 15). These carbonate-rich zones are shear zone hosted and appear in piles of pillow lavas with intrusive ultrabasic rocks. This listwaenite type of gold occurrence yield grab samples with up to 100 ppm gold. The gold is found in carbonate veins together with tourmaline, galena and arsenopyrite. The zone can be traced for several hundred metres in local shear zone within the IGB. This shear zone does unfortunately occur in an area with very few outcrops.

Figure 15: *Sheeted auriferous carbonate vein in pile of mafic and ultramafic rocks Isua Greenstone Belt. Scale 10 cm.*

Figure 16: *Shearzone hosted sheeted copper sulphide bearing quartz vein with angular fragments of deformed and metamorphosed pillow lava. Scale 10 cm.*

Gold is also found in quartz veins with chalcopyrite. These veins are found in shear zones throughout the IGB containing a few ppm of gold. During the field season 2003 a large system of metre wide quartz veins with chalcopyrite were found in the eastern part of the IGB in areas normally covered by snow patches. The veins contain angular fragments of highly sheared pillow lavas (Fig. 16). These veins indicate high hydrothermal activity in the IGB at a post metamorphic stage (not published yet).

A peculiar type of mineral occurrence is seen in the western part of the IGB. This is a galena mineralised rock with high contents of zinc, gold and silver (up to 14% combined Pb and Zn with up to 6.8 ppm Au and 180 ppm Ag). The occurrence was found by geologists from NunaMinerals A/S. Later investigations have shown that the host rock is an intrusive tonalite sheet (Myers 2001) with an age of ~3.83 Ga (Frei & Rosing 2001). The showing occurs in one metre wide bands, which can be traced for several tens of metres along strike. The ore minerals show a complex sequence of events. The first ore mineral was galena, which was replaced by sphalerite, which again was replaced by the zinc spinel gahnite. The gahnite was later replaced by a Ba-rich muscovite (Appel 2002). A peculiar feature in this showing is the high content of mercury. Up to 50 ppm Hg has been found in grab samples. This is the highest mercury content recorded from this part of Greenland. Lead isotope work (Frei & Rosing 2001) shows that the lead was extracted from >3.8 Ga old rocks. It is not known when the metals were precipitated, but the high contents of Hg indicate a low temperature environment for formation of the mineral occurrence. A suggestion is that it took place during the thermal event which affected the Isuakasia area at about 2.5 Ga (Nutman per. comm.).

Copper

Chalcopyrite and cubanite are frequently found stratabound in banded amphibolites (deformed pillow lavas) in the Isua greenstone belt. The copper sulphides rarely amount to more than a few percent, but can be traced for many hundred metres along strike. Copper is also found in late often shear zone related quartz veins as described above in the section on gold.

Chromium in Early Archaean rocks

In the area between Isukasia and Ivisaartoq (Fig. 1) numerous large ultrabasic bodies such as dunites to peridotites are seen. One of these dunites show well-developed differentiation upwards to harzburgite, gabbro anorthosite and anorthosite. In all these rock types bands of chromitite occur. The thickest bands of massive chromitites are up to 1.5 m wide (Appel, et al. 2002), Rollinson et al. 2002; Lowry et al. 2003). Chromite so far only has been found in one of the numerous ultrabasic enclaves.
The ultrabasic enclave has been metamorphosed to upper amphibolite facies. At the contact between the anorthosite and the harzburgite pargasite and red corundum has been formed closely resembling the ruby occurrences of the Fiskenæsset anorthosite south of Nuuk (Herd et al. 1969).

Mid to late Archaean Greenstone belts

These greenstone belts are well exposed from the coastal region south of Nuuk to the Inland Ice at Ivisaartoq (see Fig. 20 below). They were originally named Malene Supracrustal belts by McGregor (1969). Later work by Schiøtte et al. (1988) showed that the Malene supracrustal rock comprise rocks of different age. The term Malene supracrustal rocks was then abandoned. In this report they will be named mid to late Archaean greenstone belts. Since precious little age work has been carried out on the enclaves of mid to late Archaean greenstone belts they will be treated as one group only. The age relationships of the greenstone belts are uncertain. They are enclaves in mid to late Archaean gneisses and are cut by grey gneisses and by the ~2.5 Ga Qôrqut granite. It is possible that several generations of greenstone belts occur, but at the present time we do not know. The contact relationships between the mid to late Archaean greenstones and the surrounding gneisses either intrusive or strongly sheared.

The best preserved greenstone belt which will be described below is found at Ivisaartoq (Brewer et al. 1984; Chadwick 1985, 1986; Chadwick & Coe 1988). Further detailed work has been carried out at the coastal region (Beech & Chadwick 1980). Store Malene next to Nuuk has been mapped in detail by Appel & Garde (1987). The greenstone belt at Storø hosts very promising gold occurrences, which will be described below (Appel et al. 2000). The greenstone belts have all been metamorphosed under amphibolite facies conditions and been repeatedly deformed.

Ivisaartoq area

The greenstone belt at (Fig. 1 and 20) is more than 40 km long and up to 3 km wide. It has been mapped in 1:20.000 scale by Chadwick (1986) see maps (Chadwick maps). The belt is dominated by deformed pillow structured, low-K tholeiitic amphibolites, with unambiguous indications of the way up, which are associated with deformed pyroclastic and pillow-structured komatiites, dunitic-harzburgitic sills, stratiform gabbro and pale paragneisses sometimes sulphide-rich. On grounds of the way up in the pillow lavas, Chadwick (1986) proposed that the oldest rocks in the greenstone belt are pale quartzo-feldspathic paragneisses, ca 500 m thick with thin pyrite-rich often fuchsite-stained quartz schists. The paragneisses were interpreted as metamorphosed acid to intermediate volcaniclastic sediments (Chadwick 1986).

The pillow lavas, which overlie the paragneisses, are divided into two parts. A lower mafic part including leucogabbro and upper amphibolites including ultrabasic rocks. The two parts are separated by a sheet of ultrabasic rocks called the magnetic marker, 10 to 50 m thick and 8 km long consisting of laminated magnetite-rich forsterite-spinel-carbonate-chlorite rocks and green chlorite-tremolite-serpentine-olivine-magnetite schists with lenticular structures interpreted as deformed lapilli (Chadwick 1986). The underlying amphibolites are homogeneous with few relict pillow structures.

The younger amphibolites, above the magnetic marker comprise banded diopside-epidote-rich rocks and komatiitic rocks with abundant very well preserved pillow structures (Fig. 17). The amphibolites include beds of sulphide-rich metachert up to 4 m thick and a few hundred metres long. Three concordant intrusive sheets of metaperidotite divide the upper sequence of amphibolites into three subsections. The sheets are discontinuous due to boudinage.

Figure 17: *Slightly deformed pillow lavas in the Ivisaartoq area. Note the small patches of garnetiferous skarn. Scale 10 cm.*

Figure 18: *Boudinaged band of calc-silicates (diopside, garnet and ± vesuvianite ± scheelite) in banded amphibolites in Ivisaartoq. Hammer for scale.*

Figure 19: *Calc-silicate vein in pile of deformed pillow lavas (diopside, garnet ± vesuvianite ± scheelite) in Ivisaartoq. Hammer for scale.*

Carbonate alteration is widespread, especially in the Ivisaartoq area. The first alteration event took place after formation of the pillows and is seen as patches of calc-silicate minerals in the pillow lavas (Fig. 17). Somewhat later alteration resulted in calc-silicate formation of bands in the pillow lavas (Fig. 18). Metre-wide veins (Fig. 19) of diopside, feldspar, garnet and vesuvianite sometimes with abundant scheelite were formed after at least one phase of deformation. A very peculiar geochemical feature is displayed by the intrusive peridotite markers. They are exceptionally rich in bromine, but with comparatively low chlorine contents yielding highly unusual Cl/Br ratios (Appel 1997).

Store Malene

On Store Malene close to Nuuk (Fig. 1) an about 15 km long and several hundred metres wide greenstone belt occurs. The Ivinnguit fault from Nuuk up to Isukasia is situated within the belt and has brought together two greenstone belt enclaves of probable different age situated in two different terranes (see section on overview of Archaean evolution -- in this report). The greenstones south of the fault comprise mainly metasediments dominated by biotite-rich pelitic schists, anthophyllite-cordierite-bearing magnesian schists, siliceous, magnesian and aluminous paragneisses rich in cordierite and quartz often with high contents of sillimanite (Appel & Garde 1987). Intercalated in the metasediments are banded amphibolites with no primary structures preserved. Another rock type often found in the metasediments is tourmalinites. They are tourmaline-plagioclase rocks up to a metre thick and traceable with intervals for several hundred metres along strike. The tourmalinites have been interpreted as chemical sea floor precipitates from submarine exhalations (Appel 1988a). The tourmalinites are often scheelite bearing (see below). The greenstone enclave north of the fault is dominated by homogeneous often calc-silicate banded amphibolites and ultramafic rocks. The greenstones and the fault have been cut by numerous thick pegmatites of presumably about 2550 Ma.

Storø

Very little mapping of this important greenstone enclave has been carried out in spite of the obvious economic potential of the gold occurrence occurring on central Storø (Appel et al. 2000).

This greenstone belt is situated at the northern boundary of the Akulleq terrane boundary, which can be traced from Nuuk in Southwest to Isuakasia in Northeast. The greenstone belt at this site comprises a sequence of metasediments and metavolcanics. The sediments consist of garnet-sillimanite schists, rusty quartz mica schists, and quartzites. Quartz muscovite schists are locally fuchsite stained and contain appreciable amounts of sulphides mainly pyrrhotite and pyrite. Furthermore bands of iron formation up to a few metres thick are seen consisting of magnetite, garnet, cummingtonite and feldspar. Locally thin bands of quartz-magnetite banded bands of iron formation are seen. The greenstone belt on Storø hosts the so far the most promising gold occurrence in the Nuuk region (see below).

Coastal area south of Nuuk

Mid to late Archaean greenstones out crop on many of the islands and on the mainland south of Nuuk. They comprise various metasediments dominated by garnet-rich rocks together with quartz-mica-garnet schists. Intercalated in these metasediments are minor layers of banded amphibolites locally with thin bands of tourmalinite. A peculiar and much debated rock type can be traced across many of the islands. It is a rock dominated by anthophyllite-gedrite with minor amounts of sulphides (see below in section on VMS deposits). These have been interpreted as hydrothermally altered sea floor deposits (Beech & Chadwick 1980). Scheelite is commonly seen stratabound in the banded amphibolites (see section on scheelite below).
Lille Narssaq area on the mainland south of Nuuk is dominated by banded amphibolites, which often are partly carbonate altered. Intercalated in the amphibolites are semimassive to massive sulphide showings (see section on VMS deposits).

Mineral occurrences in the mid to late Archaean greenstone belts

Several types of occurrences are encountered, VMS deposits, tungsten and gold showings.

Volcanic massive sulphide deposits (VMS)

Volcanic massive sulphide deposits (VMS) are found in several of the enclaves throughout the Nuuk region (see Fig. 20). There are several types of VMS. In the Ivisaartoq area an about 50 m thick and many hundred metres long band of massive to semimassive pyrite and quartz is seen. The quartz is locally fuchsite stained. Kidd Creek Ltd., NunaMinerals A/S and others have grab sampled this zone, but without any exciting assay results.

Another occurrence of VMS is best seen at Lille Narssaq south of Nuuk (Fig. 20). A several tens of metre wide zone intercalated in banded amphibolites traceable for about a hundred metres consist of semimassive pyrrhotite with small amounts of pentlandite and chalcopyrite. Grab sampling yielded up to 980 ppm Ni (Appel 1990c).

Another occurrence of VMS is seen on several of the islands south of Nuuk, immediately south of Qooqqut and is probably also represented on Storø and Bjørneøen (Fig. 20). The latter two localities have been found by NunaMinerals A/S. On the islands south of Nuuk the VMS deposits consist of rhombic amphiboles with semimassive to disseminated sulphides. The sulphides comprise pyrrhotite, pyrite, chalcopyrite, sphalerite and locally molybdenite. The zinc spinel gahnite is also often present. These zones are intercalated in banded amphibolites. The following peak values have been found: 1.1 % Zn, 0.18 % Cu, 0.18 % Sn, 0.34 % Mo, 82 ppm Se and 20 ppm Ag. The origin of these showings is still debated (Appel 1988b).

VMS showings on Bjørneøen and Storø discovered by NunaMinerals A/S are not described in any detail but contain up to 3.55 % Zn, 1.33% Pb, 33 ppm Ag and 0.153 ppm Au (GEUS Report file 21514).

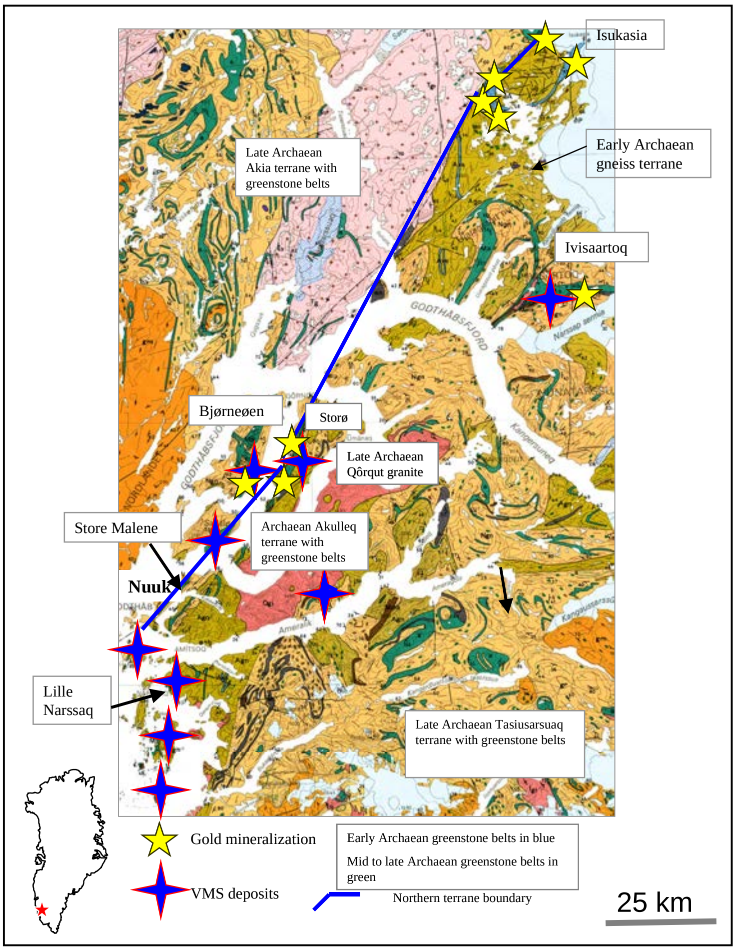

Figure 20: *Simplified geological map with VMS deposits and gold showings in greenstone belts of the Nuuk region.*

Tungsten occurrences

The first indications of scheelite in the Nuuk region were found in 1982 in heavy mineral concentrates from stream sediments (Appel 1989). Subsequent work showed that the Nuuk region constitutes a tungsten province and that scheelite is widespread especially in the mid to late Archaean greenstone belts. It also became clear that scheelite in most cases occurred in greenstone belts.

Scheelite is mostly stratabound and occurs in banded amphibolites, tourmalinites and in carbonate altered komatiitic rocks (Appel 1986, 1994). The latter are found in the Ivisaartoq whereas the two former types are most abundant in the coastal area and on Store Malene (Appel & Garde 1987; Appel 1990). Scheelite occurs as disseminated grains, as porphyroblasts, as stringers and veinlets and as up to 25 cm wide veins with massive scheelite. Scheelite mostly has very low molybdenum contents revealed by its bluish fluorescence colours. However, locally white to yellowish fluorescent scheelite is seen in cross cutting stringers. Scheelite is rarely associated with other metals of economic significance. The scheelite occurrences are interpreted as submarine exhalative and later modified and partly mobilised during subsequent deformation and metamorphism (Appel 1986, 1994).

The highest-grade tungsten is found in the magnetic and peridotite markers of the Ivisaartoq area. Channel samples revealed grades of 0.44% WO_3 over 2.5 m and 0.48% WO_3 over 1.5 m. The scheelite-rich zones can be traced with intervals for more than 10 km along strike (Appel 1990).

Gold showings

Gold has been found in greenstones in the coastal area, on Store Malene, on Bjørneøen and finally on Storø (Fig. 20). The former localities have not been explored to any extent, but some work has been done on Storø by NunaMinerals A/S. Surface sampling, limited detailed mapping and two campaigns of diamond drilling on the two prominent mountains on Storø, Qingaaq and Aappaallartoq revealed gold in several stratigraphic levels and in several different rock units (Fig. 3). For further details see chapter exploration history.

The gold occurrences on Storø are hosted mainly in altered amphibolites, but anomalous gold concentrations are found in most rock types in the greenstone belt. The main gold showing is found in a series of subconcordant, discontinuous sulphide zones within the amphibolites on the contact to metasediments. The sulphides are mainly pyrrhotite, but arsenopyrite is locally predominant. Visible gold is seen as isolated 0.5 to 2 mm big grains within sulphide-bearing amphibolites. Irregular quartz veinlets and silicification are often associated with gold-bearing zones.

Figure 21: *Sheeted auriferous quartz vein in amphibolite at Aappalaartoq. Scale 10 cm.*

On Aappalaartoq one gold mineralised zone can be traced for more than 1300 m along a contact between amphibolite and quartz-muscovite schists. Tourmalinites are often associated with thin beds of iron formation. Gold-bearing arsenopyrite enriched amphibolites have been located at five sites along an amphibolite- mica schist contact on Aappalaartoq. The gold showing has stratabound appearance, although the intensity varies along strike and the mineralised zone is discontinuous. Gold has been found in sheeted quartz-veins on Aappalaartoq (Fig. 21). Individual quartz veins are a few centimetres thick, but the combined width is up to a few metres. Gold grains up to 3 mm in size are seen and grades of composite samples of quartz veins are up to 12.9 ppm. Microprobe analyses of gold grains in sheeted quartz veins show silver contents up to 13%, very distinct from the pure gold (<1%Ag) found together with arsenopyrite.

NunaMinerals A/S has also reported significant gold grades have been found in iron formation (up to 1.4 ppm Au). Garnet gedrite rocks are found with up to 6.7 ppm gold. Rusty sillimanite schists are found with up to 3.2 ppm Au (GEUS Report file 21601). Further gold values are listed in Table 3.

Table 3. *Selected geochemical data from Storø. Instrumental neutron activation analyses. GEUS samples have prefix 407. Remainder are NunaMinerals A/S samples. From Appel et al., (2000).*

Au ppb	Ag ppm	As ppm	Fe wt%	Cu ppm	Zn ppm	Rock type	Sample no.
36 699	2.8	2 917	4.5	101	33	Amphibolite/garnetite asp and qz-stringers	106920
32 681	3.1	>10 000	5.1	187	39	Amphibolite w/ asp and qz-stringer	106921
32 181	0.3	37	5.4	38	49	Amphibolite w/ qz-stringer	106916
24 205	0.9	4 347	5.2	100	53	Amphibolite w/ asp and qz-stringer	106974
9 497	0.6	6 164	5.5	129	75	Amphibolite w/ asp and qz-stringer	106924
671	-	7		1476	116	Sulphide-rich garnetite	105605
5 657	0.7	823	4.2	108	37	Amphibolite w/ asp and qz-stringer	106967
5 148	0.4	3 013	4.3	100	50	Amphibolite w/ asp and qz-stringer	106923
4 182	0.4	5 212	3.8	281	31	Amphibolite w/ asp and qz-stringer	106973
195	<5	19	13.1			Rusty calc-silicates (?) w/asp	407828
1 577	0.2	124	2.1	35	17	Amphibolite w/ asp and qz-stringer	106927
107	<5	1.7	12.4			Calc-silicate-altered amphibolite	407829
12 900	<5	6	3.4			Sheeted qz-veins	407804
7 540	<5	3	7.3			Qz-veined amph.	407814
2 010	<5	3	7.5			Qz-veined amph.	407813
643	-	7	-	395	129	Garnet-gedrite rock	105619
498	1.3	<5	7.5			Silimanite schist	106461
319	0.6	<5	6.3	36	31	Silimanite schist w/minor GMIF	111311
25	0.3	23	3.3	358	58	Limonite-stained ultramafic rock	108505
812	<5	4.9	6.9			Iron information (GMIF)	407825
553	<5	8	40.7			Iron information (GMIF)	407834
42	<5	2	7.1			Tourmalinite	407818

At Qingaaq gold showing on Storø has been found in two major zones each with up to six subzones 2 to 10 m wide. One main zone is 60 m and the other is 20 m wide. The grades obtained are 37 ppm over 1.5 m and 32 ppm over 4 m. The gold is associated with pyrrhotite and arsenopyrite locally with thin beds of iron formation. For details on grades obtained during the drilling campaign consult the chapter on recent and ongoing exploration.

The genesis of the gold on Storø is uncertain. There is close association between gold and arsenopyrite. The main gold mineralised levels appear to occur in specific horizons near the contact between the competent amphibolites and less competent Al-rich metasediments. This suggests a structural control of the showing. The common occurrence of gold in quartz veins and stringers suggest semi-ductile-brittle fracturing in this zone. Most features indicate an epigenetic metallogenetic model of gold showing. It is, however, not known when the gold was introduced and from which source. The gold could have been mobilised from the greenstones, it could have been conducted from depth through the adjacent shear zone. It could also have been mobilised during intrusion of the Qôrqut granite.

The present amount of information does not allow any reliable metallogenetic model, but based on his field work on Storø for NunaMinerals A/S, Dave Coller from Era-Maptec suggests that the closest equivalents would be the Timmins/Kalgoorlie gold camps. Both areas have a structural and metamorphic history resembling the Storø conditions and they also have granites coeval with shear zones near the gold-bearing greenstone belts.

Geochemical data indicative of mineral occurrences

(Agnete Steenfelt, Else Moberg & Peter W. U. Appel)

This section gives an overview of available geochemical data for the Nuuk region and offers a preliminary interpretation of element distribution patterns in relation to gold mineralisation.

The DVD includes chemical data derived from systematic stream sediment sampling as well as from exploration and mapping activities by Survey geologists within the area delimited by the frame shown in Fig. 22. The acquired data concern 498 stream sediment (fine fraction) samples, 1077 rock samples and 355 samples of panned stream sediment, of which 76 have been analysed. Chemical data recorded by exploration companies can be found in scanned company reports on the DVD.

The ArcView project on the DVD contains a view for each of the three sample types with distribution maps for elements considered important for an evaluation of the mineral potential of the Nuuk region. Data acquisition is described for each sample type in later subsections. A table named “All analyses” contains all the analytical data for rock and heavy mineral concentrate samples. The tables accompanying the views for rock and heavy mineral concentrates contain information on location and analytical method. The latter has an abbreviated form in the tables. The full names and description of analytical methods are listed in Table 4 below.

Table 4: *Laboratories and analytical methods employed for samples collected within the Nuuk region.*

Abbreviation	Laboratory	Method
ACTLABS_AQRICP	Activation Laboratories Ltd.	Inductively Coupled Plasma Emission Spectrometry - Aqua Regia Digestion
ACTLABS_CVFIMS	Activation Laboratories Ltd.	Cold vapour - Flow Injection Technique
ACTLABS_FAICPMS	Activation Laboratories Ltd.	Lead Fire Assay - Inductively Coupled Plasma Spectrometry
ACTLABS_FAAICP	Activation Laboratories Ltd.	Lead Fire Assay - Inductively Coupled Plasma Emission Spectrometry
ACTLABS_FANA	Activation Laboratories Ltd.	Nickel Sulphide Fire Assay - Instrumental Neutron Activation Analysis
ACTLABS_ICPTOTAL	Activation Laboratories Ltd.	Inductively Coupled Plasma Emission Spectrometry - Total Digestion (Aqua regia)
ACTLABS_INAA	Activation Laboratories Ltd.	Instrumental Neutron Activation Analyses
CHEMEX_FAAICP	Chemex Laboratories Ltd.	Lead Fire Assay - Inductively Coupled Plasma Emission Spectrometry
CLEGG_FAA	Bondar-Clegg and Co. Ltd.	Lead Fire Assay - Inductively Coupled Plasma Emission Spectrometry
CLEGG_INAA	Bondar-Clegg and Co. Ltd.	Instrumental Neutron Activation Analyses
CLEGG_XRF	Bondar-Clegg and Co. Ltd.	X-Ray Fluorescence Spectrometry
GEUS_AASXRF	GEUS Rock Geochemical Lab.	X-Ray Fluorescence Spectrometry (Fusion) - FeO determined by Titration - Na2O determined by Atomic Absorption Spectrometry
KU_XRF	Copenhagen University Geology	X-Ray Fluorescence Spectrometry
RIS_CD	Risø National Laboratory	Cadmium-isotope excited X-Ray Fluorescence Spectrometry
RIS_DNC	Risø National Laboratory	Delayed Neutron Counting
RIS_GAM	Risø National Laboratory	Gamma-ray Spectrometry
RIS_PLU	Risø National Laboratory	Plutonium-isotope excited X-Ray Fluorescence Spectrometry

Indications of gold mineralisation, high-level granites and hydrothermal activity

Distribution of gold anomalies

In geochemical stream sediment maps of gold and pathfinder elements over the entire West Greenland, the Nuuk region is outlined as a gold prospective province (Steenfelt 1996, 2001). This is illustrated in Fig. 22 showing a number of distinct gold anomalies located within the Isua Greenstone Belt and along a NNE trending line from Sermitsiaq through Storø to Kangiussap Nunaa.

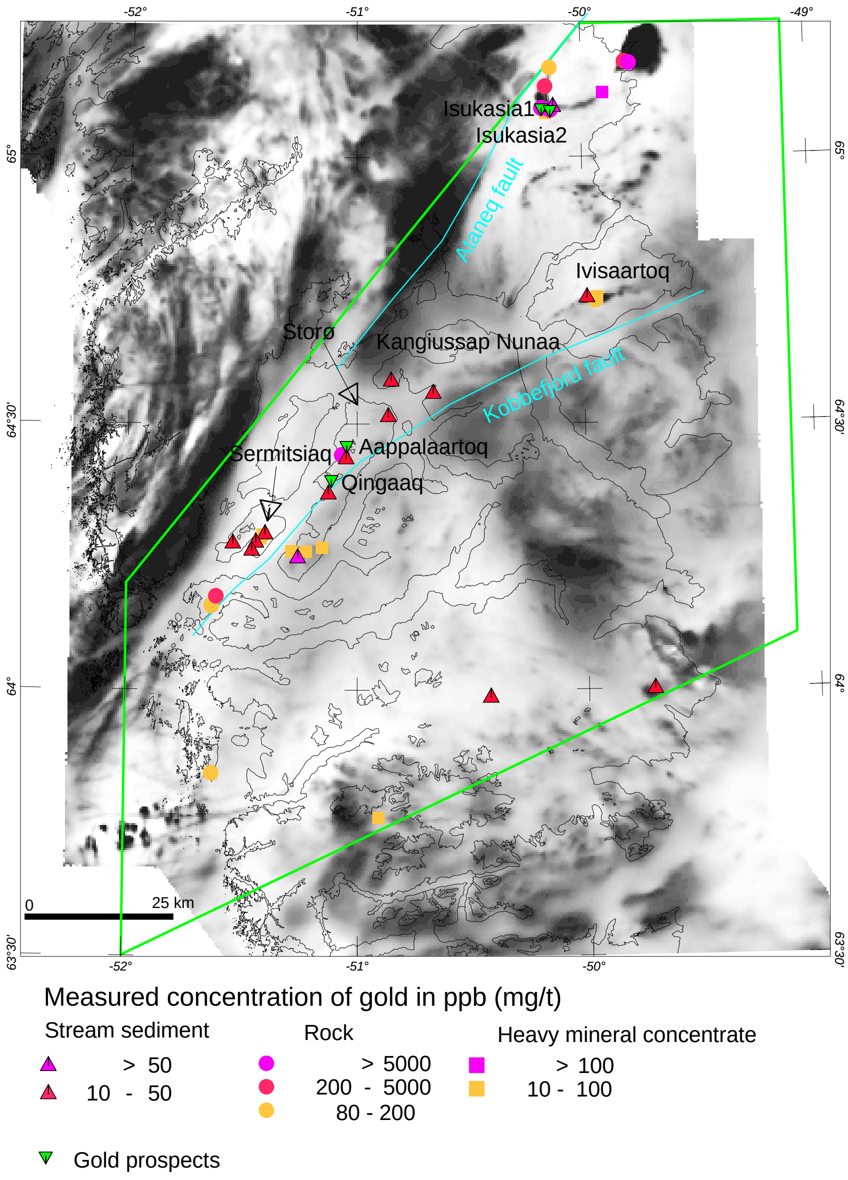

Figure 22. *Gold anomalies in stream sediment, rock and heavy mineral concentrate plotted on grey-scale image of the total magnetic field. Study area outlined in green.*

Two additional anomalies are located within the greenstone belt at Ivisaartoq. The total distribution pattern of stream sediment (both fine fraction and heavy mineral concentrate) anomalies suggest that gold mineralisation has occurred beyond the known mineralisation at Storø, Isukasia and Ivisaartoq.

The distribution of the anomalies also suggests that gold mineralisation took place in zones aligned with predominant fault structures such as the Kobbefjord and Ataneq faults, see Fig. 22. In the southeastern part of the Nuuk region, there are a few scattered gold anomalies, which are not readily relatable to known structures.

Pathfinder elements

A heating event accompanied by hydrothermal activity commonly gives rise to mobilisation of a range of elements besides gold. Among those are As, Mo, Sb, Se, W, Zn, Cu and U. Arsenic is generally very sparse in the Nuuk region, compared to Archaean gold mineralised areas elsewhere in Greenland, such as Disko Bugt and Sermiligaarsuk (Steenfelt 1996). However, local As-mineralisation occurs at Isukasia and Storø as seen in the rock data. Another traditional pathfinder element for gold is Sb. Except for samples of the gold mineralisation “Isukasia2”, which have very high Sb, the Sb concentrations in stream sediments and rocks from the Nuuk region are low. The distribution of high Cu values is within the same trend as the gold anomalies, and also Mo and Zn are high in samples form this trend, although the Mo and Zn anomalies are not confined to the trend.

High-level granitic magmatism and hydrothermal activity

Epigenetic gold mineralisation is commonly generated at high crustal levels during hydrothermal mobilisation and deposition of metals around rising granitic melts. The Nuuk region hosts an abundance of granite and pegmatite veins of various ages, which provides evidence that high-level granite emplacement has taken place recurrently during the region’s geological evolution. The latest known and most voluminous was the emplacement of the 2.55 Ga old Qôrqut granite magma, which resulted in numerous pegmatite veins outside the main granite sheets, see the section on the Qôrqut granite complex. In geochemical maps, the Qôrqut granite is reflected by high K, Rb and Th (Steenfelt 1987, 1994). The granite and, in particular, the pegmatites also have high concentrations of U, but field observations in connection with uranium exploration have sustained that U is not confined to the granite; it also forms numerous small mineralisations in amphibolite outside the granite. It has not, however, been ascertained whether the uranium was mobilised in connection with the intrusion of the Qôrqut magma or whether there were also older or younger remobilisation events.

Another element indicating high-level granite veining and pegmatites is caesium (Cs), and there is a pronounced enrichment in Cs in a zone trending NNE like the general structural trend and the magnetic boundary, see Figs. 22 and Fig. 27. The zone includes the Nuuk peninsula, Sermitsiaq, Storø and continues northwards to Isukasia. Fig. 23 shows the distribution of lithophile elements in stream sediments of the Nuuk region. The dark shades of the grey-scale grid represent high Rb, while the other symbols are high U and Cs. The map shows clearly that the lithophile elements are enriched in a zone embracing the trend of gold anomalies. This suggests that the entire zone have a potential for gold mineralisation.

Uranium is a mobile element and its distribution outside the Qôrqut granite and pegmatites identifies tracks of hydrothermal fluid systems, some of which may have been gold bearing. The U anomalies in stream sediments (Fig. 23 and U measured by airborne gamma-spectrometry (Fig. Radiometri 2) show a broad enrichment trend following the margins of the mapped Qôrqut granite in the south-west and extending towards Ivisaartoq and connecting Storø and Isukasia.

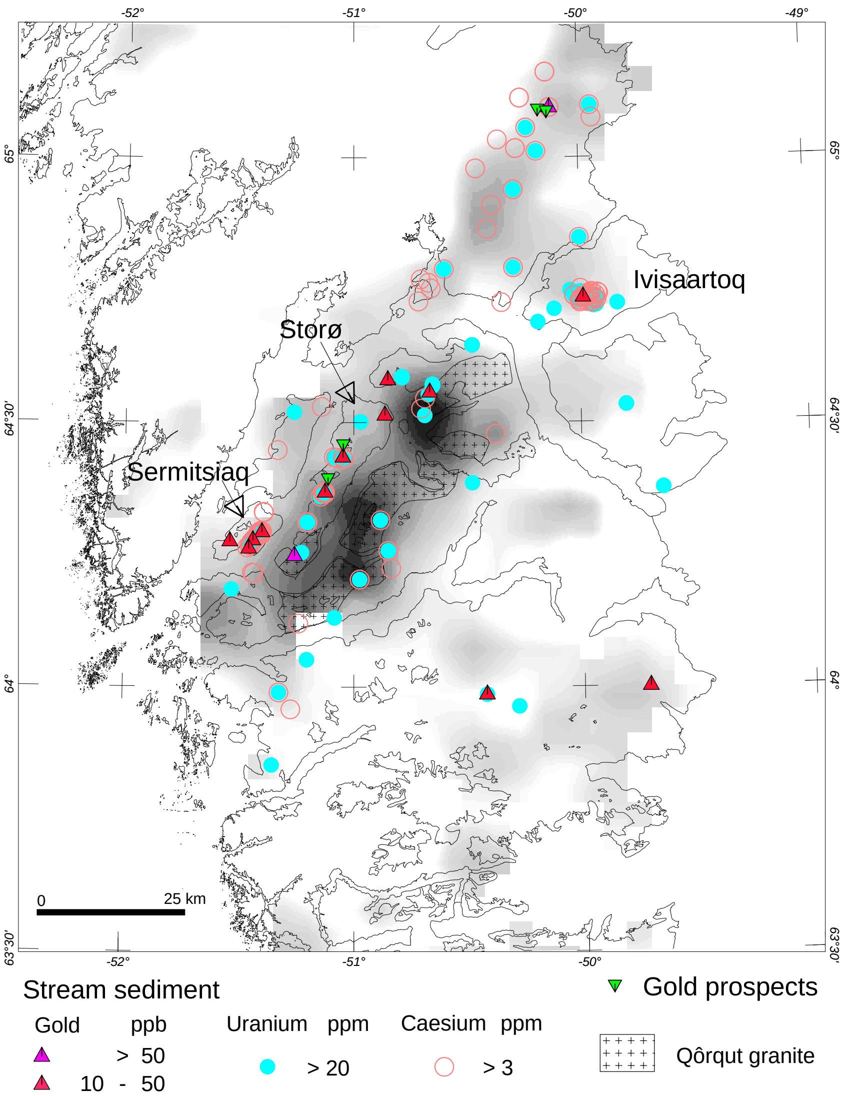

Figure 23. *Enrichment of lithophile elements within the Nuuk region illustrated by stream sediment data. High values of U and Cs plotted together with gold anomalies on grey-scale grid image of Rb. The extent of the Qôrqut granite is from the geological map of Greenland, 1:2 500 000 (Escher & Pulvertaft 1995).*

Deposition of hydrothermally transported gold commonly takes place in structures hosted by basic and reducing rock types such as amphibolites, ultramafic rocks, carbonates, iron formation and sulphides. This also appears to be the case in the Nuuk region. The geochemical maps on the DVD, therefore, include the distribution of high values of MgO, Fe_2O_3 and Ni to outline where suitable host rocks are present. The distribution of high Ni in stream sediments follows the same zone as the lithophile elements.

Data acquisition, presentation and comments for each sample type

Stream sediment (fine fraction)

Stream sediment samples have been collected in the Nuuk region by the Geological Survey of Greenland in several campaigns: Uranium exploration in 1979 and 1981, tungsten exploration in 1985 and low-density (1 sample per 30 km^2) geochemical mapping in 1986 and 1993 (see Steenfelt 1999). The stream sediment view on the DVD shows the location of all stream sediment samples. Sample preparation has been the same for all sample batches, and the less than 0.1 mm grain size fraction has been used for analysis. However, the analytical methods and determined elements vary among the campaigns, see the theme tables in the view “Stream sediment chemical anomalies” on the DVD.

Analytical raw data are not included in the present DVD. Such data are available at cost from GEUS. In stead, the stream sediment view contains a number of maps showing the distribution of anomalously high values of gold and other elements of importance for recognising gold mineralisation. The general chemical character of the Nuuk region is documented in the Thematic Map Series by the Geological Survey of Greenland (Steenfelt et al. 1990) and in a geochemical atlas of West and South Greenland (Steenfelt 2001). Selected stream sediment data from the Nuuk region have previously been presented by Steenfelt (1988, 1990, 1994).

The tables accompanying the ‘Stream Sediment Chemical Anomalies’ view show the sample numbers, location, analytical method and two classes of anomaly level shown in the legend. Some of the samples with anomalous concentrations appear twice or thrice in the table because they have been analysed by more than one method.

The distribution of anomalies shown on the DVD is discussed above.

Rock samples

The analytical data for rock samples are extracted from a GEUS database comprising samples collected within fieldwork in GGU (Geological Survey of Greenland) or GEUS regie. The information is accessible in the Rock Chemistry View on the DVD. All extracted data are contained in the table assigned to the theme “All analyses”. The theme “Sample location' contains information on sample location and sample collector. The samples have been analysed by a variety of methods, see table with the theme 'All analysis ' in the view and Table 4 of this report. Element distribution maps are presented for a selected number of the elements.

The data are not quality controlled, and it is known that a bias exists between analytical methods and the time of analysis (Steenfelt 1999). Also the concentrations measured in samples of mineralised rock are commonly beyond the calibration range for the method where the accuracy is low, and very high concentrations of some elements may influence the determined concentrations of other elements. In the tables, negative values indicate that the concentration is below the detection limit of the analytical method.

The element distribution maps are designed to emphasise the location and character of the mineralised sites or sites with concentrations above the range for non-mineralised rocks, and the problems with accuracy are not important for this kind of use.

Comments on the distribution of high element concentrations

Isukasia to Ivisaartoq

The samples from the Isua greenstone belt reflect the different kinds of mineralisation occurring in the belt, see section on "Greenstone belts and mineral occurrences". Ultrabasic intrusive rocks host Ni and Cr showings and two gold associations are registered, one with high As (Isukasia1), the other with high Sb (Isukasia2). High Ag is found in both associations. In south-western Isukasia the zinc-lead-silver-mercury occurrence stands out. The high Ba-contents are due to late-stage alteration.

The area between Isukasia and Ivisaartoq is anomalous in the following elements: Co, Cr, Cu, Ni, Pd, Zn and Zr. The area has abundant early Archaean greenstone enclaves, and many enclaves of ultrabasic rocks such as dunites and peridotites of unknown origin. Their age is >3.8 Ga (Nutman et al. 1996). One of these is a layered dunite intrusion with bands of chromitite. The intrusion furthermore has sulphide-rich pods with pentlandite and chalcopyrite (Rollinson et al. 2002).

Ivisaartoq

The compiled data illustrate the complex nature of the mineralisation pattern in this area. Above normal concentrations of Au, As, Ba, Br, Cl, Cd, Co, Cs, Cu, Hf, Mo, Ni, Pd, Pt, W, Zn and Zr are registered. Samples with high Cr, Ni, Pd and Pt are from to peridotite intrusions and komatiitic pillow lavas. The area hosts the best tungsten mineralisations in the Nuuk region (Appel 1990a, 1994). The high bromine and chlorine contents and very unique Cl/Br ratios are puzzling (Appel 1997).

Storø

Many of the rock samples from Storø are collected from the gold occurrences and document the enrichment in As, Mo, Nb, Pb W besides Au (Appel, 1990b). Samples with high U, Th and Zr are collected from radioactive anomalies in pegmatites and amphibolites in connection with uranium exploration.

Store Malene

Highly anomalous in Au, Cs, Cu, Hf, Mo, Ni, W and Zn. Abundant tungsten showings and small VMS deposits account for most of the geochemical anomalies (Appel, 1990c).

South of Qooqqut Fjord

Samples from a VMS deposit in a fairly small greenstone belt also hosting one of the rare examples of banded iron formation in late Archaean greenstone belts are anomalous in Cl, Se, Sn and Zn.

Coastal area South of Nuuk

The abundant greenstone enclaves in this area host VMS deposits and stratabound scheelite which explain most of the geochemical anomalies seen here.

Heavy mineral concentrates from stream sediments

Panned stream gravel has been collected from 355 sites within the Nuuk region, of which 345 were used in scheelite prospecting. About 10 kg (~4 litres) of coarse gravel was collected and passed through a ~2 mm screen. The fines were panned and the concentrate was inspected under UV-light in the field for scheelite. The scheelite grains were counted and their colours noted. Most grains displayed bluish fluorescence, but some also showed white to yellowish fluorescence. Immediate follow-up was made when concentrates with high amounts of scheelite grains were found (Appel, 1989, 1990). Seventy six of the heavy mineral concentrates were analysed, and the results are listed on the DVD. Plots of selected elements are included in the Heavy Mineral Concentrate View of the ArcView project.

Indication of mineral occurrences

Tungsten

Scheelite was discovered in stream sediments in 1982. During the following years stream sediments were collected throughout the Nuuk area and in the area south of Nuuk. A plot of scheelite grain contents per litre of coarse sediment is shown (Fig. 24). The plot shows that scheelite is widespread throughout the Nuuk area and that most of the scheelite is confined to greenstone belts.

The first in situ scheelite showings were found on Storø in 1982. They occur in small enclaves of early Archaean greenstone belts. At first it was thought that the scheelite was confined to the early Archaean greenstones of the Nuuk area. However, subsequent work revealed that scheelite occur in both early and mid to late Archaean greenstone belts, and is most abundant in the younger greenstone belts (Appel, 1986, 1990).

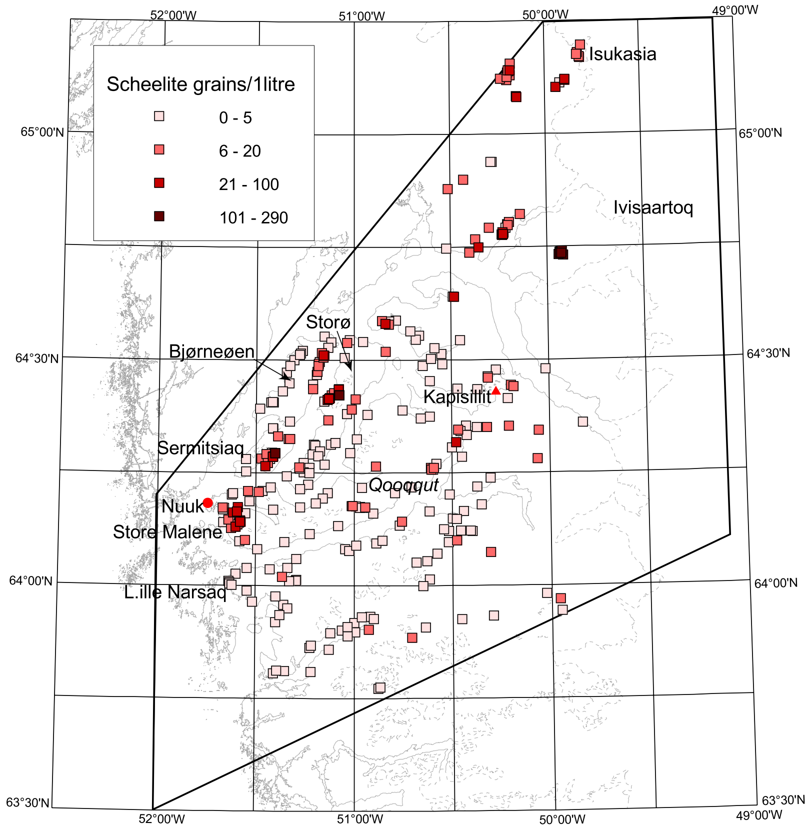

Figure 24. *Scheelite grains per litre in heavy mineral concentrates from stream sediments*

Gold

One sample from Isukasia has 1 ppm of gold, while other samples have only somewhat elevated gold concentrations (6-40 ppb). The gold-bearing samples form clusters at Isukasia, southern Storø and at Sermitsiaq, and they suggest that gold mineralisation also occur south and west of the Storø showings.

Other anomalies

Isuakasia

Isukasia displays anomalies of the following elements: As, Au, Co, Ni, Sb, W, Zn and Cr. Arsenic is derived from arsenopyrite found in some of the gold showings. Nickel and chromium are derived from the ultrabasic intrusive rocks occurring in abundance in the Isua Greenstone belt (IGB). The distribution pattern at Isukasia indicates an origin from ultrabasic rocks, but the proximity to the Ataneq fault (see Fig. 22) may prove to be significant. Zinc and antimony anomalies are probably derived from late lead-zinc occurrence with high contents of gold, silver, antimony and mercury (see description in section on mineralisations in the IGB).

Storø

Central Storø, where the gold occurrences occur, displays anomalies of As, U, Th, W and Hf. Arsenopyrite is abundant in the gold occurrences (see chapter on greenstone belts). Tungsten probably originates from the mid-to-late Archaean greenstone belt.

Southern Storø displays a peculiar anomaly pattern with high concentrations of Au, Co, Ni, Cr and Zn. A large part of this area consist of sheets of Qôrqut granite with intercalated remnants of orthogneiss and greenstone belts. It is worthwhile to follow-up on these anomalies.

Sermitsiaq

Gold anomalies and an abundance of scheelite have been found on this island. No follow up has been done.

Store Malene

The mountain next to Nuuk displays anomalies in U, Th, W and Zn. The tungsten can be ascribed to high-grade tungsten occurrences within the greenstone (Appel and Garde 1987). Zinc is probably derived from sulphide mineralisations. Uranium and thorium are probably derived from pegmatites, which may be connected to the Qôrqut granite complex, although they could also be older.

Airborne and ground radiometric measurements
(Agnete Steenfelt)

An airborne gamma-spectrometric survey covering southern West Greenland, including the Nuuk region, was conducted in 1976 by the Geological Survey of Greenland in co-operation with the Risø National Laboratory (Secher 1977). Grid images of total radiation, potassium, equivalent uranium and equivalent thorium of the Nuuk region are presented on the DVD in the view "Radiometry" together with a map of total gamma-radiation based on ground measurements at stream sediment localities (see Steenfelt 2001).

Data acquisition and presentation

Airborne survey
A four-channel gamma-ray spectrometer with a detector-volume of 11 litres installed in a fixed-wing aircraft was used to measure the gamma-radiation at a height of about 90m above the ground. Flight lines followed the topographical contours. Further technical details of the survey and data treatment are given in Tukiainen et al. (2003). The data were corrected for background radiation, and counts recorded in the K, U and Th channels were corrected for contributions from decay series of the other radioelements (stripping). The measurements were not corrected for variation in ground clearance, but the data were screened to include only those obtained within an interval of 75 to 105 metres above terrain. Furthermore, all negative values in the data sets were removed before gridding. Negative values result from the stripping in situations where conditions are not ideal.

The screened data are presented as contoured grid images. The total gamma-radiation is given in the international unit Ur (Unit of radioelement concentration), and the data from the other channels as equivalent concentrations of the overflown ground, K in %, eq. U and eq. Th in ppm. The grids and contoured images were produced using software from Geosoft Inc.

Ground measurements
During the systematic stream sediment sampling for geochemical mapping the total gamma-radiation was measured at each sampling site with a scintillometer. The measurements are recorded as counts per second. The data are shown as colour-scaled dots in the view "Radiometry" on the DVD.

Radioelement distribution patterns

The enrichment of radioelements in the Akulleq terrane relative to the surrounding Akia and Tasiusarsuaq terranes is clearly displayed in radioelement maps over West Greenland (Steenfelt et al*.* 1990; Steenfelt 2001; Tukiainen et al*.* 2003) and has been commented on previously (Steenfelt 1987, 1990). Figures 25 and 26 illustrate this and also show an interesting difference in the distributions of highest values of eq.Th and highest values of eq. U. The highest concentrations of eq. Th (Fig. 25) is very closely associated with the mapped extent of the Qôrqut granite, which forms abundant sheets in Nunatarsuaq.

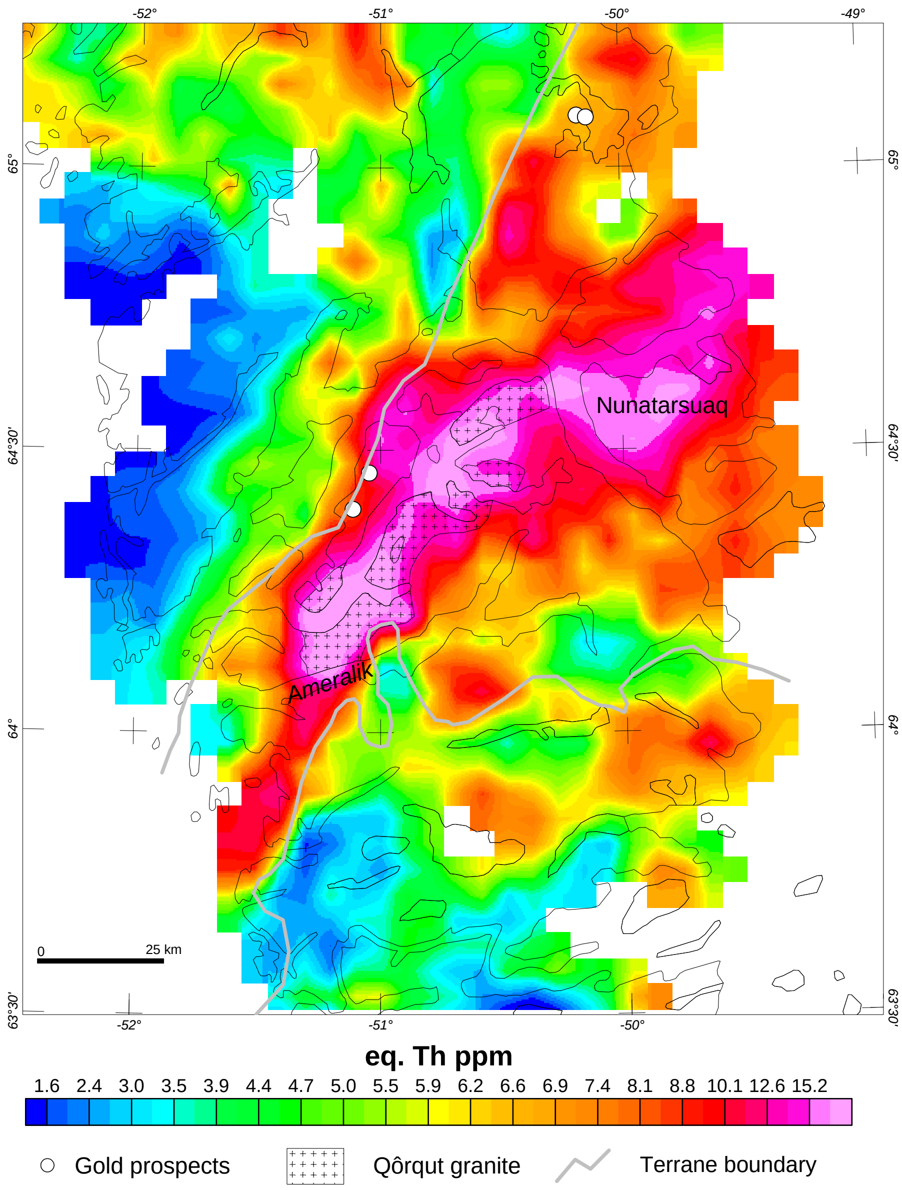

Figure 25. *Grid image of equivalent Th measured by airborne gamma-spectrometry within the Nuuk region. The extent of the Qôrqut granite is from the geological map of Greenland, 1:2 500 000 (Escher & Pulvertaft 1995), and terrane boundaries are from McGregor et al. (1991).*

The pattern of highest concentrations of eq. U has several narrower and linear trends, one of which aligns with Storø and includes the gold prospects there. Another trend follows the eastern side of the Ataneq fault (see Fig. 4) heading towards the gold prospects in Isukasia. The trend of high eq. U over the Qôrqut granite continues over Ivisaartoq in stead of Nunatarsuaq as in the case of eq. Th. A fourth interesting trend, coinciding with the trend of high eq. Th, follows the terrane boundary between the Færingehavn and the Tasiusarsuaq terranes, south of Ameralik Fjord.

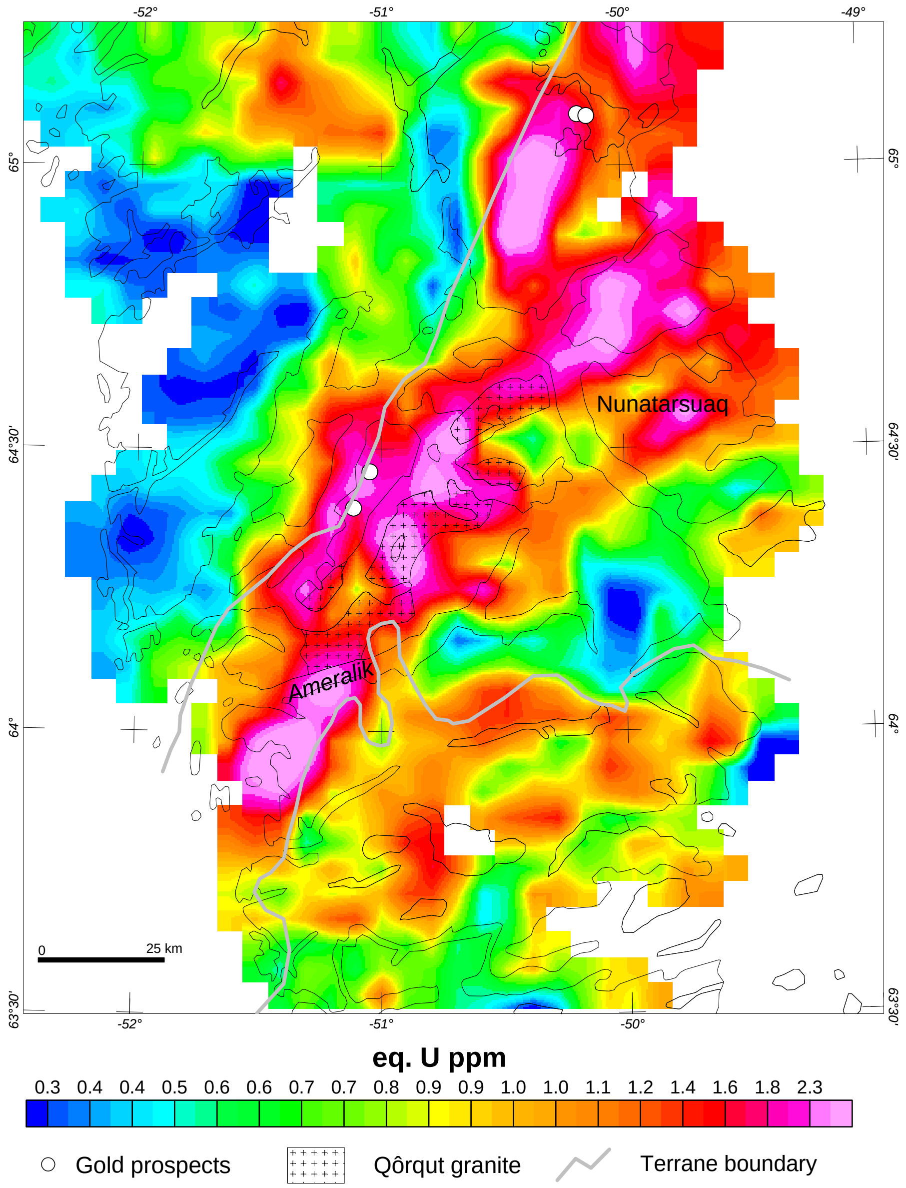

Figure 26. *Grid image of equivalent U measured by airborne gamma-spectrometry within the Nuuk region. The extent of the Qôrqut granite is from the geological map of Greenland, 1:2 500 000 (Escher & Pulvertaft 1995), and terrane boundaries are from McGregor et al. (1991).*

The trends of the high eq. U outside the Qôrqut granite reflect the occurrence of pegmatites and the existence of uranium mineralisation located in greenstone sequences surrounding the granite.

The aeroradiometric maps reflect the radioelement concentrations in exposed rocks. The stream sediment chemical maps presented earlier show almost the same distribution patterns (Fig. 23) and sustain a close coherence between exposed rocks and stream sediment composition. The possible connection between gold mineralisation and the distribution patterns for high uranium is indicated in the section on “Geochemical data”.

The ground measurements of total radiation outline the extent of the Qôrqut granite and the entire Nunatarsuaq as more radioactive, but do not differentiate between thorium and uranium.

Magnetic, electromagnetic and gravity data

(Thorkild M. Rasmussen & Adam A. Garde)

Summary

Aeromagnetic data available from both regional and detailed surveys are shown to be valuable in the interpretation of the geology within the Nuuk region. The regional data that cover the entire Nuuk region provide information on large-scale crustal segments and the data are useful in the structural interpretation of the geology. In general, a good correlation between mapped geological units and the magnetic responses are observed. In several areas, the magnetic data are indicative of so far unmapped geological structures. Although the regional data provide valuable information, considerably better resolution of the magnetic field variations and thereby the geology can be obtained from the detailed surveys that are flown at low altitude but within smaller areas

The regional aeromagnetic data has been modelled jointly with gravity data from the region. A boundary between the Akia terrane and the Akulleq terrane is found to dip towards northwest.

Petrophysical data

In general the amount of petrophysical data such as magnetic properties and density measured on rock samples are very limited from Greenland. This also applies to the Nuuk region. In order to provide data for the interpretations in this report, a few samples of some of the main rock units have been analysed in the laboratory and a number of in situ magnetic susceptibility measurements have been carried out in 2003. The quoted in situ measurements are averaged valued within areas of 10–20 m^2

Table 5 presents the results of the laboratory measurements and the locations for the samples are shown on the simplified geological map in Fig. 27. The values for the induced magnetisation K have been converted in accordance with external field strength of 55500 nT such that the magnetisation m is directly comparable to the remanent magnetisation.

The lowest density values are obtained for the Qôrqut granite. The Amitsoq gneiss show slightly higher values. The density contrast between these two units and the tonalites is about 0.1–0.2 g/cm^3, which is sufficient to generate anomalies of significant amplitude. The ultramafic rocks and the anorthosite have the highest density.

The sample of the Qôrqut granite has a slightly higher magnetic susceptibility than the Amitsoq gneiss. Both rock types have low to intermediate values with respect to both magnetic susceptibility and remanent magnetisation. In contrast, the tonalitic gneiss is very high in magnetic susceptibility and has a high remanent component. The amphibolite rocks have intermediate values.

The in situ measurements on the Qôrqut granite gave a mean value about one order of magnitude higher than the laboratory measurements. In situ measurements were made at two localities separated some hundred metres apart. The mean values are 4570 µSI and 1550 µSI. Some local variations for the in situ measurements were observed at both places, and the laboratory result is above the lower value for the in situ measurements. The mean in situ value for the Amitsoq gneiss is close to the value of the laboratory measurements. All 25 in situ measurements except one on the tonalite gneiss gave values below the value obtained from the laboratory measurements. The mean for the in situ measurements is 17850 µSI units.

Table 5. *Results from petrophysical measurements in the laboratory on rock samples.* ***D*** *refers to density,* ***K*** *is the magnetic susceptibility,* ***m*** *is the induced magnetisation caused by an external field of 55500 nT and* ***J*** *is the remanent magnetisation. Some of the samples were split in two parts (referenced as a and b) before analysis. The locations of the samples are shown on Fig. 27 as numbers 1–9 in black colour. The numbering 1–9 corresponds to GEUS sample no. 491206–491214.*

sample	**longitude**	**latitude**	**rock**	**D**(kg/m3)	**K**(uSI)	**m**(mA/m)	**J**(mA/m)
1	-51.14186	64.300056	Qôrqut granite	2596	320	12.8	30
2	-51.14769	64.301056	Amitsoq gneiss	2719	270	10.8	0
3	-51.06725	64.418500	amphibolite	2971	750	30	0
4	-51.08050	64.415417	metasediment	2854	440	17.6	10
5	-50.70653	64.731056	anorthosite	2890	12	5	0
6a	-50.62183	64.879778	tonalite	2705	50490	2019.6	650
6b	-50.62222	64.879750	tonalite	2785	114650	4586	1400
7a	-50.25008	64.986583	Amitsoq gneiss	2643	50	2	0
7b	-50.25008	64.986583	Amitsoq gneiss	2645	50	2	0
8a	-50.17747	65.091900	ultramafic	2776	1620	64.8	730
8b	-50.17747	65.091900	ultramafic	2796	1660	66.4	730
9	-50.18890	65.091410	Amitsoq gneiss	2645	70	2.8	0

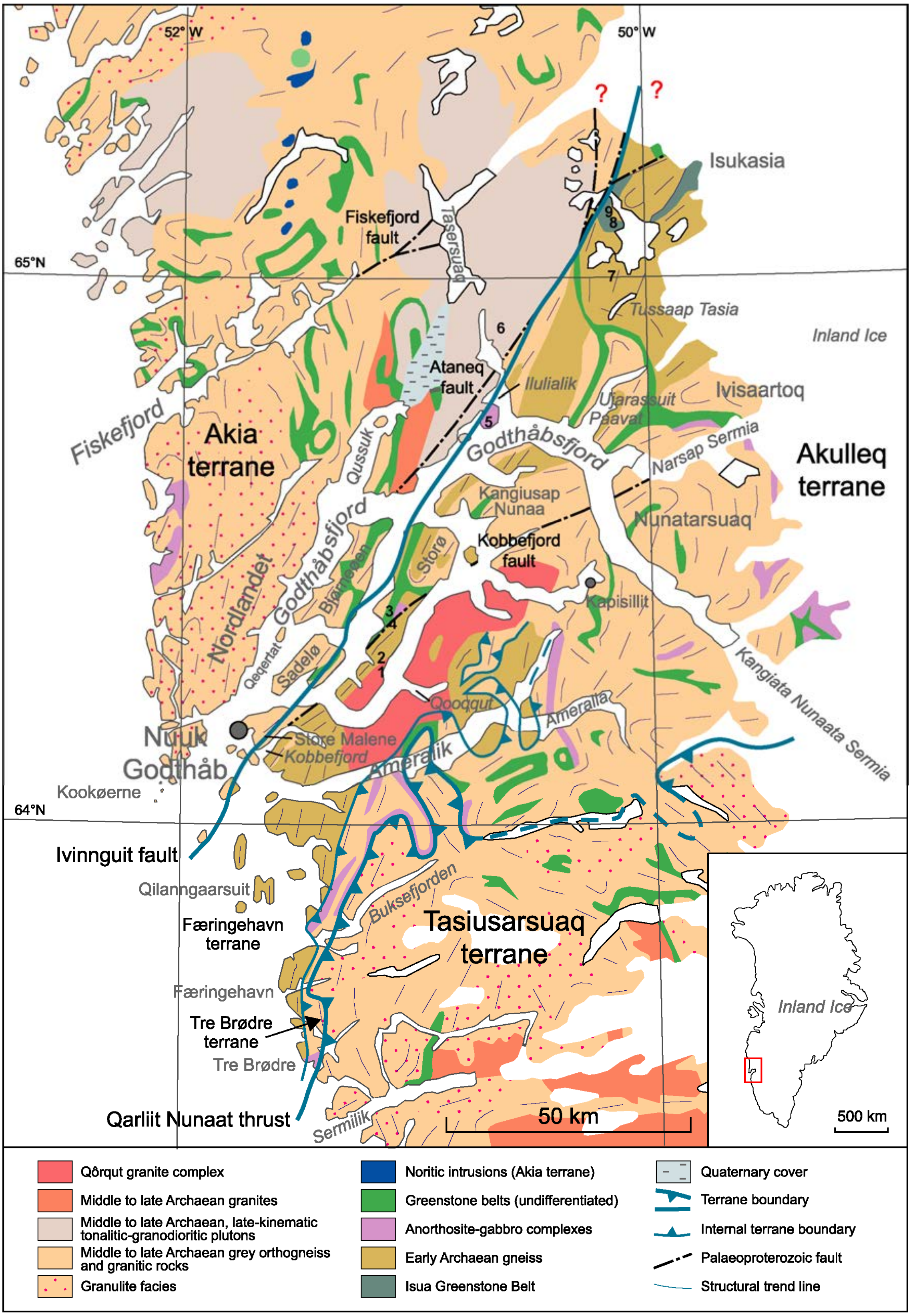

Figure 27. *Simplified geological map of the Nuuk region with place names used in the description of the aeromagnetic and gravity data. The numbers 1–9 in black colour refer to samples with petrophysical measurements (Table 5).*

Description and qualitative interpretation

Aeromagnetic data

Regional magnetic surveys 'Aeromag 1998' and 'Aeromag 1996'

The descriptions and interpretations of aeromagnetic data from the Nuuk region are largely based on regional magnetic data from the GEUS projects 'Aeromag 1998' (Rasmussen & Thorning 1999) and ‘Aeromag 1996 ’(Thorning & Stemp 1997). Both projects were financed by the Home Rule government in Nuuk. The 1996 survey was flown by Geoterrex Ltd and the 1998 project by Sander Geophysics Ltd. For this report the data have been merged to produce the following maps (also included in the DVD):

Fig. 28: Total magnetic field anomaly with shadow; shadow modelled with an illumination inclination of 45° and declination 315°.
Fig. 29: Calculated vertical gradient of the total magnetic field
Fig. 30: Horizontal gradient in east direction of the total magnetic field
Fig. 31: Horizontal gradient in north direction of the total magnetic field
Fig. 32: Amplitude of the horizontal gradient vector of the total magnetic field
Fig. 33: Amplitude of the analytic signal
Fig. 34a–c: Separation filtered total magnetic field anomaly
Fig. 35: Pseudo-gravity field

Technical details on the various types of calculations used for the displayed quantities can be found in the appendix that is found at the end of this chapter. An upward continuation of 200 m has been applied to all maps that included horizontal gradients.

The resolution of the data from the regional 'Aeromag' projects is limited by the altitude and line spacing of the flights. The line spacing is 500 m and the nominal altitude above ground is 300 m. Modelling and interpretation are further impeded by the generally alpine topography in the fjord area; further inland the topography is more gentle although not insignificant. These limitations imply that it has only been possible to identify and model large magnetic features with dimensions of at least a few kilometres. Accordingly, many known geological targets of limited size but great interest are not visible in the data. For example is the complex of interleaving greenstone belts and othogneisses with gold occurrences on Storø and Bjørneøen not shown by the regional aeromagnetic data.

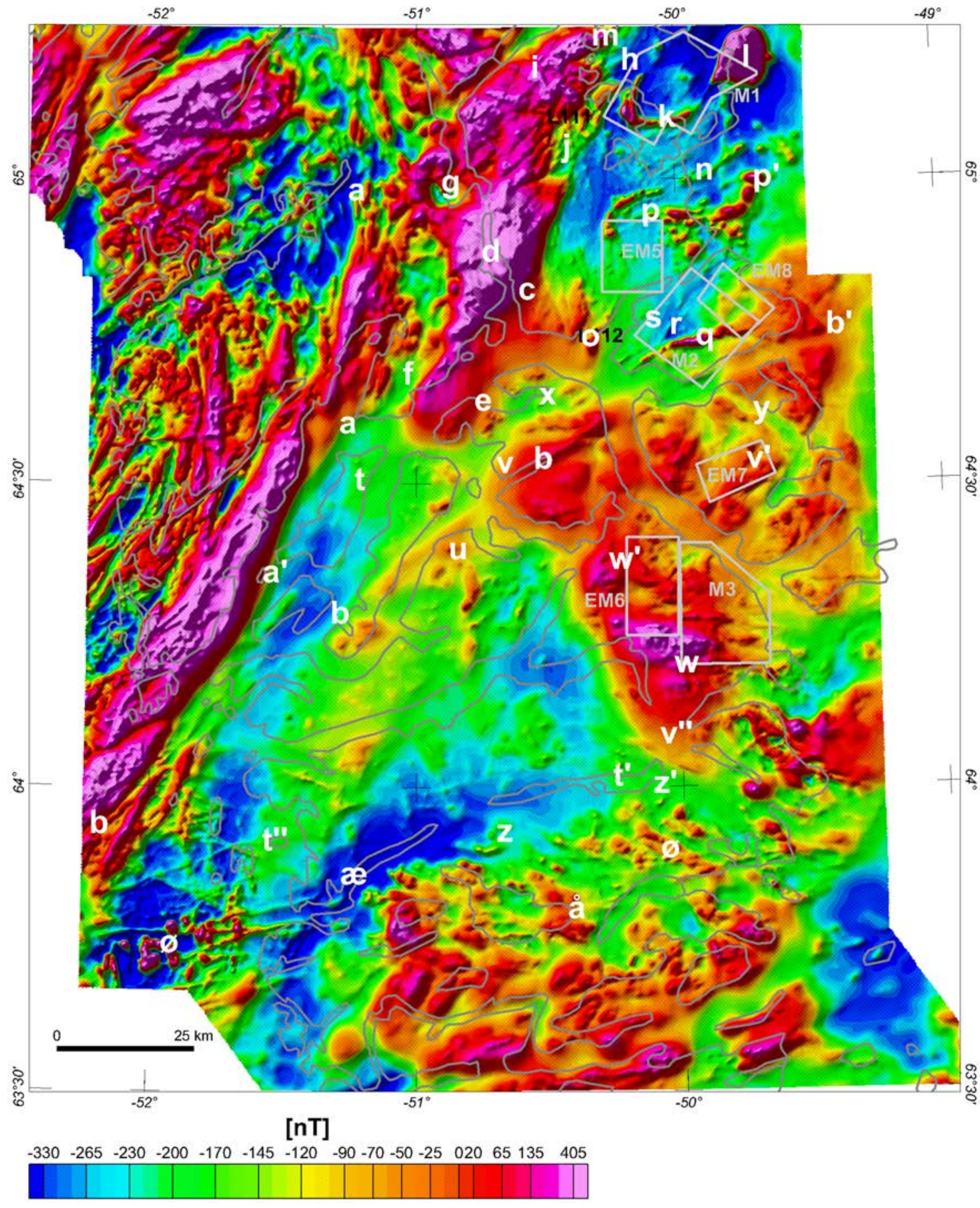

Figure 28. *Magnetic total field anomalies from the regional aeromagnetic surveys 'Aeromag 1998' and 'Aeromag 1996' by GEUS and BMP. Shadow is superimposed by modelling a light-source illumination of 45° and declination 315°. The labels in white are all referenced in the descriptive text. The five areas covered by detailed surveys are indicated with grey lines and labels M1, M2, M3, EM5, EM6, EM7 and EM8.*

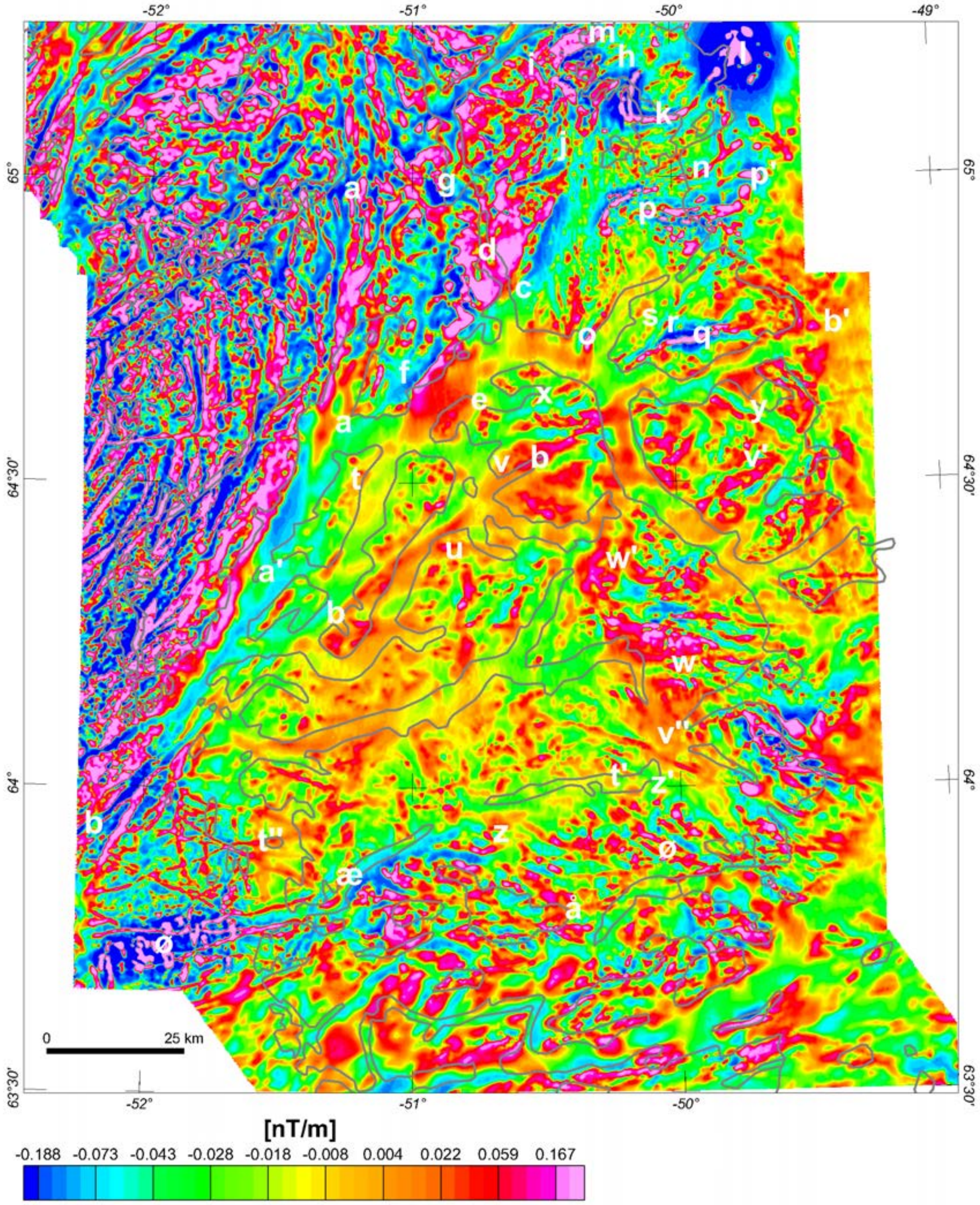

Figure 29. *Calculated vertical gradient of the magnetic total field data from the regional aeromagnetic surveys 'Aeromag 1998' and 'Aeromag 1996' by GEUS and BMP.*

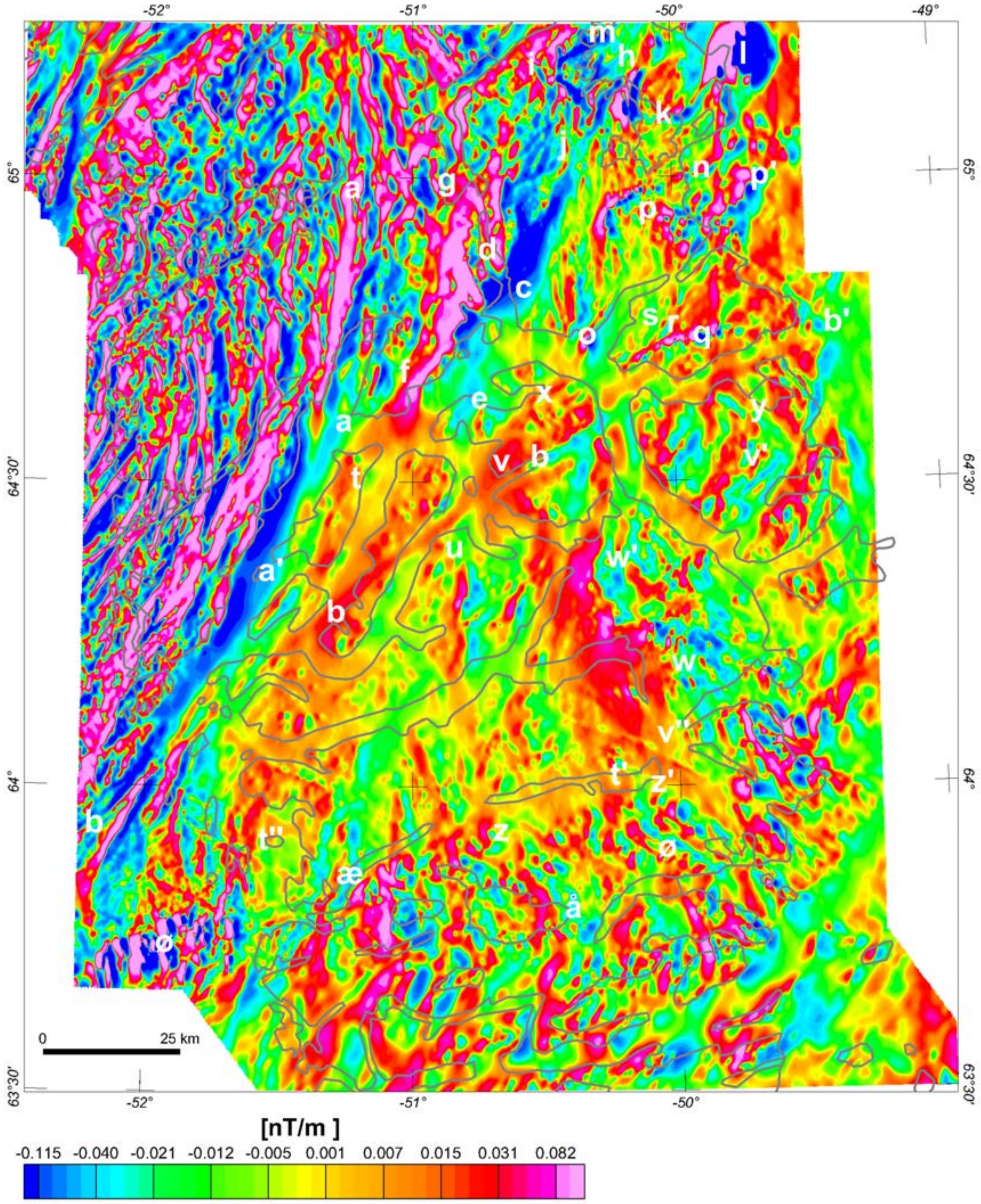

Figure 30. *Calculated horizontal gradient in east direction of the magnetic total field data from the regional aeromagnetic surveys 'Aeromag 1998' and 'Aeromag 1996' by GEUS and BMP.*

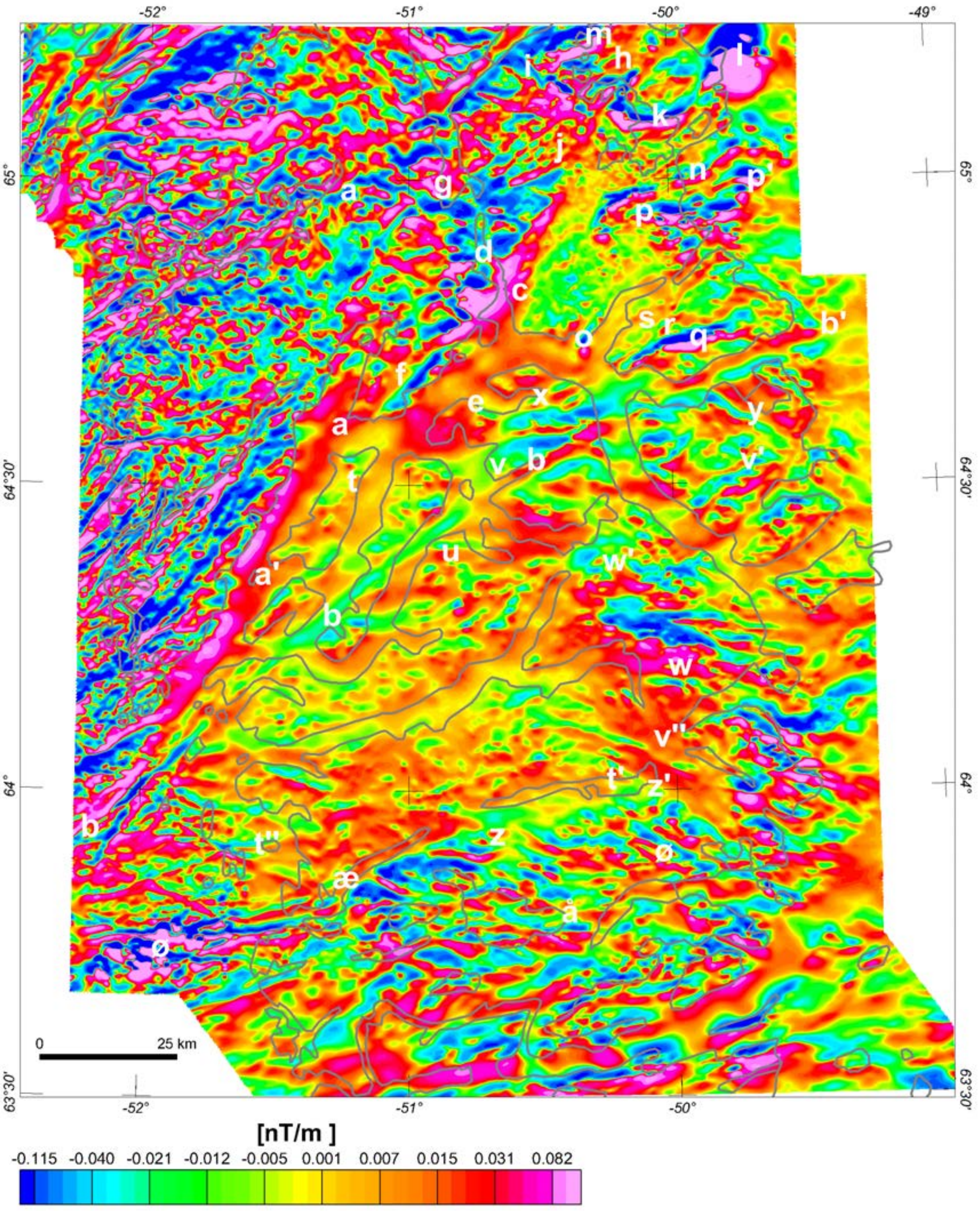

Figure 31. *Calculated horizontal gradient in north direction of the magnetic total field data from the regional aeromagnetic surveys 'Aeromag 1998' and 'Aeromag 1996' by GEUS and BMP.*

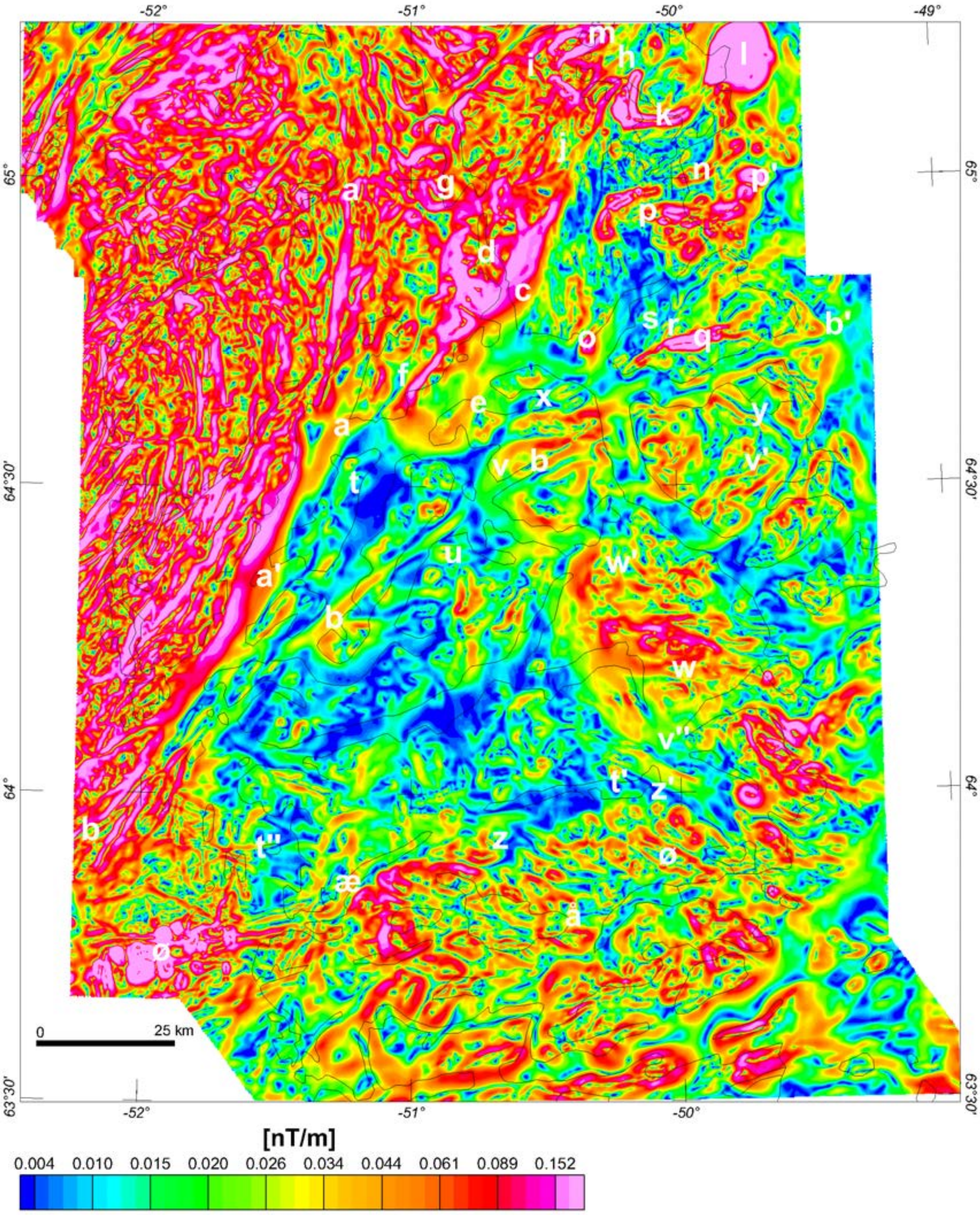

Figure 32. *Calculated amplitude of the horizontal gradient vector for the magnetic total field data from the regional aeromagnetic surveys 'Aeromag 1998' and 'Aeromag 1996' by GEUS and BMP.*

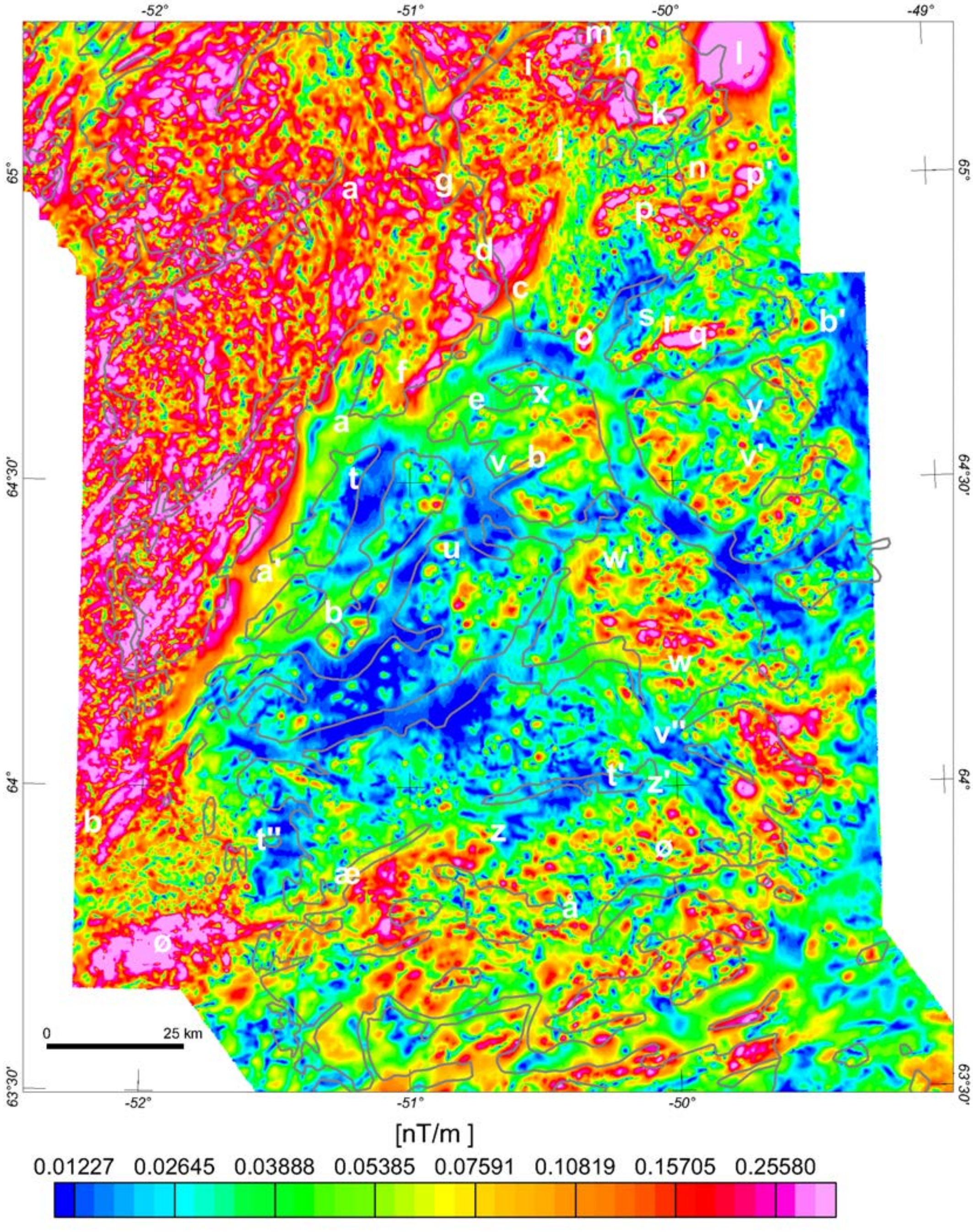

Figure 33. *Calculated amplitude of the analytic signal of the magnetic total field data from the regional aeromagnetic surveys 'Aeromag 1998' and 'Aeromag 1996' by GEUS and BMP.*

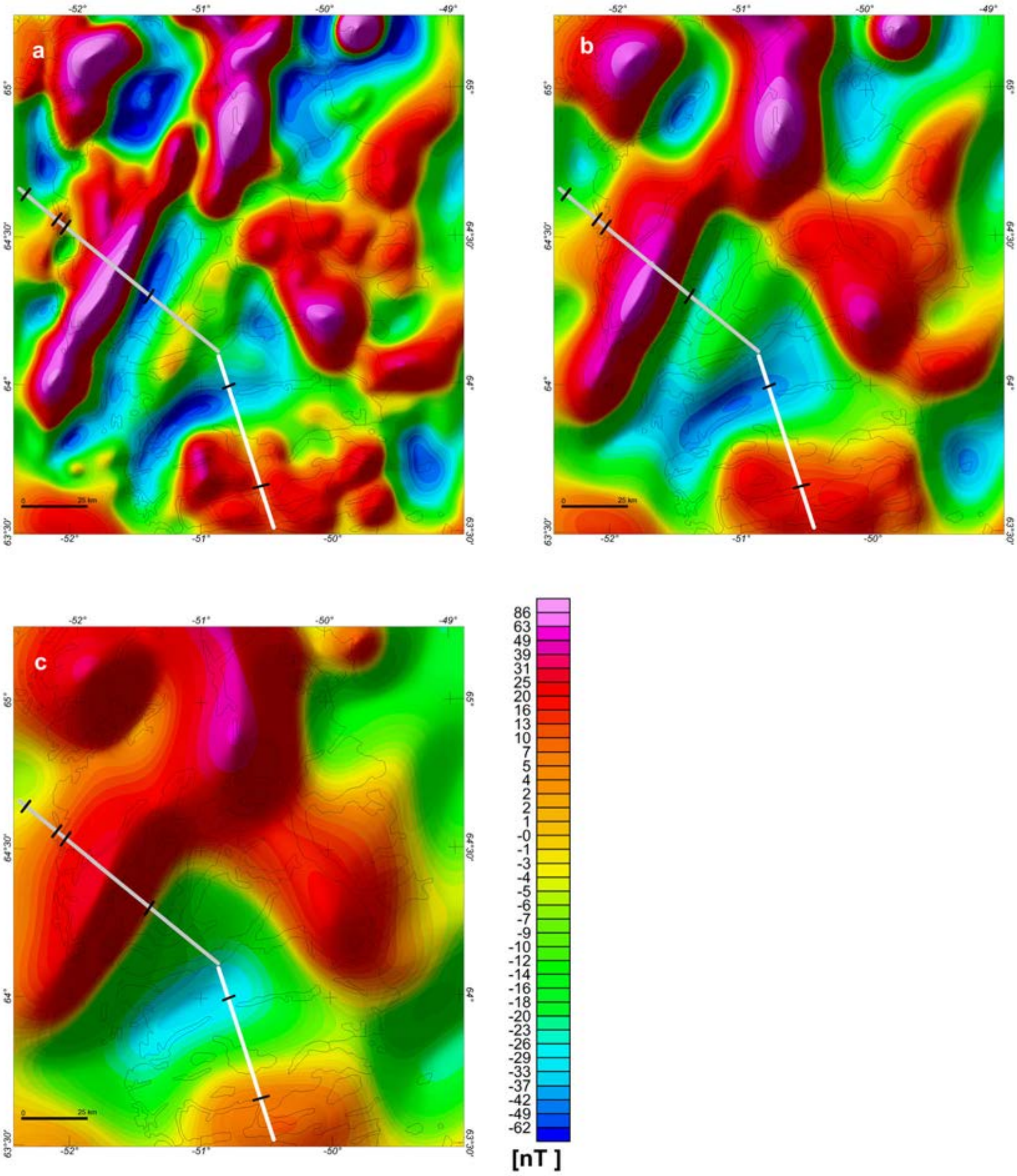

Figure 34. *Separation filtered magnetic field for depth interval (a) 3000–6000 m, (b) 6000–12000 m and (c) 12000–24000 m of the magnetic total field from the regional aeromagnetic surveys ‘Aeromag 1998’ and ‘Aeromag 1996’ by GEUS and BMP. The separation filter is defined as the difference between upward continued fields at altitudes corresponding to twice the depth values for the selected depth interval (Jacobsen, 1987). A grey line (profile 1) and white line (profile 2) show the locations of profiles used in a joint inversion of gravity and magnetic data The black lines orthogonal to the profiles show the location of the upper corners of the tabular bodies used in the modelling. For profile 2, only the two northern most edges are within the map limits.*

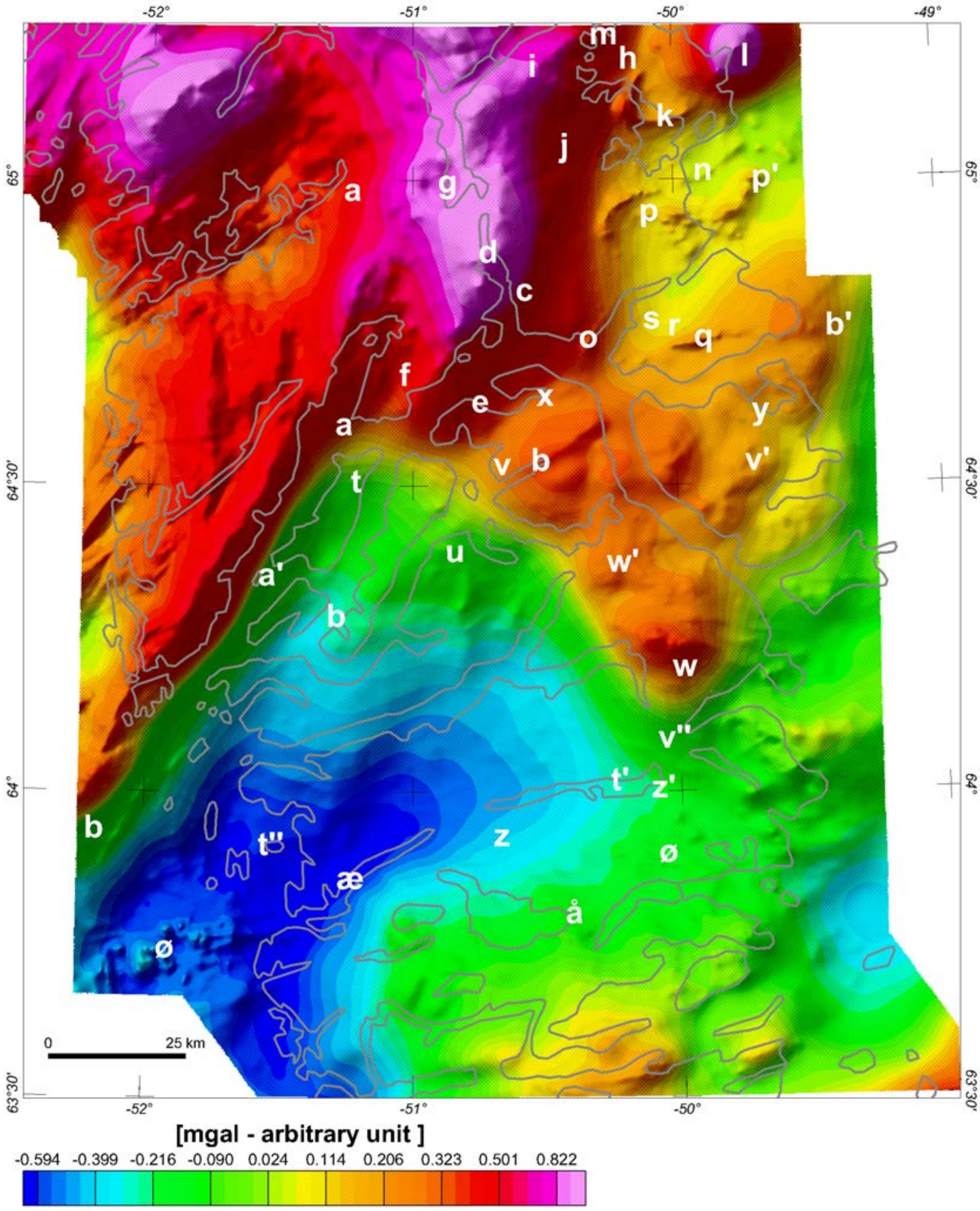

Figure 35. *Calculated pseudo gravity field of the magnetic total field from the regional aeromagnetic surveys by GEUS and BMP. The gravity units are arbitrary unit.*

Detailed aeromagnetic data by Sander Geophysics Ltd for NunaOil A/S

NunaOil A/S has produced detailed aeromagnetic maps of the Isua greenstone belt and of the central part of the Ivisaartoq greenstone belt based on a line spacing of 200 m and nominal altitude above ground of 120m. These surveys were flown by Sander Geophysics Ltd (GEUS Report File 21694 and 21697).

Fig. 36 shows the magnetic total field anomalies and Fig. 37 the vertical gradient of the total magnetic field from the central Ivisaartoq area. Fig. 38 shows the magnetic total field anomalies and Fig. 39 shows the vertical gradient of the total magnetic field from the Isua greenstone belt. Other maps (horizontal gradients, analytic signal and pseudo gravity) are also included in the DVD of this report. The surveyed areas are indicated as area M1 and M2 in Fig. 28.

Data from a third area flown by Geoterrex Ltd for Aber Resources exist from the Kapisillit area. These data are not available from GEUS in digital form and are not included here. A black and white map is included in Aber Resources Ltd (1997) (GEUS Report File 21507). The surveyed area is indicated as area M3 in Fig. 28.

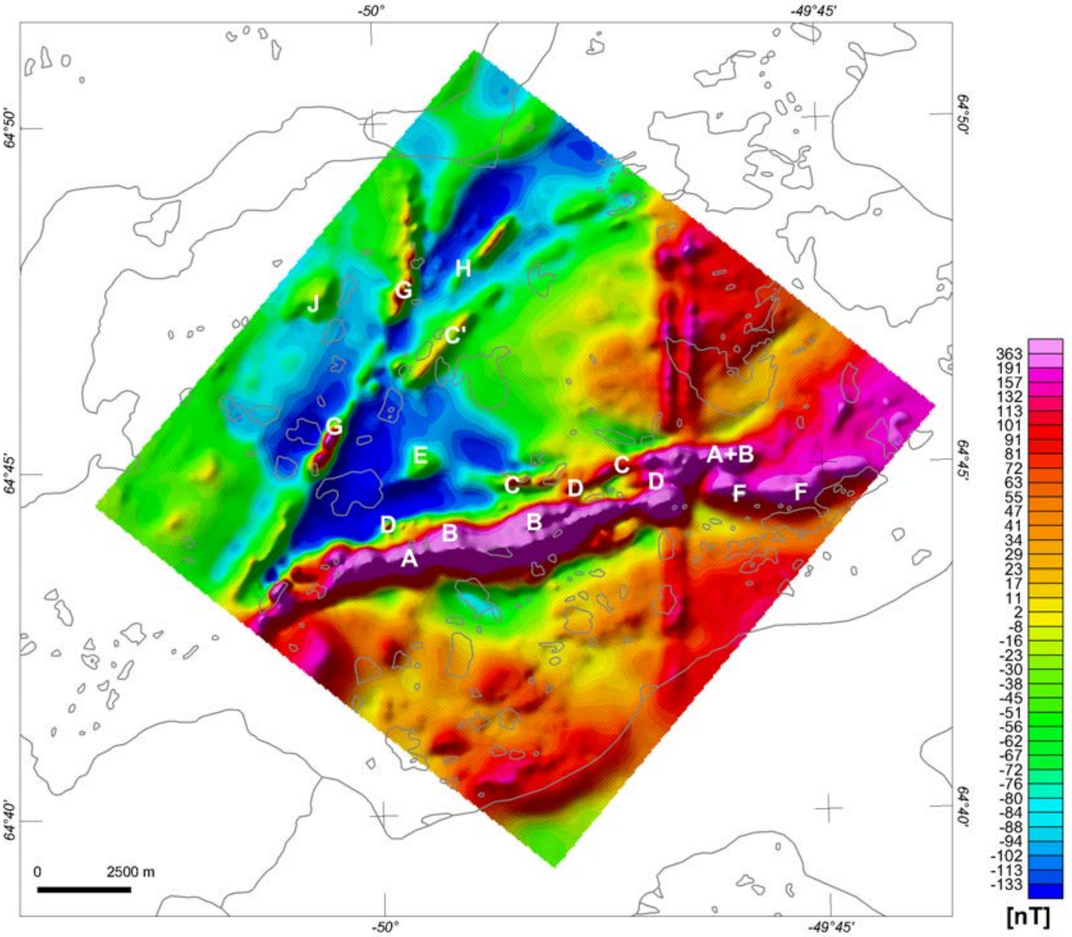

Figure 36. *Magnetic total field anomalies for the Ivisaartoq greenstone belt from the aeromagnetic survey by Sander Geophysics Ltd for NunaOil A/S. Shadow is superimposed by modelling a light-source illumination of 45° and declination 315°.*

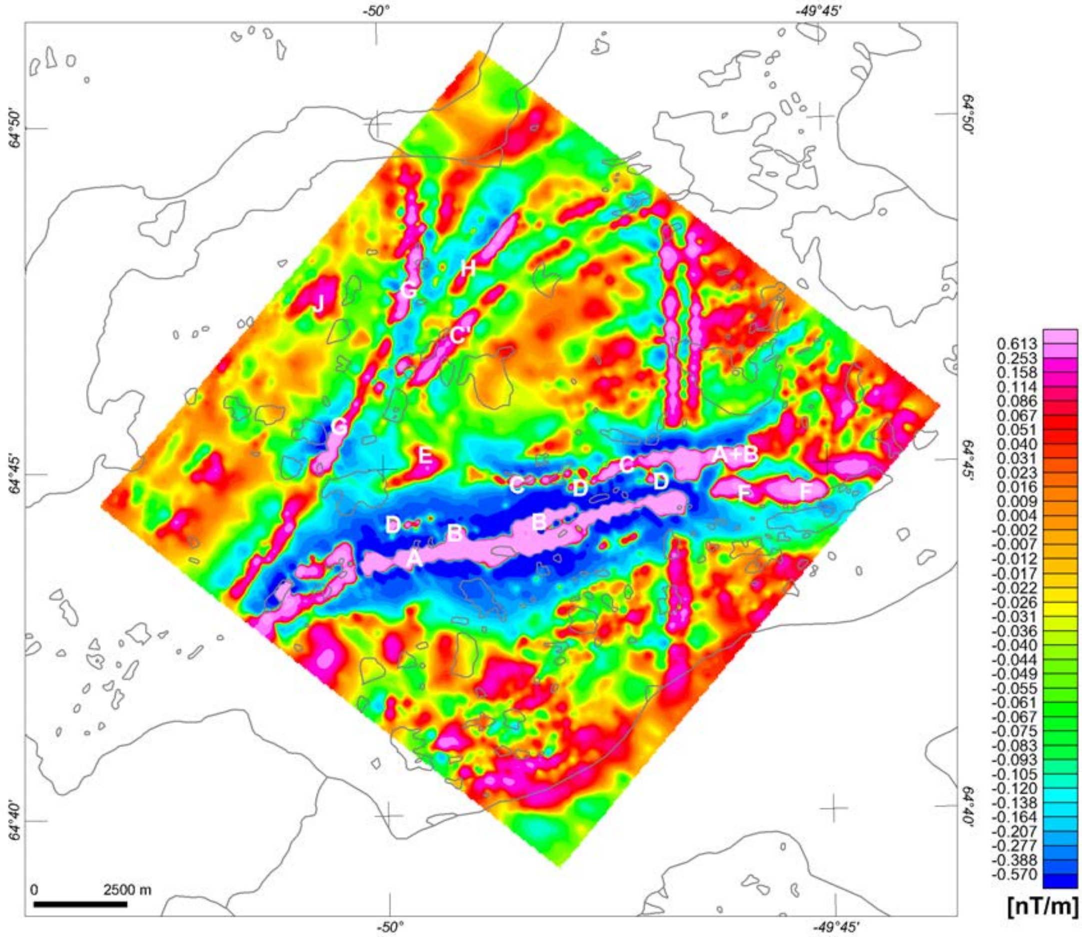

Figure 37. *Calculated vertical gradient of the magnetic total field for the Ivisaartoq greenstone belt from the aeromagnetic survey by Sander Geophysics for NunaOil A/S.*

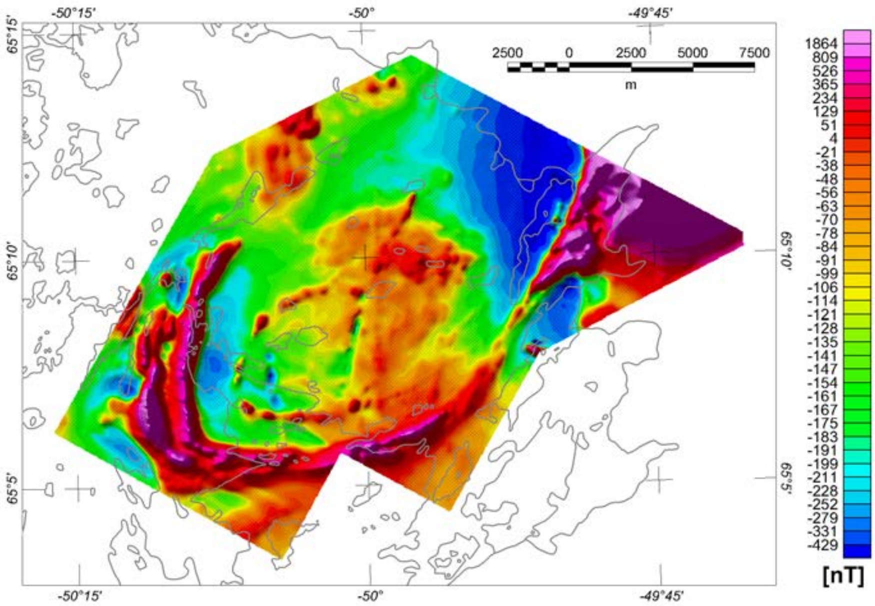

Figure 38. *Magnetic total field anomalies for the Isua greenstone belt from the aeromagnetic survey by Sander Geophysics Ltd for NunaOil A/S. Shadow is superimposed by modelling a light-source illumination of 45° and declination 315°.*

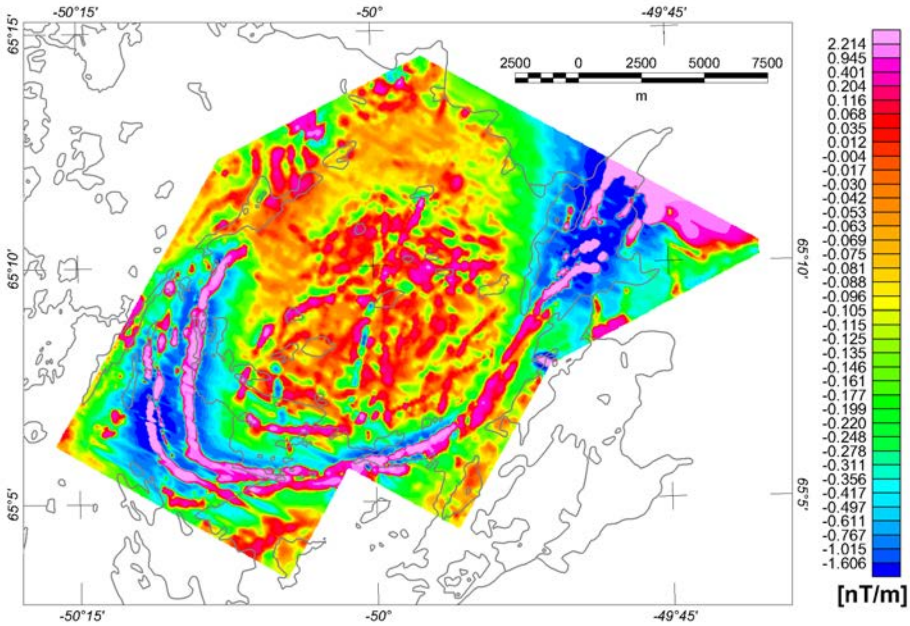

Figure 39. *Calculated vertical gradient of the magnetic total field for the Isua greenstone belt from the aeromagnetic survey by Sander Geophysics Ltd for NunaOil A/S.*

Combined detailed aeromagnetic and electromagnetic data by Aerodat Inc for Fjordland Minerals Ltd

Four small areas within the Nuuk region (besides 8 other areas in southern West Greenland) were surveyed geophysically by Aerodat for Fjordland Minerals Ltd in the search for kimberlites (Aerodat Inc 1997, GEUS Report File 21604). The surveyed areas are indicated as areas EM5, EM6, EM7 and EM8 in Fig. 28.The geophysical system was a helicopter-borne combined frequency domain electromagnetic and magnetic system (HEM system). Figs. 40–47 show the magnetic total field and vertical gradient of the magnetic field based on a line spacing of 300 m and altitude above ground of approximately 45 m. Other geophysical maps from the same areas (horizontal gradients of magnetics, analytic signal and pseudo gravity, and apparent resistivity from medium and low frequency data) are included in the DVD of this report. The electromagnetic data generally show high resistivities and do not provide much information about the bedrock geology except for a few electrical conductive zones. Some of conductors show a correlation to the magnetic anamalies. The electromagnetic data are not discussed here, but interpretations can be found in Aerodat Inc (1997).

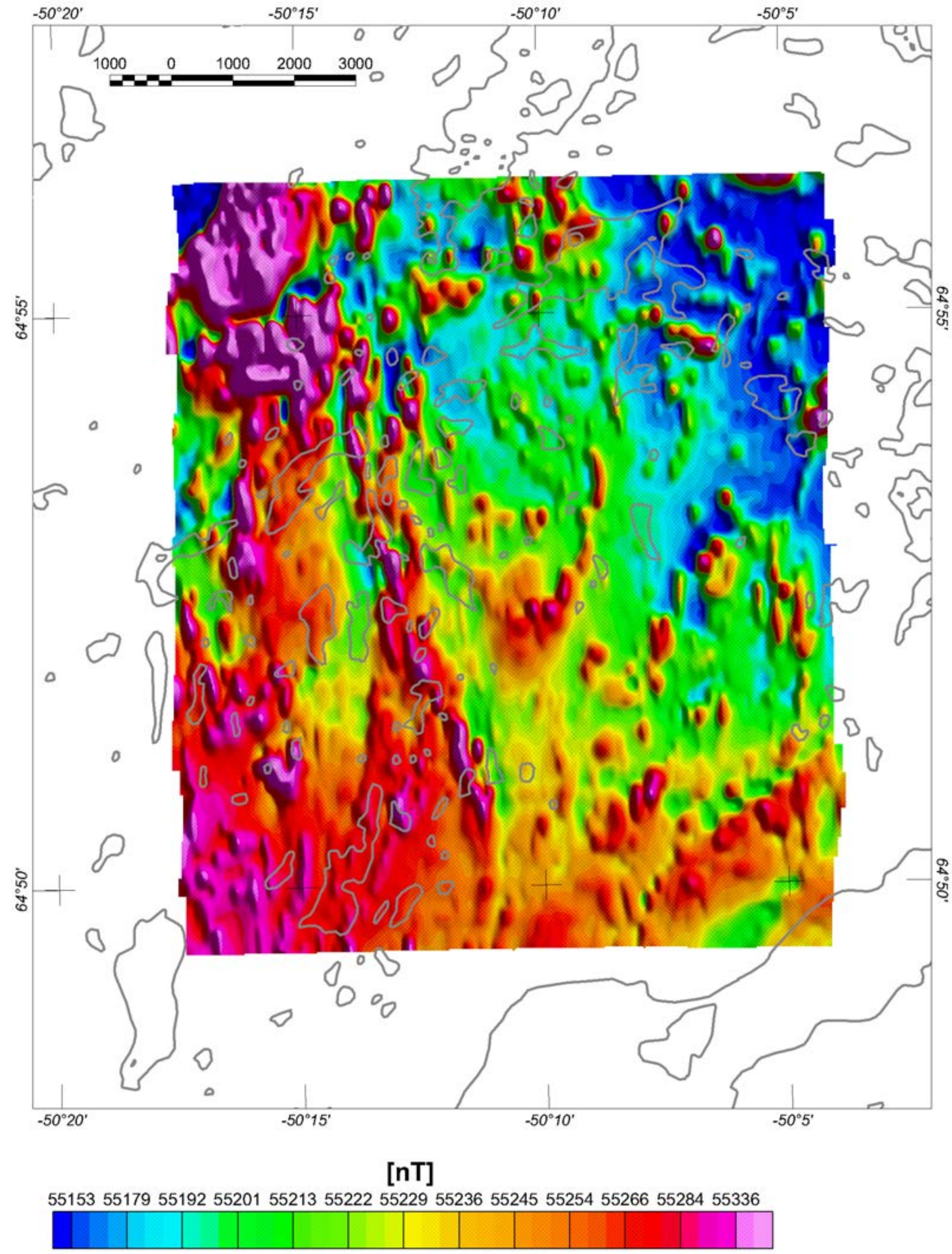

Figure 40. *Magnetic total field anomalies for the area north of Ujarassuit Paavat (survey block no. 5) from the helicopterborne combined electromagnetic and magnetic survey by Aerodat Inc for Fjordland Minerals Ltd. Shadow is superimposed by modelling a light-source illumination of 45° and declination 315°.*

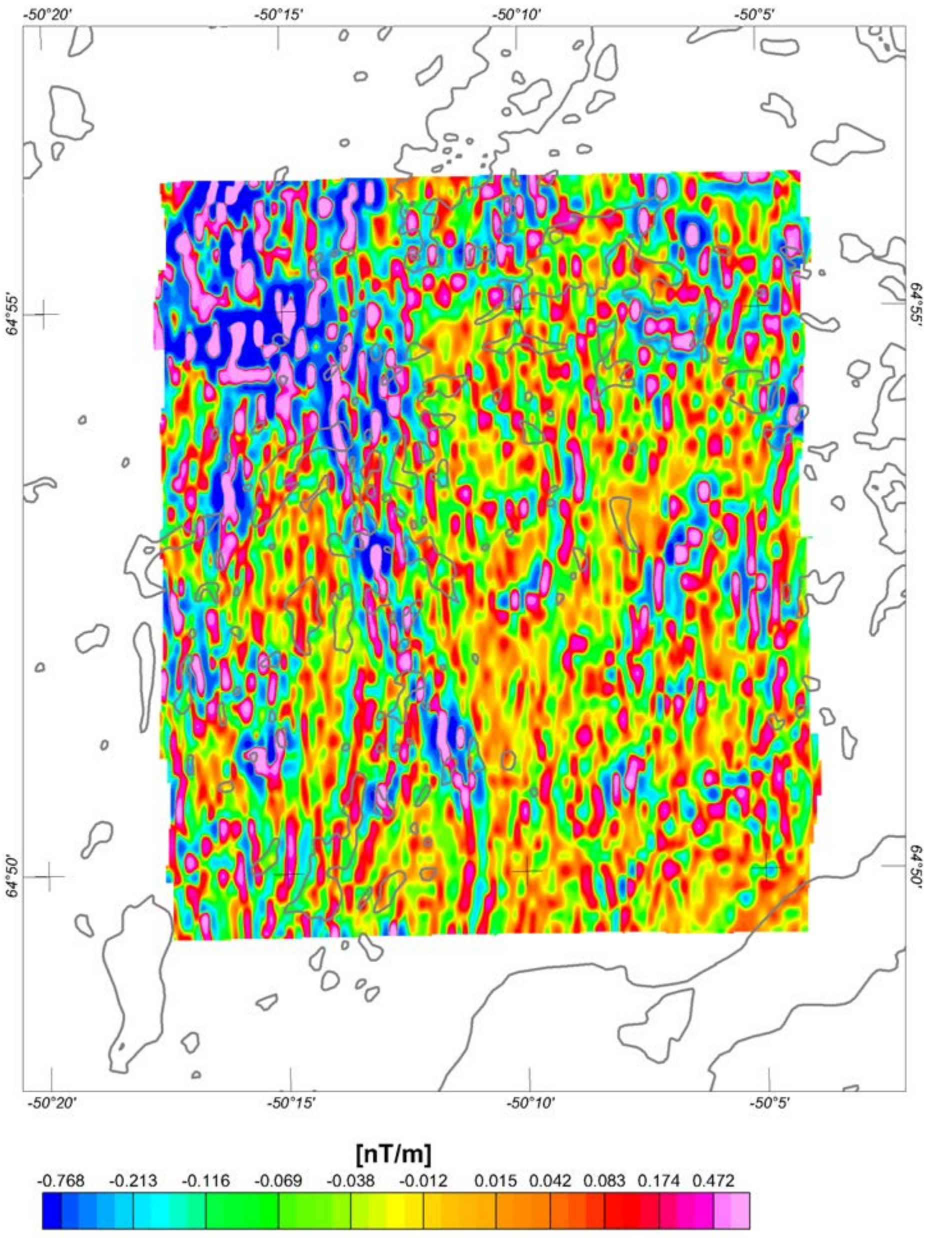

Figure 41. *Calculated vertical gradient of the magnetic total field for the area north of Ujarassuit Paavat (survey block no. 5) from the helicopterborne combined electromagnetic and magnetic survey by Aerodat Inc for Fjordland Minerals Ltd.*

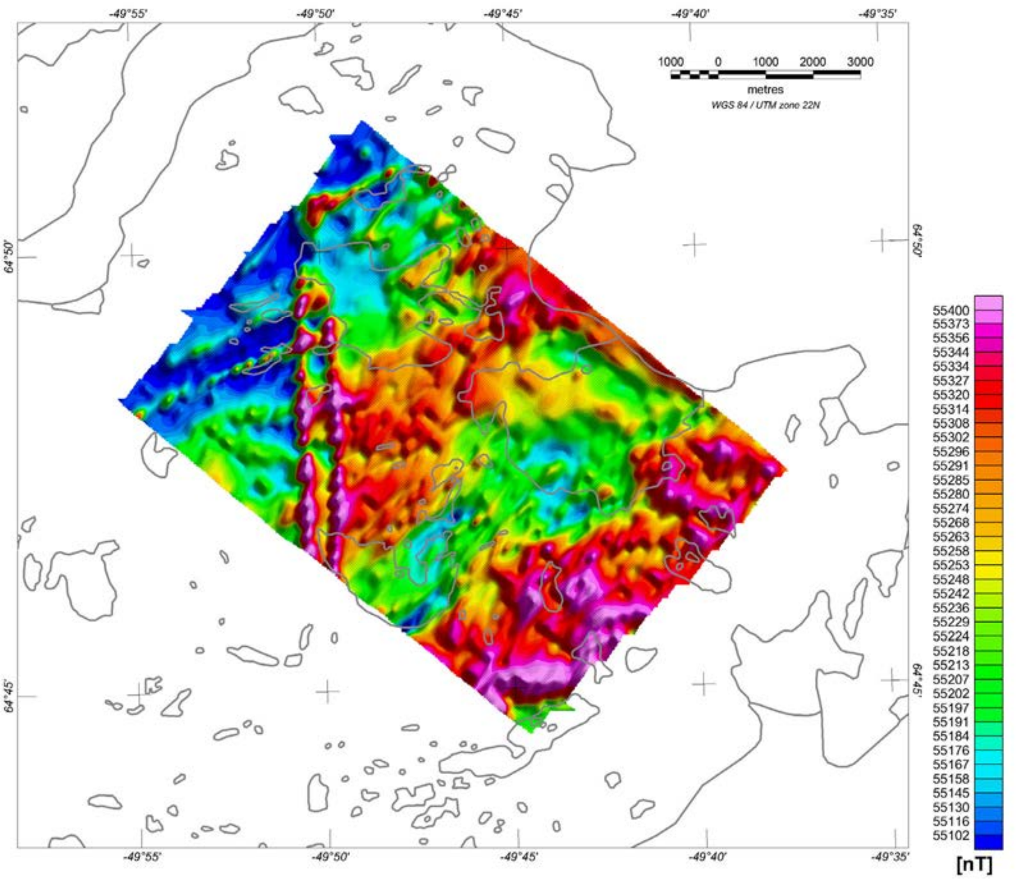

Figure 42. *Magnetic total field anomalies for the area north of for the Ivisaartoq greenstone belt (survey block no. 8) from the helicopterborne combined electromagnetic and magnetic survey by Aerodat Inc for Fjordland Minerals Ltd. Shadow is superimposed by modelling a light-source illumination of 45° and declination 315°.*

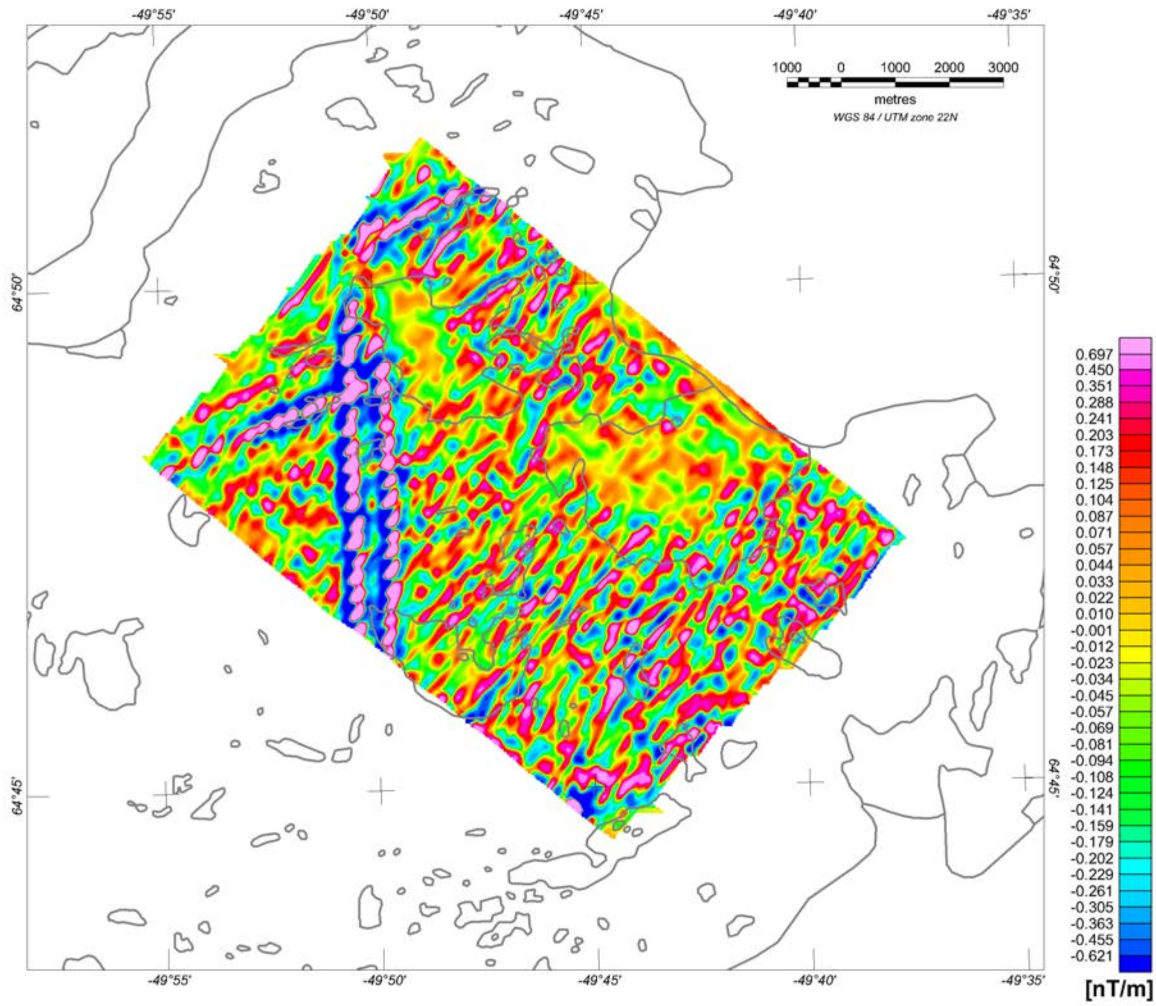

Figure 43. *Calculated vertical gradient of the magnetic total field for the Ivisaartoq greenstone belt (survey block no. 8) from the helicopterborne combined electromagnetic and magnetic survey by Aerodat Inc for Fjordland Minerals Ltd.*

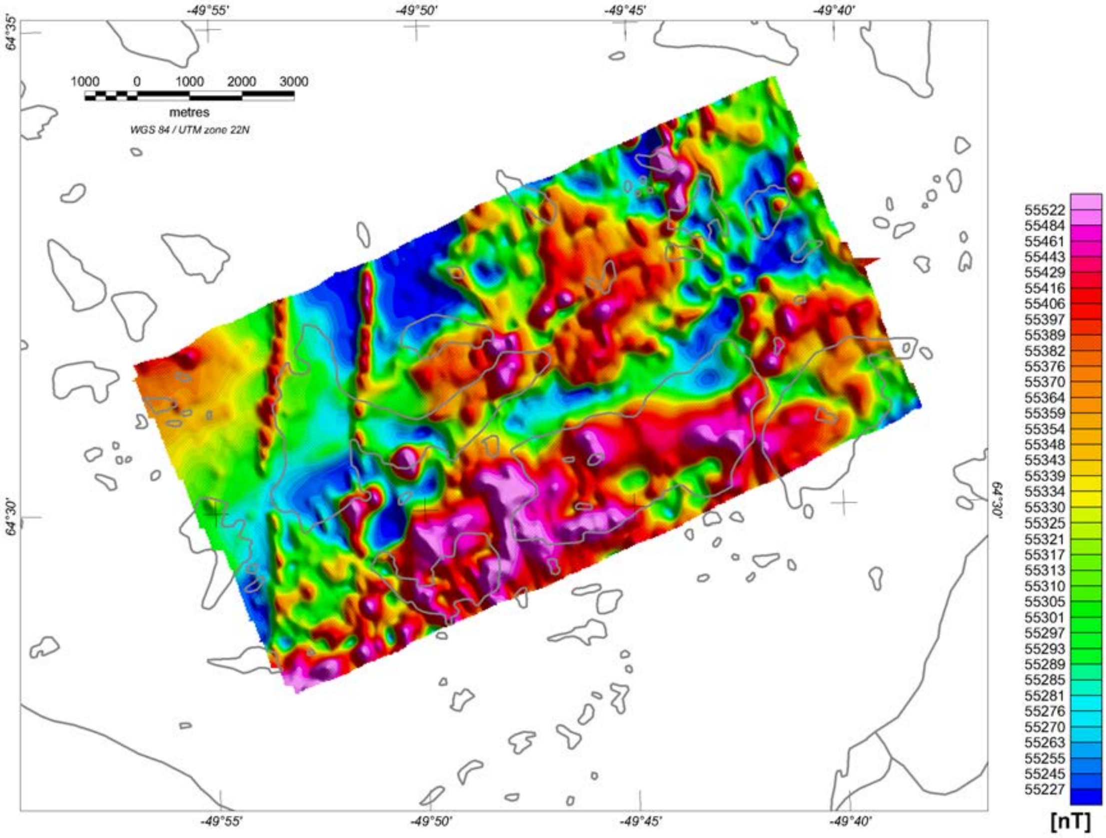

Figure 44. *Magnetic total field anomalies for the Nunatarsuaq area (survey block no. 7) from the helicopterborne combined electromagnetic and magnetic survey by Aerodat Inc for Fjordland Minerals Ltd. Shadow is superimposed by modelling a light-source illumination of 45° and declination 315°.*

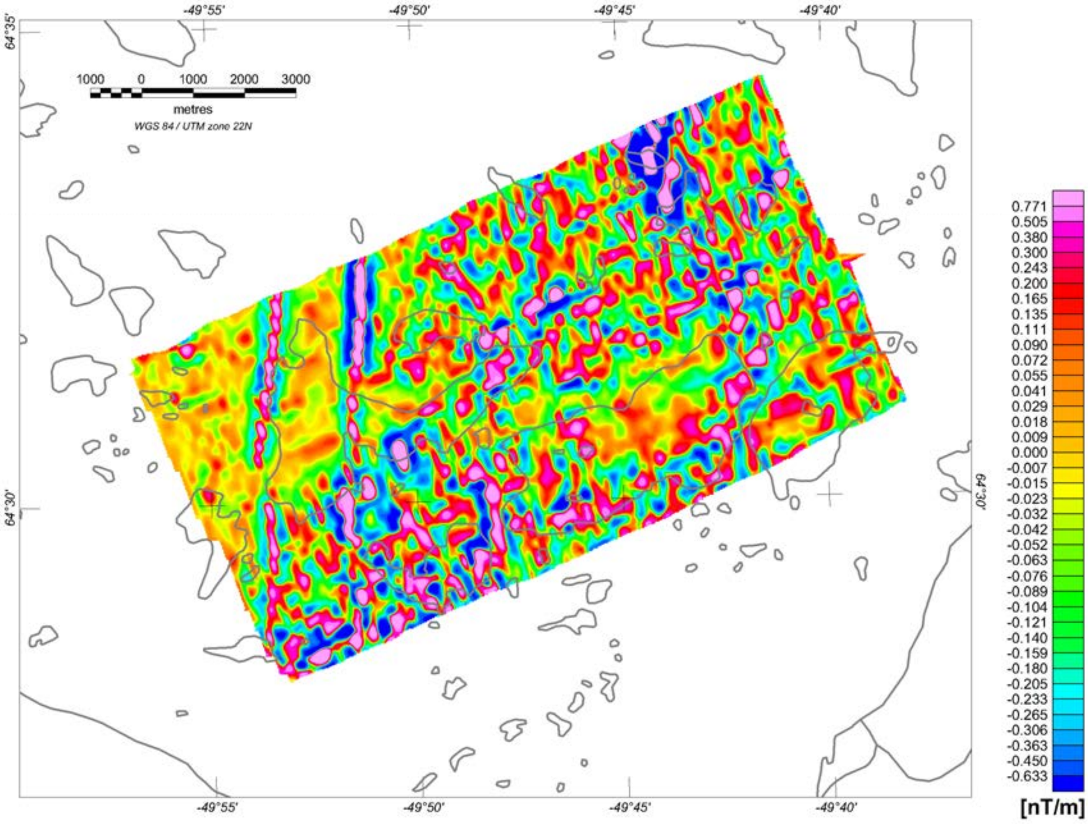

Figure 45. *Calculated vertical gradient of the magnetic total field for the Nunatarsuaq area (survey block no. 7) from the helicopterborne combined electromagnetic and magnetic survey by Aerodat Inc for Fjordland Minerals Ltd.*

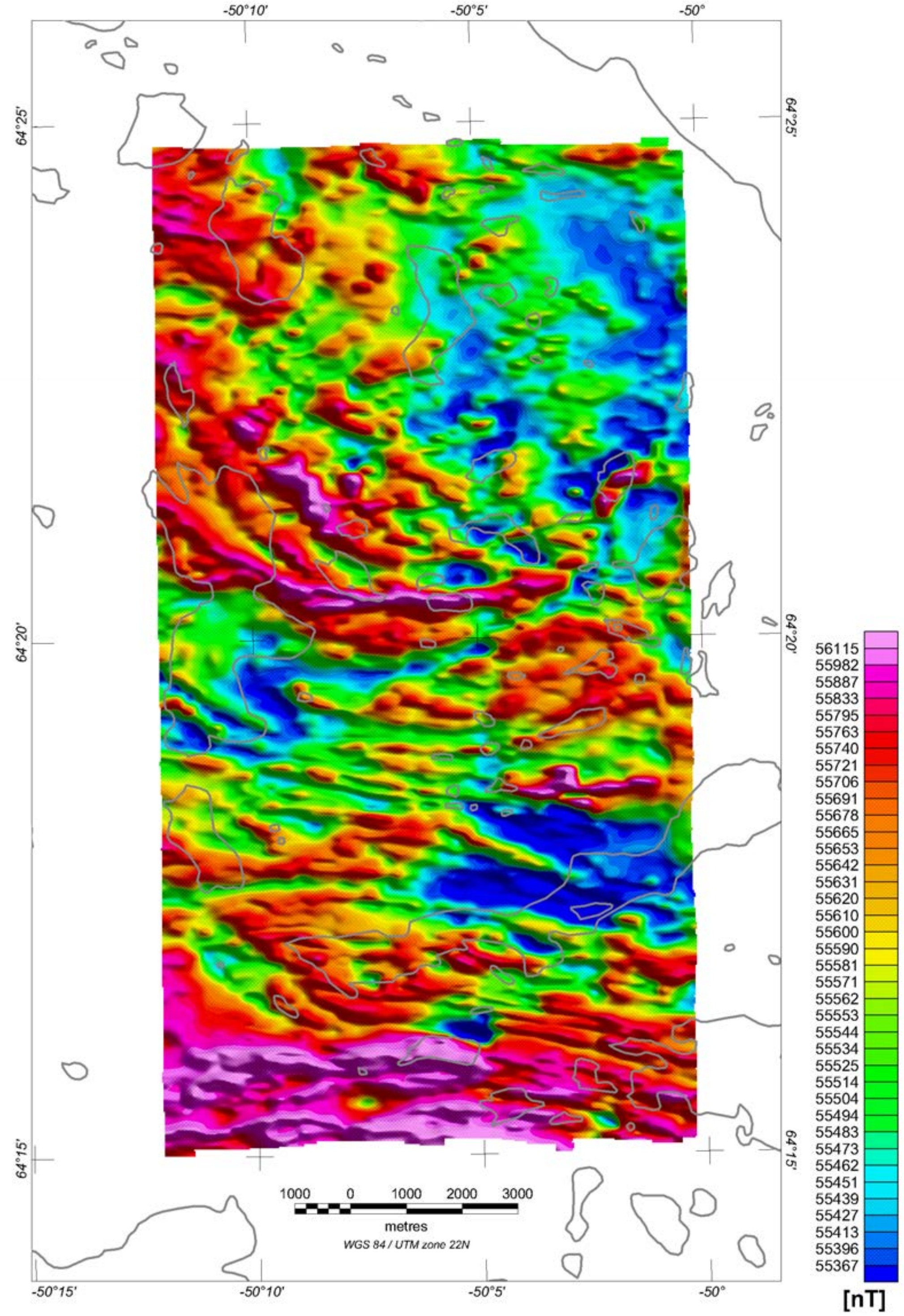

Figure 46. *Magnetic total field anomalies for the area between Ameralla and Kangersuneq (survey block no. 6) from the helicopterborne combined electromagnetic and magnetic survey by Aerodat Inc for Fjordland Minerals Ltd. Shadow is superimposed by modelling a light-source illumination of 45° and declination 315°.*

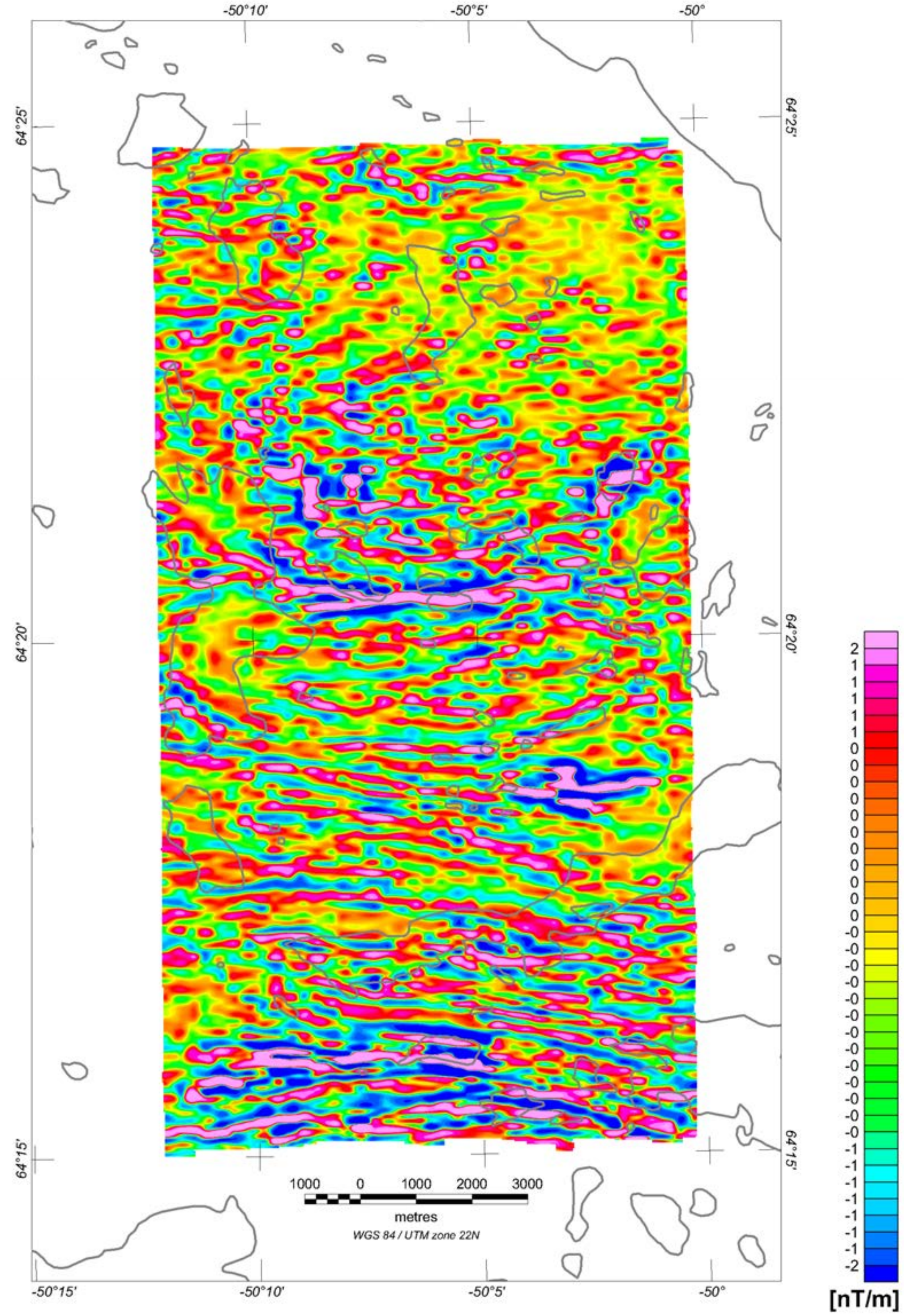

Figure 47. *Calculated vertical gradient of the magnetic total field for the area between Ameralla and Kangersuneq (survey block no. 6) from the helicopterborne combined electromagnetic and magnetic survey by Aerodat Inc for Fjordland Minerals Ltd.*

Gravity data

The gravity data from Kort- og Matrikelstyrelsen (Kenyon & Forsberg, R. 2000; Andersen, Knudsen & Trimmer 2001; Strykowski & Forsberg 1998 and Forsberg 2002) are shown as a Bouguer gravity field map (Fig. 48). The spacing of the gravity measurements does not allow detailed description of the gravity field. The Bouguer gravity field shows a broad minimum of 50 mgal in the centre of the Akulleq terrane. It is dissected by three branches with higher values, which show no apparent correlation with the aeromagnetic or regional geological data.

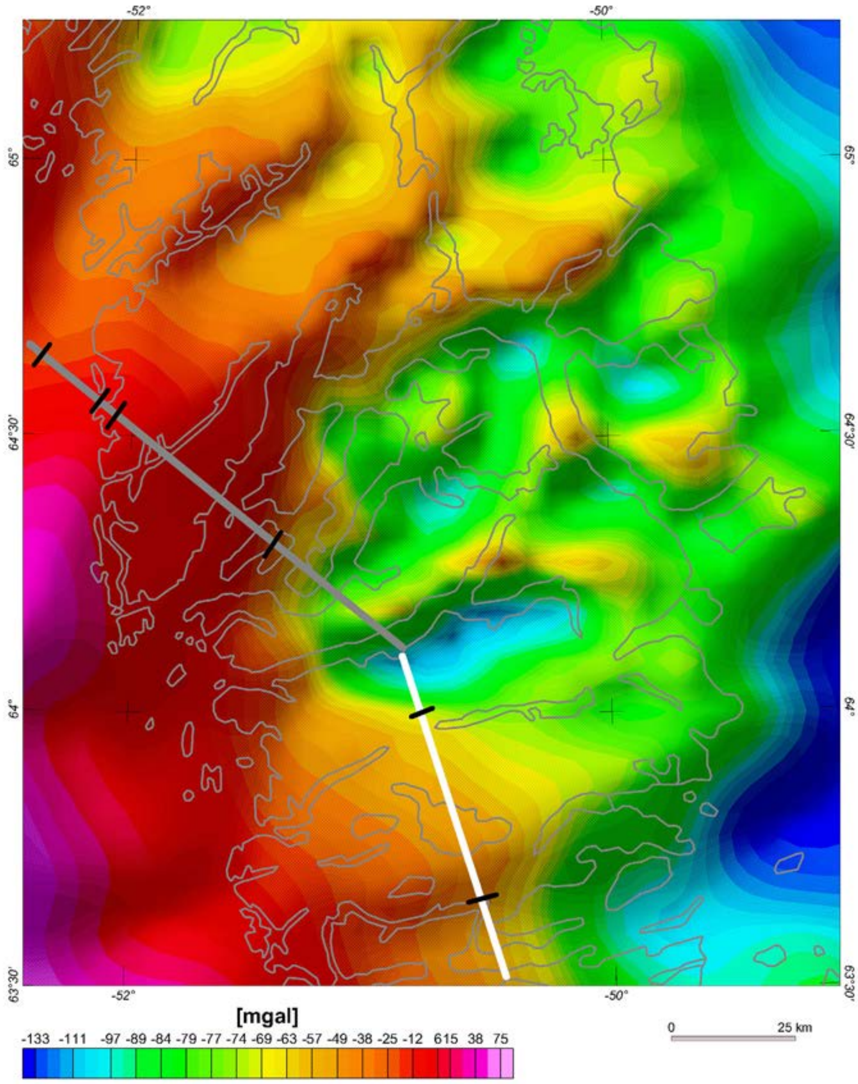

Figure 48. *Map of Bouguer anomalies for on-shore areas merged with free-air anomalies for off-shore areas. Data from KMS. A grey line (profile 1) and white line (profile 2) show the locations of profiles used in a joint inversion of gravity and magnetic data. The black lines orthogonal to the profiles show the location of the upper corners of the tabular bodies used in the modelling. For profile 2, only the two northern most edges are within the map limits.*

Ground geological data

The main source of ground geological data used for comparison and correlation are the published Survey maps from the region at scale 1:500 000 (Frederikshaab Isblink - Søndre Strømfjord, Allaart 1982) and 1:100 000 (Ivisaartoq: Chadwick & Coe 1988; Isukasia: Garde 1987; and Qôrqut: McGregor 1993). The 1:500 000 scale map is outdated by the newer Fiskefjord, Isukasia and Ivisaartoq map sheets, whereas it provides the only published map coverage of the Kapisillit map sheet area, however, only based on reconnaissance data.

Qualitative analysis of the magnetic field

The descriptions and interpretations in the following sections mainly refers to Figs. 28–35 with data from the regional 'Aeromag' surveys, Figs. 36–47 from the detailed surveys and the above mentioned geological maps. All place names can be found on Fig. 27 and the referenced labels (a–å; A–J) are found on the maps with the geophysical data.

The north-western boundary region of the Akulleq terrane

The Nuuk area, Bjørneøen, Storø, and NW Nuuk region

The north-western boundary of the Akulleq terrane between 64°N and 64°30'N from the Nuuk area through Sermitsiaq, Bjørneøen and western Storø is juxtaposed against the Akia terrane along the Ivinnguit fault of McGregor *et al.* (1991), see Fig. 27. This terrane boundary has not been detected on the aeromagnetic maps. However, a major magnetic boundary **(a)** follows north-western Godthåbsfjord inside the Akia terrane between 5 and 15 km to the north-west of the terrane boundary (Figs. 28–29). This magnetic boundary separates the c. 3.2 Ga granulite facies dioritic orthogneiss on Nordlandet (Garde *et al.* 2000), which displays a magnetic high, from a large area of c. 3.0 Ga amphibolite facies orthogneiss and supracrustal rocks with a magnetic low in the south-eastern Akia terrane and south-western Akulleq terrane. This boundary along eastern Nordlandet is also very pronounced on the maps with derivatives of the magnetic field.

We interpret the aeromagnetic boundary as a major shear zone or fault. In outer Godthåbsfjord it has a large vertical offset, juxtaposing amphibolite and granulite facies rocks from significantly different crustal levels. It dies out towards the head of Fiskefjord in the north-north-east, where the amphibolite and granulite facies domains are now separated by a wide, diffuse zone of partially retrograde rocks. Modelling of the aeromagnetic data, suggests that the boundary dips c. 45° towards NW. This is described in more detail in the sections below on quantitative modelling of the magnetic data.

The NE trending Kobbefjord fault that crosses the central part of Storø is clearly visible on the magnetic total field map, where it begins in the west as a magnetic low south-east of Kookøerne **(b)** and continues through Kobbefjord, towards north-east across Storø **(b)**, into Kangiusap Nunaa **(b)**, and further east towards Narsap sermia and the Inland Ice **(b')**. Cutting the south-western boundary of the Akulleq terrane, the Kobbefjord Fault must be of Palaeoproterozoic or still younger age.

Gold mineralised structure on Storø

The NNE trending greenstone belt along western Storø and the details of the complicated gold bearing structure in the central part of the island are unfortunately not resolved on the regional aeromagnetic map. The aeromagnetic signature of the Qôrqut granite complex is discussed in a later section.

Qussuk-Ilulialik to Isukasia

In the Qussuk-Ilulialik area the eastern margin **(c)** of a magnetic high **(d)** (Fig. 28 and also a sharp boundary on the associated maps with derivatives) follows the eastern boundary of the Taserssuaq tonalite (Garde 1997 and the boundary shown on the 1:100 000 scale Fiskefjord and Ivisaartoq maps). This is also the north-western boundary of the Akulleq terrane (Fig 27). However, we believe that the terrane boundary itself does not contribute to the anomaly. The magnetic boundary does not strictly follow the terrane boundary along the Ivinnguit fault, and it is diffuse **(e)** south-east of Ilulialik, possibly due to a topographic effect by the fjord. The magnetic boundary is also accentuated by the Ataneq fault just inside the Akia terrane between Ilulialik and Qussuk (Fig. 27). The Ataneq fault separates the Taserssuaq tonalite from the Qugssuk granite to its west and is supposed to be Palaeoproterozoic (see Garde, this report); the sharp magnetic boundary **(f)** suggests a significant vertical movement on the fault.

The Qugssuk granite close to the eastern margin of the Akia terrane has a low and variable magnetic signal that trends NNE, towards a pronounced minimum **(g)** visible in an unexposed area inside the Taserssuaq tonalite (the southern part of the lake Tasersuaq, Fig. 27 and Fig. 28). The magnetic response associated with the Qugssuk granite is seen clearly in the map with separation filtering of the field for the depth interval 3000–6000 m (Fig. 34) and in the map of the magnetic total field (Fig. 28).

The Isukasia region north and west of the Isua greenstone belt

The fault splay zone hosted by orthogneiss that is shown on geological maps west of the Isua greenstone belt (Fig. 27) appears as an irregular low **(h)** on the aeromagnetic maps of Figs. 28–32 and appears to confirm that this area is not part of the Taserssuaq tonalite. The supposed terrane boundary itself is not visible, but a couple of NE to EN trending anomalies **(i)** just inside the Akia terrane appear to be truncated by it.

A lozenge-shaped low **(j)** occurs within the Taserssuaq tonalite at the terrane boundary ca. 20 km SW of the Isua belt. In this area there is a disagreement between geology shown on the 1:100 000 scale Isukasia and Ivisaartoq maps respectively, and the magnetic low suggests that grey orthogneiss (with a low magnetic signal) is larger than shown on the Ivisaartoq map sheet or underlies the Taserssuaq pluton close to the surface.

Field work in 2003 by the first author of this chapter revealed that the southern and western parts of the horse shoe-shaped magnetic high **(k)** that outlines the Isua greenstone belt is derived from ultrabasic rocks. In this area the banded iron formation, which was previously considered to be the source (Bliss 1996, GEUS Report File 21453), mainly consists of cherty rocks with low magnetic susceptibility. However, the previous interpretation of the intense magnetic high to the north-east **(l)**, in part under the Inland Ice, is indeed due to a large occurrence of banded iron formation and remains unchanged.

A distinct narrow, NE trending high **(m)** at the Inland Ice in the Akia terrane ca. 10 km north-west of the Isua greenstone belt corresponds to amphibolite. Another, larger amphibolite body directly north of the Isua greenstone belt gives no magnetic response.

Detailed aeromagnetic survey, Isua greenstone belt: data collection and overall patterns

NunaOil A/S has produced a detailed aeromagnetic map of the of the Isua greenstone belt from flights with a line spacing of 200 m and an altitude of 120 m above ground (NunaMinerals 2003, GEUS REPORT file 21694). The following description refers to Fig. 38 showing the magnetic total field and Fig. 39, showing the vertical gradient.

The detailed survey has a significantly better resolution in comparison with the regional survey. This is evident by the response of the horse-shoe-shaped magnetic pattern within the greenstone belt, which on the regional map form a single anomaly whereas on the detailed map is seen as two spatially separated anomalies. As mentioned previously, ultramafic rocks are causing these anomalies. Within the central gneiss dome, a number of anomalies are visible in the map showing the vertical gradient of the field. These anomalies seem to correlate with mapped Archaean dykes (White *et al.* 2000).

Early and mid to late Archaean supracrustal rocks in the Ivisaartoq region

A narrow, ENE trending magnetic high **(n)** on Figs. 28–29 extends westward from the Inland Ice at 65°N and swings south towards the north-western side of Tussaap Tasia (Fig. 27). It follows a train of ultrabasic enclaves of the early Archaean Akilia association, which probably give rise to the anomaly - perhaps aided by fragments of early Archean Tarssartôq basic dykes (Gill & Bridgewater 1979, Garde, this report).

A less intense magnetic high **(o)** follows the SSW trending amphibolite west of Ujarassuit Paavat of presumed mid-Archaean age. Another magnetic high **(p)**, parallel to **(n)** to the sout-east of structure **(n)** follows a train of ultrabasic enclaves. Its eastward continuation under the Inland Ice suggests a larger ultrabasic body may be hidden there **(p')**. The pattern of magnetic high **(o)** appears to merge with the southeastern extension of the magnetic high **(n)**. However, the structural interpretation is not straightforward. Anomalies **(n)** and **(p)** may represent a west-facing isoclinal fold closure that ends in **(p')** under the ice but could also represent a juxtaposition of two different units, where **(n)** continues southwards to **(o)**. A third possibility is that the weak anomaly joining **(o)** with **(n)** is caused by a fault.

A prominent E–W trending magnetic high north of Narsap sermia **(q)** follows a narrow ultrabasic zone within the main part of the Ivisaartoq greenstone belt, in part where the so-called magnetic marker was mapped by Chadwick (1990). The triangular, central part of the greenstone belt forms a magnetic low **(r)**, whereas the northern branch of the belt that straddles the head of Ujaragssuit Paavat is only just visible **(s)** with a low to intermediate signal.

The Ivisaartoq region in detail

Detailed aeromagnetic survey north of Ujarassuit Paavat: data collection and overall patterns

Aerodat Inc has for Fjordland Minerals Ltd produced a detailed aeromagnetic map of the area north of Ujarassuit Paavat based on a helicopterborne combined electromagnetic and (Aerodat Inc 1997, GEUS REPORT file 21604). The detailed aeromagnetic map of Figs. 40 and 41 confirms and builds out the above interpretation based on the regional aeromagnetic data set. Ultramafic components within the supracrustal belt are seen as magnetic highs, and a number of N-S trending lineaments correspond well with the structural trend mapped by Chadwick & Coe (1988). Interestingly, the north-western corner, shown by them as early Archaean orthogneisses, have a higher magnetic response than those mapped to the south and east as Nûk gneiss and undifferentiated granitic gneisses of presumed mid- to late Archaean age.

Detailed aeromagnetic survey, Ivisaartoq greenstone belt: data collection and overall patterns

NunaOil A/S has produced a detailed aeromagnetic map of the central part of the Ivisaartoq greenstone belt from flights with a line spacing of 200 m and an altitude of 120 m above ground (NunaMinerals 2003). The following interpretation refers to Fig 36 showing the magnetic total field and Fig. 37 showing the vertical gradient. At this detail the local geology is easily visible in the geophysical data. The main geological reference is the description by Chadwick (1990), besides the 1:100 000 scale geological map (Chadwick & Coe 1988) and field maps by B. Chadwick at scale ca. 1:20 000, which are included in the DVD of this report (Chadwick).

The magnetic field is largely determined by the response from thin, elongate structures in the central, E–W trending part of the Ivisaartoq greenstone belt and its two northern branches, which all show up as positive anomalies. The strong positive linear signals are associated with broad shoulders with negative amplitude, which broadly coincide with the extent of the greenstones. Within these shoulder areas, there are only very few small-scale structures with positive magnetic response.

The rest of the map areas consist of orthogneiss domes according to Chadwick (1990 + field map). These areas are characterised by magnetic anomalies of low amplitudes and intermediate to long wavelengths, and a gradient towards higher magnetic response in the east. In addition, two N–S trending dolerite dykes of presumed Palaeoproterozoic age in the eastern part of the map area show up as distinct highs.

The magnetic signature of the Ivisaartoq greenstone belt

On the southern flank of the syncline, the 'magnetic marker' of Chadwick (1990) is clearly visible on the aeromagnetic map (vertical gradient) of Fig. 37 and labelled on this as **(A)**. In places also the 'olivine-rich ultrabasic marker I' **(B)** stands out. The hinge zone in the area to the east is cut by the above mentioned two N–S trending dolerite dykes with strong positive anomalies, but also the hinge zone itself displays a positive anomaly. This area has a complicated geological structure but presumably mainly comprises the magnetic marker and olivine-rich ultrabasic marker I **(A+B)**, which together form the tight fold hinge.

On the northern flank of the syncline, the ultrabasic marker I and the magnetic marker together form a distinct linear anomaly **(C)**, which continues towards north and north-east **(C')**, flanking a large gneiss dome in the central part of the Ivisaartoq peninsula. Inside the syncline, small parts of ´ultrabasic marker II' **(D)** are visible on both flanks, and within the western part of the hinge zone, the folded ´ultrabasic marker III' forms a clear arrow-shaped anomaly **(E)**.

An elongate, E–W trending positive anomaly (**F**) east of the synclinal hinge zone, 3–4 km east of the two dolerite dykes, corresponds to a large ultrabasic sheet that appears to be stratigraphically below the magnetic marker (Chadwick 1990).

A moderate to strong positive linear anomaly **(G)** follows the north-westernmost branch of the Ivisaartoq greenstone belt. A close inspection of Chadwick's field map B (a scanned version of which is included in this report) reveals that this anomaly is centred in rocks mapped as amphibolite just within this northern branch of the greenstone belt, and that it only locally coincides with mapped ultrabasic lenses. We therefore suggest that a magnetic marker or magnetic ultrabasic rocks such as those mapped in the south-central part of the greenstone belt are also present here.

A similar, NNE trending linear magnetic anomaly **(H)** occurs between anomalies **(G)** and **(C')**, inside the wedge of orthogneiss that separates the two northern branches of the greenstone belt. It follows a depression with Quaternary cover, and it is therefore possible that the bedrock consists of supracrustal rocks.

A weak positive anomaly **(J)** about 2.5 km west of the western boundary of the greenstone belt correlates with a c. 100 m thick amphibolite horizon, occurring within orthogneiss.

A ca. 2 by 6 km large area within the orthogneiss dome north of the thickest part of the greenstone belt is covered by Quaternary drift. We have not observed any magnetic anomalies in this area to suggest that these surficial deposits hide supracrustal cocks.

Detailed magnetic survey north of the Ivisaartoq greenstone belt

Fig. 42 and 43 show the aeromagnetic maps of part of the gneiss dome north of the Ivisaartoq greenstone belt, straddling the northern branch of the latter. There is a good agreement with the data set described in the previous section (Figs. 36 and 37) where the two surveys overlap, and the two N–S striking dykes are again clearly visible. In the southern corner of the survey area, a strong positive anomaly extends from the greenstone belt to the north-east. On the geological map this area is shown as undifferentiated granitic gneiss. Enclaves of ultrabasic rocks like those shown elsewhere within the gneiss may provide an explanation of the positive anomaly.

In the northern corner, an ENE trending positive anomaly coincides with Quaternary surficial deposits.

The central and eastern parts of the Akulleq terrane

The regional survey data
The central and eastern parts of the Akulleq terrane are largely underlain by late Archaean grey gneisses and granitic rocks (Fig. 27) including the Qôrqut granite complex, besides early Archaean grey gneiss shown as Amîtsoq gneiss on the published maps. Only few geological data are available from the central part of the Akulleq terrane. Especially the geology of the Kapisillit map sheet area east of the Qôrqut sheet is poorly known and only published at scale 1:500 000, based on reconnaissance data. The distribution of e.g. supracrustal rocks and early Archaean gneisses is therefore uncertain.

The central part of the Akulleq terrane displays a rather uniform, low to intermediate magnetic signal on Fig. 28 **(t-t'-t'')**. Areas tentatively mapped as Amîtsoq gneiss generally coincide with magnetic lows, but this correlation is uncertain in view of the limited published age data available to support the distinction between early and late Archaean gneisses.

A slightly elevated, NE trending area **(u)** in the magnetic field map (Fig. 28) corresponds closely with exposures of the 2550 Ma Qôrqut granite complex (Brown *et al.* 1981, Friend *et al.* 1985) as it is shown on the 1:100 000 scale Qôrqut and Ivisaartoq map sheets, in particular its western boundary on Storø. The magnetic expression of the Qôrqut granite is also clear in the maps with gradients of the total magnetic field (Figs. 29–33).

The south-eastern part of the terrane is dominated by a large, roughly triangular magnetic high **(v-v'-v'')** which stands out in sharp contrast to the regional low covering the central and southern parts of the terrane. We tentatively interpret this as largely underlain by late Archaean granitic rocks *s.l.* such as the Ikkatoq gneisses of Nutman *et al.* (1989), in spite of a rather poor correlation with the lithological units and boundaries shown on the published and unpublished geological maps. As mentioned above, some of these maps are only of reconnaissance nature.

Within this triangular magnetic high region there are several linear magnetic ridges trending E–W or NW–SE. Some of these coincide with up to 1 km wide greenstone belts, notably those west of Kangiata Nunaata Sermia **(w)** and at the head of Ameralik east of Naujat kuât **(w)**. Other such magnetic ridges, e.g. those south of Kapisillit **(w')**, only have poorly defined geological expressions.

A prominent, ENE–WSW trending magnetic low **(x)** transects Kangiusap Nunaa c. 5 km north of the Kobbefjord fault in the northernmost part of the triangular magnetic high region **(v-v'-v'')**. It has no surface geological expression.

Another magnetic low **(y)**, possibly connected to the former, trends WNW–ESE and underlies the south-easternmost extension of Godthåbsfjord called Kangersuneq. It is more or less perpendicular to the geological structures shown in this region, and may reflect a hidden fault. A Palaeoproterozoic fault with this orientation is exposed on strike of the magnetic structure some 50 km to the WNW across Qussuk, and hosts a few m thick granitic dyke dated at approx. 2085 Ma (Garde 1997). The latter fault is conjugate with the NE trending Fiskefjord fault in the Akia terrane.

Some of the largest supracrustal units shown on the 1:500 000 scale map south and east of Kapisillit (and inferred from reconnaissance geological mapping) have no magnetic expressions, suggesting that they may not be nearly as large as drawn on the map.

Detailed magnetic survey on Nunatarsuaq

Figs. 34 and 35 in central Nunatarsuaq cover the easternmost part of the large triangular magnetic high described in the previous section. The signatures of two N–S trending dolerite dykes are again prominent. Besides, the generally high plateau covering most of Fig. 34 is dissected by magnetic lows which correspond well to fault systems shown on the geological map (Chadwick & Coe 1988). Several small positive anomalies, also within larger lakes, are also visible but difficult to interpret.

Detailed magnetic survey between Ameralla and Kangersuneq

The detailed aeromagnetic maps of Fig. 36 and 37 between Ameralla and Kangersuneq show a close correlation with an isoclinally folded, E–W trending amphibolite shown on the 1:500 000 scale map (Frederikshåb Isblink - Sønderstrømfjord). Besides, there are several positive, NW-trending anomalies to the north of this structure, suggesting that at least one additional greenstone belt is missing here from the regional geological map. There are also several other, narrow elongate positive anomalies throughout the map of Fig. 36. The most conspicuous ones are found in its southernmost part and trend E–W. We also interpret these as originating from basic or ultrabasic magmatic rocks.

The anomaly pattern is transected by N–S and NW–SE trending lines with apparent breaks in the predominantly E–W trending anomaly pattern. We interpret these as faults with small offsets.

The south-eastern and south-western boundaries of the Akulleq terrane

The southern boundary region of the Akulleq terrane is also a boundary between the amphibolite facies gneisses in the former terrane and gneisses in granulite facies or partially retrogressed from granulite facies in the Tasiusarsuaq terrane to the south. This geological boundary coincides with a magnetic boundary between the regional low on the Akulleq side and a region to the south of intermediate to high magnetic signature (Fig. 28). We interpret this boundary as primarily reflecting the different metamorphic histories across the terrane boundary (see Garde, this volume), in analogy with the strong magnetic difference between the granulite and amphibolite facies rocks along western Godthåbsfjord. A magnetic minimum zone **(æ)** close to Buksefjorden in the southernmost Akulleq terrane, adjacent to the north-western border of the Tasiusarsuaq terrane (Fig. 27), may correspond to the Tre Brødre terrane, which is a local tectono-stratigraphic subdivision of the Akulleq terrane (Fig. 27, Nutman *et al.* 1989; McGregor *et al.* 1991).

In the south-western part of the Akulleq terrane and in the northern part of the Tasuisarsuaq terrane there are several straight, narrow, positive magnetic ridges **(ø)** which may cross the terrane boundary. Some of these are readily correlated with Palaeoproterozoic dolerite dykes which are parallel to the conjugate, ENE–WNW trending Fiskefjord fault system. Also other narrow magnetic highs may relate to similar unmapped dykes, hidden under water, drift, or ice.

An elliptic magnetic high **(å)** in the Tasiusarsuaq terrane 10 km ESE of the eastern end of Taserssuatsiait coincides with a c. 5 km large supracrustal body comprising both amphibolite and ultrabasic rocks.

Lineaments from regional magnetic data

The magnetic data from the regional magnetic survey have been analysed with respect to lineaments. The analysis is based on detection of local maxima and minima in the recorded magnetic total field data and is performed along lines in the interpolated and gridded data. Fig. 49 shows the maxima and minima for analysis along the E–W oriented lined and Fig. 50 the maxima and minima along N–S oriented lines. The locations of maxima and minima define lines that are easily correlated to some of the major structures. In addition a number of other structures are indicated. The digital maps enclosed on the DVD are most suitable for further analysis and data integration. Faults often show up as lines with minimum values of the field, whereas dykes and other bodies have a positive signature. It is important to note that magnetic responses are always associated with both maxima and minima.

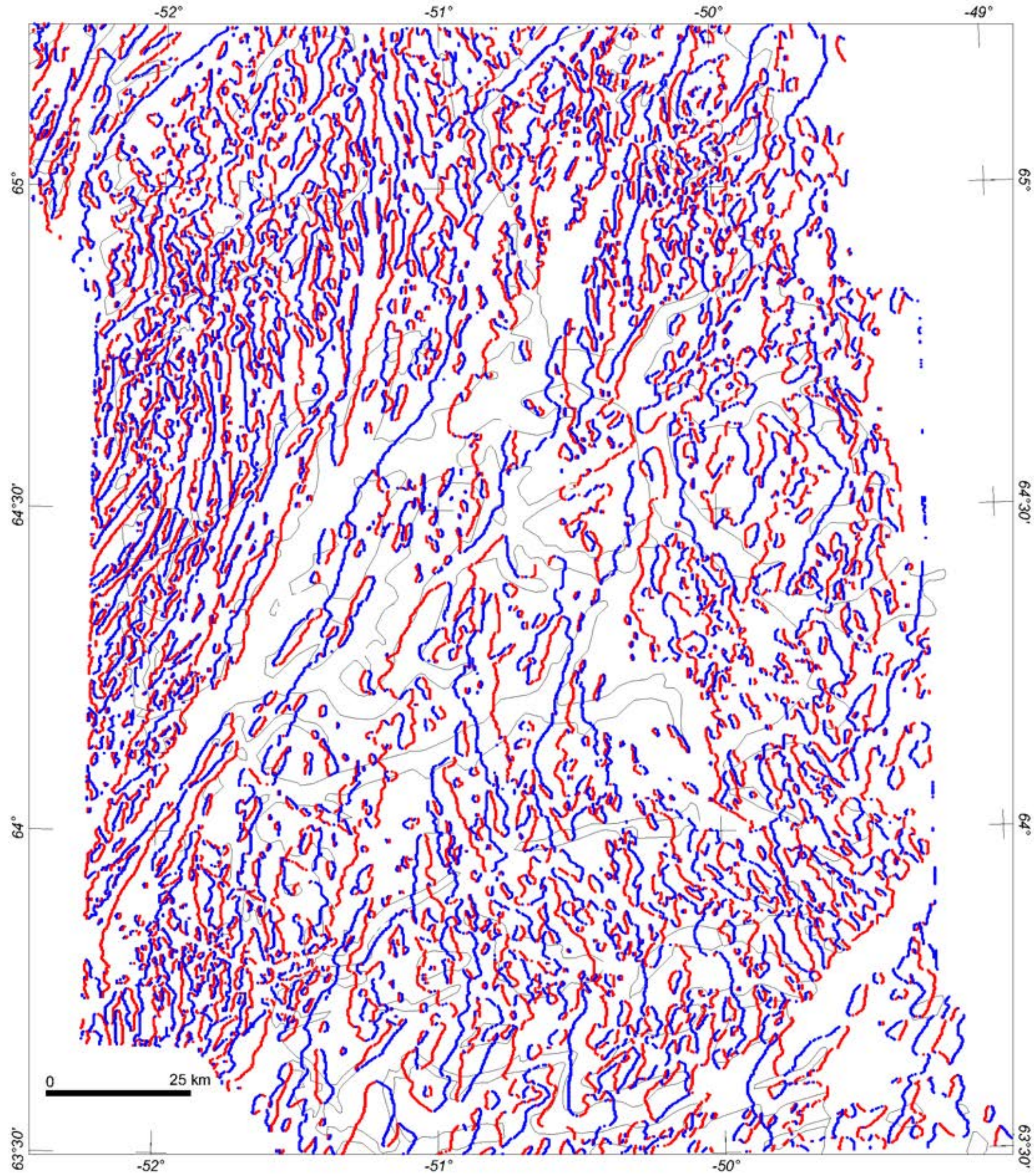

Figure 49. *Location of minima (blue dots) and maxima (red dots) in the magnetic total field along gridlines in E–W direction.*

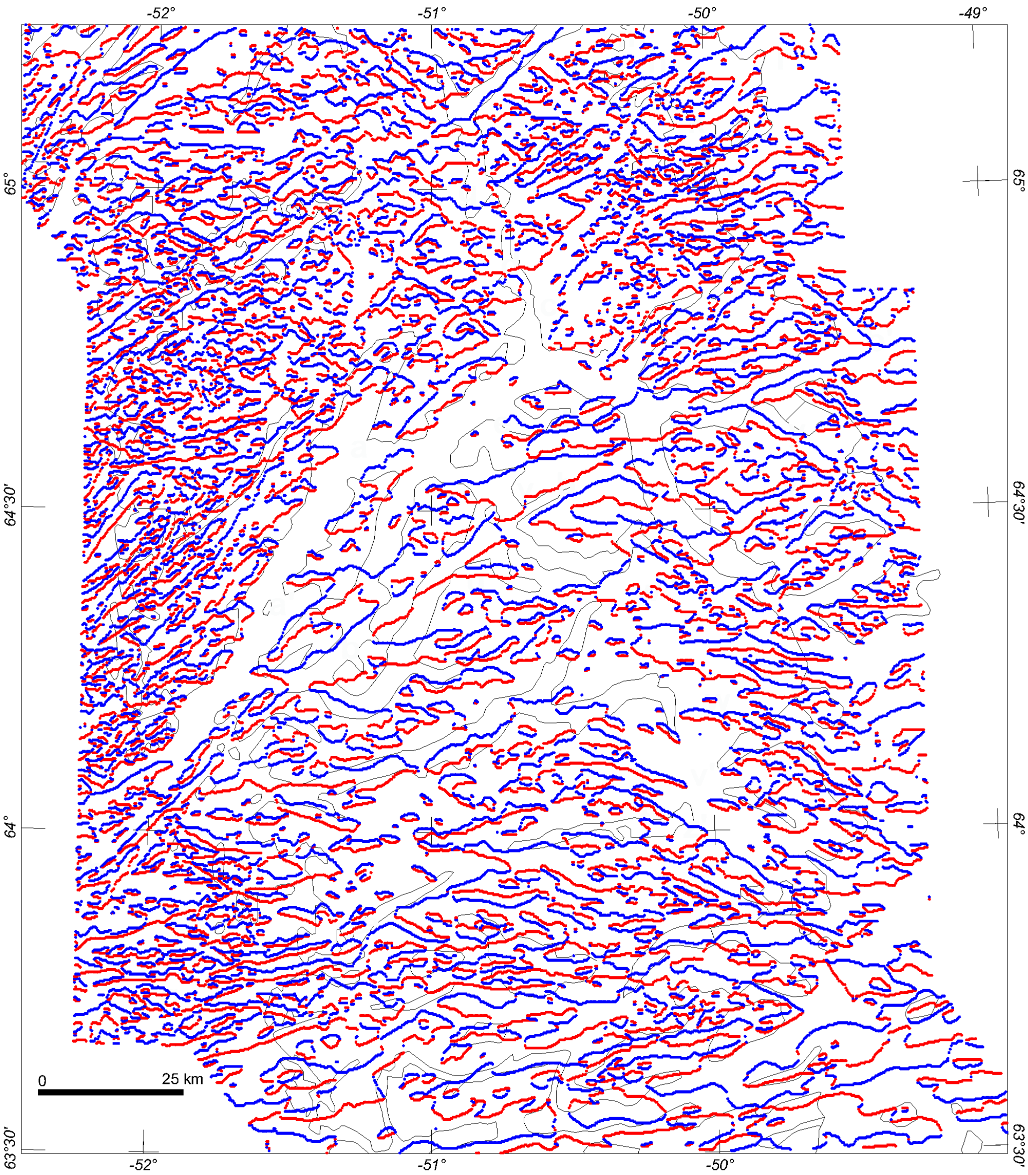

Figure 50. *Location of minima (blue dots) and maxima (red dots) in the magnetic total field along gridlines in N–S direction.*

Quantitative interpretation of aeromagnetic and gravity data

Improved source parameter method – regional structures

In this section a modelling of the regional structures with respect to the dip of the larger crustal blocks are presented. In general, the interpretation of potential field data is nonunique and constraints from other observations or assumptions are needed in the modelling. We apply three assumptions that seem plausible with respect to the magnetic data from the Nuuk area.

The first assumption is that the crust can be subdivided into a number of segments that are fairly uniform with respect to distribution of magnetic properties when observed at a sufficient high altitude. The validity of this assumption relates to the fact that the response from magnetic bodies of limited spatial extent resembles the response of a magnetic dipole. Thus, the response of the large-scale crustal segments having internal similarity with respect to the magnetic material can be treated in the modelling as homogenous segments or blocks. A standard upward continuation technique is used for the calculation of the field at high altitudes.

The second assumption is that the location of the boundaries between adjacent segments is defined by the location of abrupt changes in the pattern of the magnetic anomalies when displaying the magnetic field at the original survey altitude. Usually maps displaying the gradients, either vertical, horizontal or combinations of these, are suitable for this purpose. The validation of this assumption can be viewed in terms of the standard separation filter as described by Jacobsen (1987). In this context, the vertical derivative is interpreted simply as the separation filter corresponding to a 0.5 m thick horizontal slice at a depth of half the original measuring height.

The third assumption is that the upward continued field can locally be considered as originating from a two-dimensional structure. The locations at which this assumption is valid can be verified partly by a display of the upward continued field, and partly by the analysis of some of the calculated quantities from the modelling.

The modelling is done by applying the improved source parameter method (iSPI) of Smith *et al.* (1998) and Thurston *et al.* (2002) to the upward continued field. The method uses a two-dimensional slab model as principal model in the analysis (see Fig. 51). A function named k_b, among a number of other functions, is calculated from the original field. This function has some very simple properties with respect to the geometry of the slab model. The function k_b has one peak, is symmetric, and has a characteristic bell-shaped appearance. The location of the peak is at the position defined by the middle of the upper and lower edges of the slab, and the value of k_b equals the inverse distance to this point. The function k_b does not provide information about the dip direction of the edge of the slab. However, by utilising the information in the gradient field of the original data (the second assumption) about the location of upper edge, we have two points on the sloping interface and are able to estimate the direction of the dip.

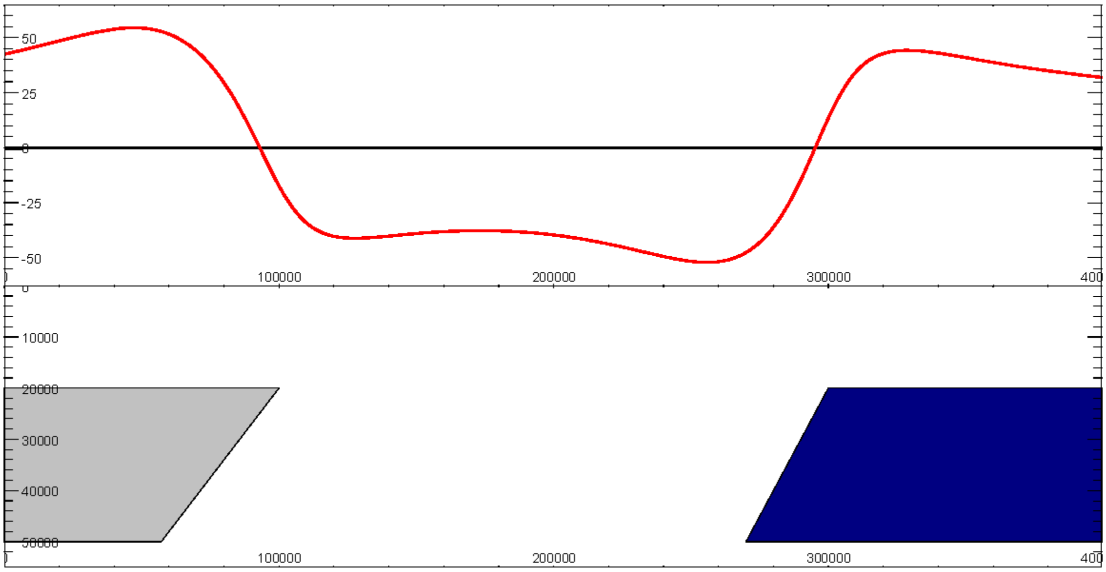

Figure 51. *Principal slab model used in the iSPI method. The upper panel shows the magnetic total field anomaly for the model in the lower panel. Units are nT and km. The magnetisation for the two slabs shown in grey and blue is 0.01SI units.*

The results presented in this report are based on an upward continuation of the original field measured at 300 m to an altitude of 30 km. In terms of the standard separation filters of Jacobsen (1987), an altitude on 30 km corresponds to responses caused mainly from structures below a depth 15 km, i.e. the analysis focuses on structures penetrating the crust. Although the separation filter does not provide a perfect separation of responses from different depth intervals, it does put lower weights on responses from local near-surface structures. The main advantage of using the upward continuation operator as a separation filter is that the filtered responses are in accordance with measurable quantities, i.e. it has a direct physical meaning.

Details on the calculation of the k_b functions are given in the appendix at the end of this chapter. The method is performed along lines of the upward continued grid of the magnetic field, and the analysis are presented separately for lines in E–W direction and lines in N–S direction. If the strike of the assumed two-dimensional structure structures are not perpendicular to the line direction, the k_b function is modified by a factor of 1/sin(α) where α is the angle between the strike and the line direction. Deviations from two-dimensionality may shift the level for the k_b function so that the depth estimates obtained from the inverse value of k_b at the peak location are biased. In cases where the strike of the structures is at an oblique angle to both directions, the peaks obtained for the two directions must coincide. Deviations in locations indicate that the assumption of two-dimensionality is not fulfilled.

The calculated k_b functions based on lines along the E–W direction are shown in Fig. 52, and for lines along the N–S direction in Fig. 53. It is evident that the peaks do not coincide in the cases where the strike angle has an oblique angle to the both grid line directions. In particular, the peaks found on Nordlandet (Fig. 53) within the Akia terrane show such a discrepancy. A possible explanation for the deviations is that the merged data set may contain artefacts due to differences in the base level for the new onshore aeromagnetic data and the older offshore data. If this is the case, the results obtained from analysis along N–S directed lines are more reliable than those along the E-W lines. Lines representing the locations of the segment boundaries at surface are drawn in white colour on the maps. These lines are based on the total field and the calculated gradients of the field at the measuring altitude (Figs. 29–33). The arrows (black colour) on Fig. 53 indicate the dip direction based on analysis along the N–S lines. It is evident from the analysis that a major crustal boundary located close to the mapped northern boundary of the Akulleq terrane dips towards NW.

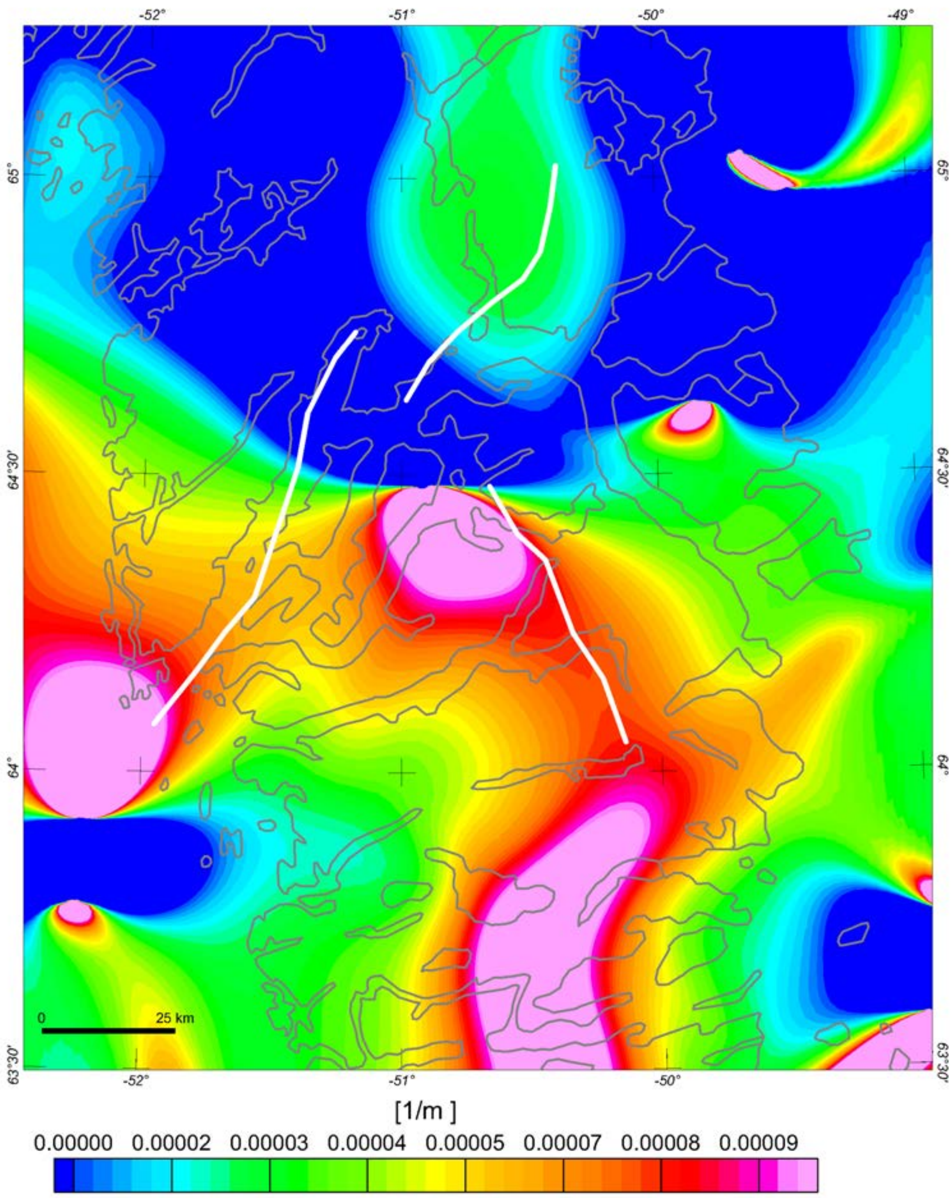

Figure 52. *The calculated source parameter function k_b based on lines in E–W direction in the grid of the 30 km upward continued magnetic field. The white lines show some of the major boundaries separating crustal segments with distinct differences in magnetic properties.*

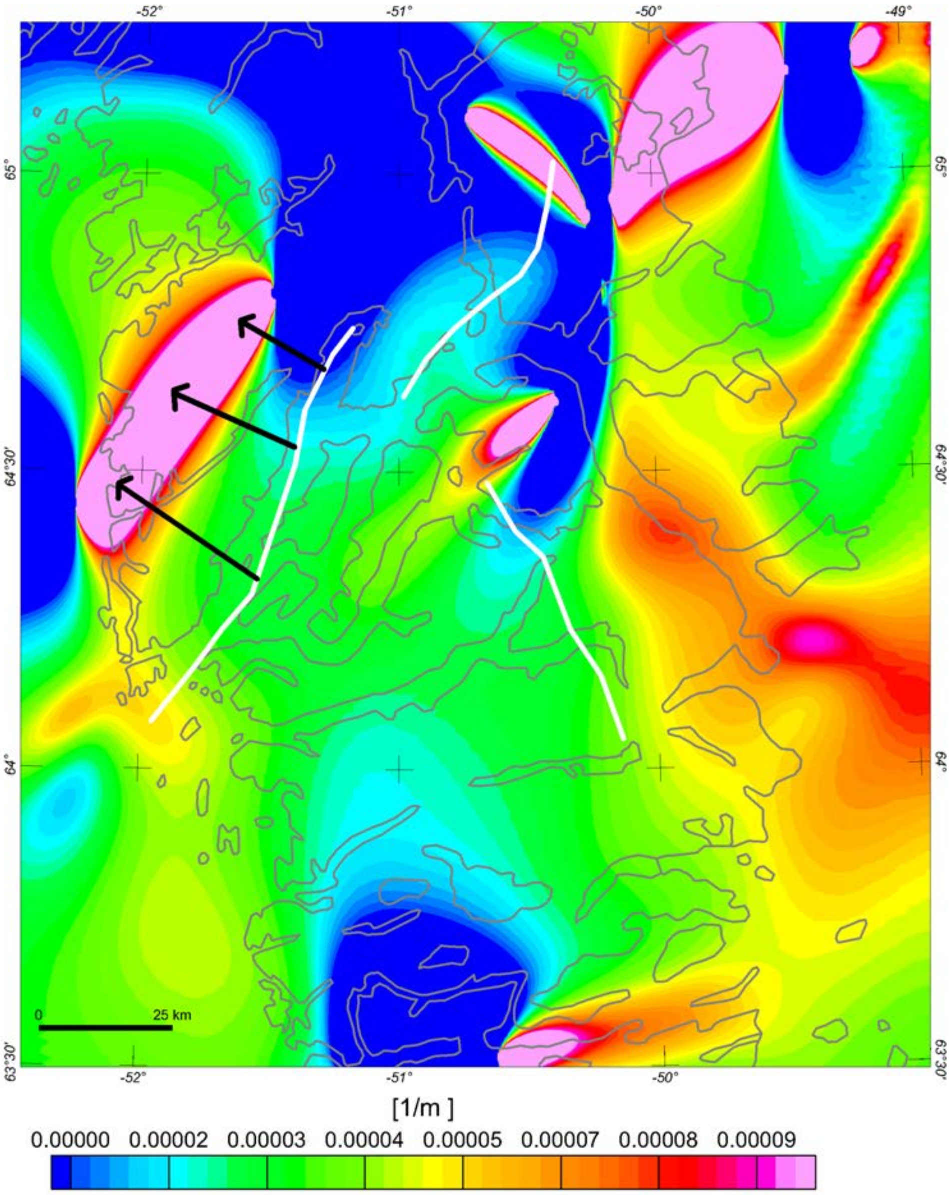

Figure 53. *The calculated source parameter function k_b based on lines in N–S direction in the grid of the 30 km upward continued magnetic field. The white lines show some of the major boundaries separating crustal segments with distinct differences in magnetic properties. The black arrows show the interpreted dip direction.*

Inversion of magnetic field data and gravity data – regional structures

The regional magnetic data upward continued to an altitude of 20 km and the Bouguer gravity data have been interpreted by an inversion technique that uses tabular bodies as the principal model. The upward continuation of the field before inversion implies that the responses from local near surface structures are attenuated and that the models represent large-scale averages of crustal segments. Thus, the results are comparable to the results obtained from the iSPI method applied to the upward continued regional magnetic field data. Two profiles have been selected for inversion. Profile 1 crosses the boundary between the Akia and Akulleq terranes in a NW–SE direction, and profile 2 crosses the boundary between the Akulleq and Tasiusarsuaq terranes in a N–S direction. The locations of the profiles are shown on Figs. 35 and 48. The models obtained from the inversions are shown in Fig. 54 for profile 1 and in Fig. 55 for profile 2. Density and susceptibility values are chosen based on the petrophysical measurements. Only induced magnetisation is modelled.

The model obtained for profile 1 consists of two tabular bodies with dips of 45 degrees towards NW. The model is consistent with the results obtained from the iSPI analysis and are able to fit the measured data. Some minor deviations can be observed between the measured and modelled responses, but they can easily be fitted by adding smaller blocks close to the surface. The excess density of the two bodies is 0.1g/cm^3; the susceptibility is 0.012 SI for the southernmost block and 0.003 SI for the northernmost block.

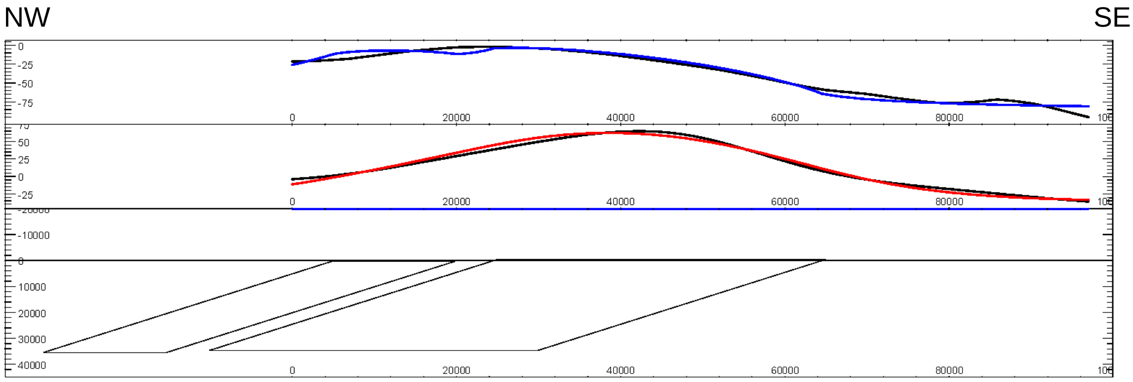

Figure 54. *Two-dimensional model along profile 1 (see Figs 35 and 48) based on inversion of Bouguer gravity data and magnetic total field data in units of nT at an altitude of 20 km. The upper panel shows the measured Bouguer gravity field in units of mgal with a black line and the model response with a blue line. The middle panel shows the magnetic total field data with a black line and the model response with a red line. The units for the horizontal axis is km.*

The model obtained for profile 2 consists of two tabular bodies that both dips towards N. The model is consistent with the results obtained from the iSPI analysis and are able to fit the measured data. The excess density of the largest bodies is 0.12 g/cm^3 and has similar magnetisation as used for the background. The smallest block has no excess mass but has a susceptibility of 0.012 SI relative to the background.

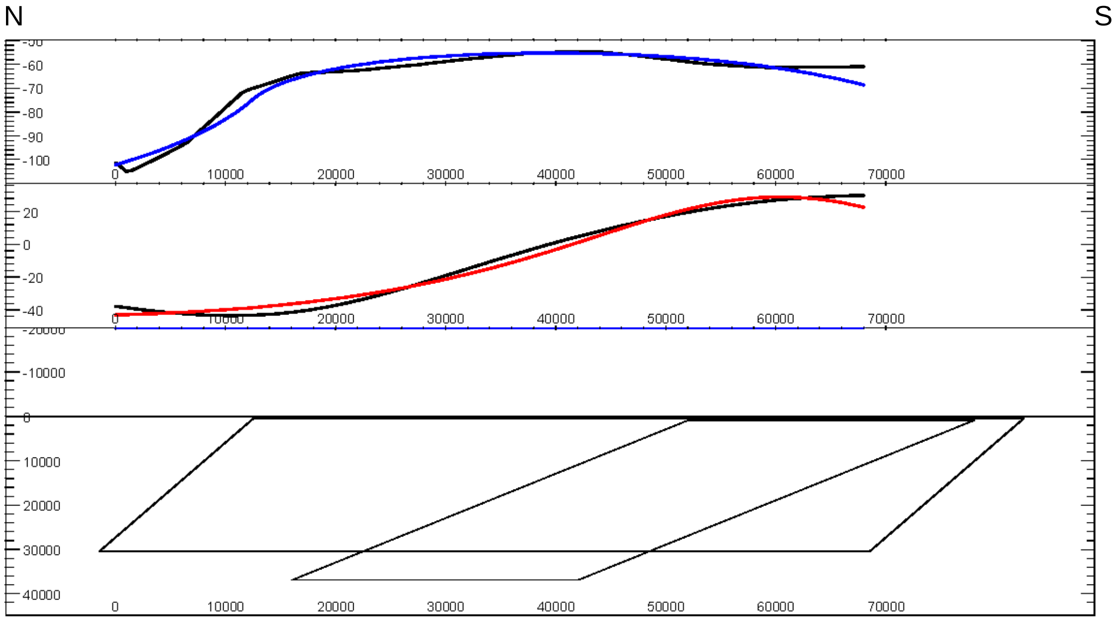

Figure 55. *Two-dimensional model along profile 2 (see Figs 35 and 48) based on inversion of Bouguer gravity data and magnetic total field data in units of nT at an altitude of 20 km. The upper panel shows the measured Bouguer gravity field in units of mgal with a black line and the model response with a blue line. The middle panel shows the magnetic total field data with a black line and the model response with a red line. The units for the horizontal axis is km.*

Improved source parameter method – local structures

In the section above on the application of the iSPI method to the upward continued field, a slab model was used as principal model for the interpretation. The iSPI method can also be used with a dyke as principal model. Also in this case, the k_b function is symmetric. The peak of the function is centred above the upper edge of the dyke, and the depth to the top is given by the inverse of the maximum value. In order to justify which of the two principal models are applicable, a careful analysis of another calculated function named k_a is required (Smith *et al.* 1998; Thurston *et al.* 2002). Furthermore, considerations about the degree of superposition of anomalies from adjacent structures must be made in order to extract quantitative information about depth. In this section we present the calculated k_b function for the magnetic field upward continued to an altitude of 200 m above the original flying height. The main reason for upward continuation is to suppress noise from aliasing due to large line separation in the original data.

At this stage we do not put much emphasis on the actual values of the peaks because of the difficulties in separating responses from different structures and because of deviations from two-dimensionality. Instead we suggest to use the calculated k_b function to outline structural trends in the measured data. In principle, the same structural information could be extracted directly from a visual inspection of the original data. However, the calculated function is very suitable for outlining of small anomalies that are not properly displayed in maps of the total field, because of limitations with respect to the dynamic range in the maps.

Fig. 56 displays the k_b function for analysis along lines in the E–W direction and Fig. 57 displays k_b calculated along lines in the N–S direction. The maps are particularly useful for identifying abrupt changes of elongated structures and for the identification changes in structural style. The digital maps included on the enclosed DVD are most suitable for the extraction of information from the calculated functions.

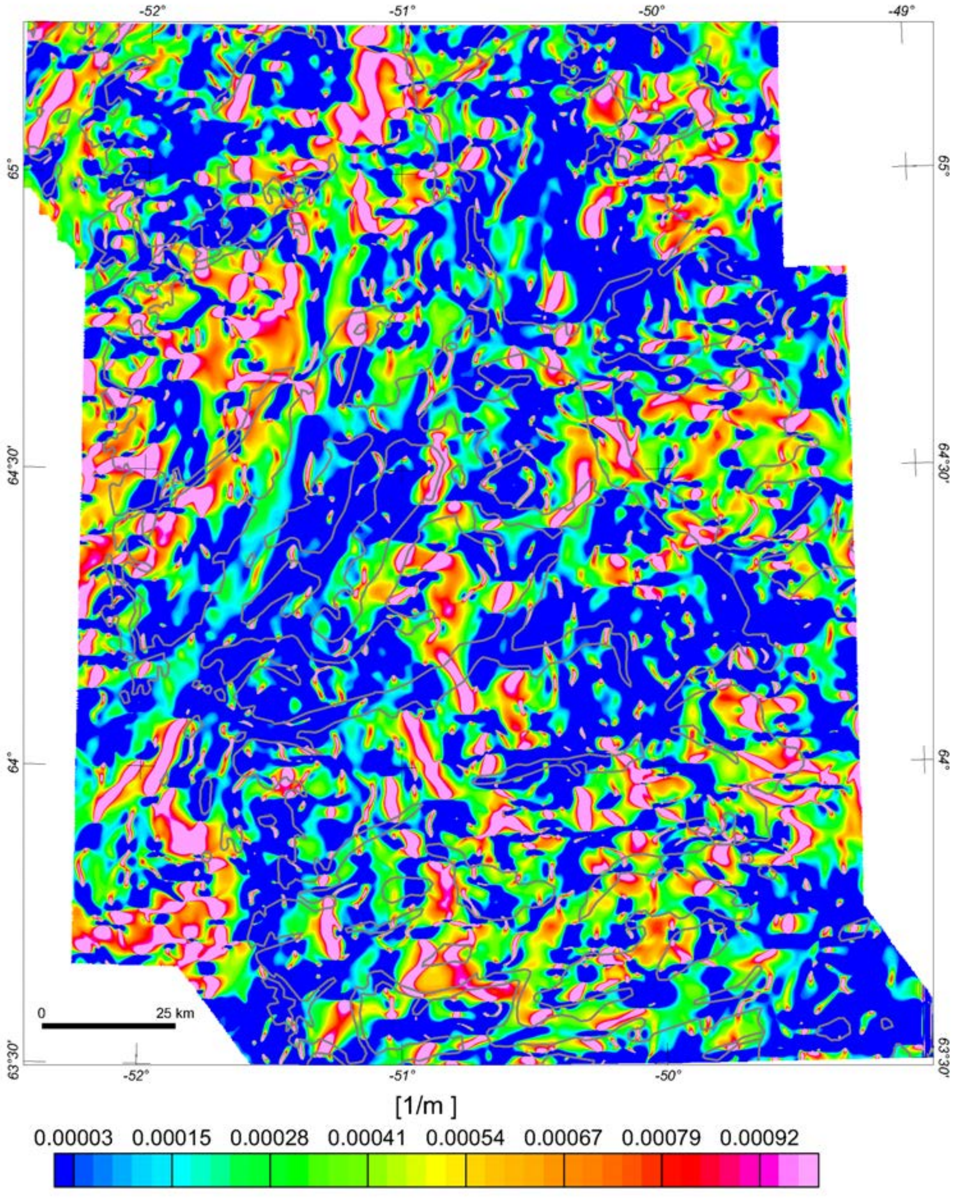

Figure 56. *The calculated source parameter function k_b based on lines in E–W direction in the grid of the 200m upward continued magnetic field*

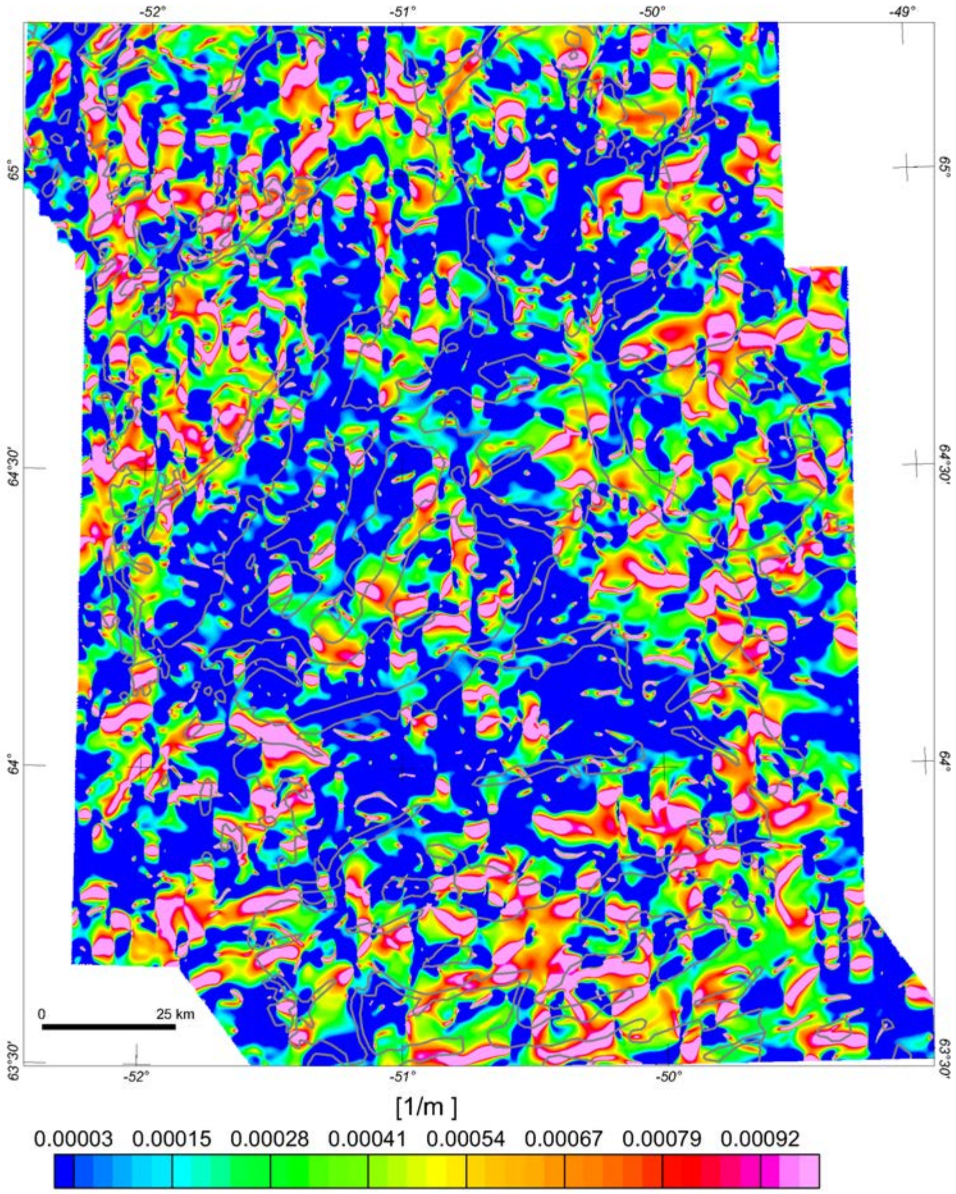

Figure 57. *The calculated source parameter function k_b based on lines in N–S direction in the grid of the 200m upward continued magnetic field*

Appendix – technical details

Map products

The maps with geophysical data are based on the following definitions:

The magnetic total field anomaly ΔT is given by the measured field strength ΔT corrected for the diurnal geomagnetic variations measured a base station and subtracted the International Geomagnetic Reference Filed IGRF corresponding to the time of recording.

In the following we use a right handed co-ordinate system (x, y, z) with x defined as the northing, y easting and z vertical and positive downwards.

The vertical gradient of the total field anomaly is given by $\partial\Delta T / \partial z$

The horizontal gradient in the east direction of the magnetic total field anomaly is given by $\partial\Delta T / \partial y$

The horizontal gradient in the north direction of the magnetic total field anomaly is given by $\partial\Delta T / \partial x$

The amplitude of the gradient vector of the magnetic total field anomaly is given by $\sqrt{\left(\partial\Delta T / \partial x\right)^2 + \left(\partial\Delta T / \partial y\right)^2}$

The amplitude of the analytic signal is given by $\sqrt{\left(\partial\Delta T / \partial x\right)^2 + \left(\partial\Delta T / \partial y\right)^2 + \left(\partial\Delta T / \partial z\right)^2}$

The separation filtered magnetic field for the depth interval z_1 to z_2 is given by $F^{-1}\left((e^{-\kappa 2z_1} - e^{-\kappa 2z_2})F(\Delta T)\right)$; where F and F^{-1} are the two-dimensional Fourier and inverse Fourier transform respectively and κ is the wavenumber. The two terms in the parenthesis are the upward continuation operator to height of $2z_1$ and $2z_2$ respectively.

The pseudo gravity field is given by $F^{-1}\left(\kappa_z / (\kappa_z e_z + i\boldsymbol{\kappa}_h \mathbf{e}_h)^2 \, F(\Delta T) * c\right)$ where κ_z is the wavenumber corresponding to the vertical direction and $\boldsymbol{\kappa}_h \mathbf{e}_h$ is the dot product between the horizontal components of a unit vector in the direction of the inducing field $\mathbf{e} = (\mathbf{e}_h, e_z)$ and the wave vector $\boldsymbol{\kappa} = (\boldsymbol{\kappa}_h, \kappa_z)$. The factor c is a constant (arbitrary) conversion factor for the transformation of susceptibility to density.

The iSPI method and the k_b parameter

The parameter κ_b is calculated as $\kappa_b = 2 \cdot k_1 - k_2$ where

$$\kappa_1 = \partial / \partial x \tan^{-1}\left[\frac{\partial \Delta T}{\partial x} \Big/ \frac{\partial \Delta T}{\partial z}\right] \text{ and } \kappa_2 = \partial / \partial x \tan^{-1}\left[\frac{\partial^2 \Delta T}{\partial x \partial z} \Big/ \frac{\partial^2 \Delta T}{\partial z^2}\right]$$

Economic potential of the Nuuk region

Gold

Presently, gold is the most prospective of the metals with potential for future exploitation within the Nuuk region. The high crustal level of the Akulleq terrane, the occurrence of greenstone belts and the long geological history with recurrent events of granite magmatism, shearing and faulting renders the NNE-trending zone from Nuuk to Isukasia favourable for gold mineralisation. The zone follows a terrane boundary and hosts the known gold showings on Storø and at Isukasia together with gold anomalies in stream sediment (fine fraction and heavy mineral concentrate). Other gold showings and stream sediment anomalies at Ivisaartoq are located on the south-eastern side of the zone. Distribution patterns of large ion lithophile and radioactive elements demonstrate that high-level granite magmatism followed the same zone. Although gold showings are presently known at three sites only, there is a possibility that they are manifestations of a large gold mineralising system affecting the entire zone.

The terrane boundary is identified as a narrow mylonitic zone, the Ivinguit fault, formed during continent-continent collision. The collision may have happened as early as about 3.0 Ga or as late as 2.8-2.7 Ga as granite veining at *c.* 2.7 Ga clearly post-dates the collision. The last major intrusion of granite, the Qôrqut granite, took place at *c*. 2.5 Ga, and it is likely that the intrusion was accompanied by rejuvenation of the shear zones and additional faulting. Although mobilisation of gold could have taken place earlier, the structural setting at 2.5 Ga is probably the most favourable for mobilisation and deposition of gold.

Dave Coller from Era-Maptec, Dublin, has drawn a preliminary sketch of the tectonic setting of the Nuuk region at the time of the intrusion of the Qôrqut granite (Fig. 58), and suggests that possible equivalents to a Nuuk gold camp could be the world class gold camps at Timmins (Fig. 59) and Kalgoorlie. One of the features of such greenstone-hosted gold mineralisation is the range in tectonic styles and structural traps within a single gold system. Similar conditions in the Nuuk region would provide a potential for focussing of gold in a range of structures and host rocks, which have not yet been fully explored.

The strike length of the major crustal structure in Timmins exceeds 200 km, is a major magnetic feature and thus truly a large structure of polyphase history. The bounding structure at Kalgoorlie is also crustal scale in size and would have similar chacteristics, although it is shorter along strike. At Nuuk, the bounding structure, the Invinnguit fault zone, would be of the same size.

In Timmins and Kalgoorlie the gold is very focussed. In Timmins the gold is very concentrated in the Hollinger McIntyre and Dome deposits, which are part of the fluid pathway and are linked at depth. They account for around 50 million oz and lie within a 5 km type area as part of one system. There are several other deposits along strike of this concentration which lie within a 20-30 km area and are hosted by slightly different traps. The deposits range from 5 million oz (Hoyle Pond), 4 million oz (Pamour) to several around the 1 million oz. The big question is whether gold is focussed at Nuuk or rather spread out in a series of more moderate deposits.

Base metals

Copper, lead and zinc have been found in a variety of settings, such as the VMS deposits in mid- to late Archaean greenstone belts of the Nuuk region. Since only a small fraction of these belts have been properly investigated there are good reasons to believe that more VMS deposits could be found in the future. It is, however, not only in the greenstone belts that economically interesting base metal deposits may be found. The base metal showing with silver and gold found in tonalite gneisses in the Isukasia region opens a possibility for base metal occurrences hosted by other lithologies than greenstones. It is possible that the fluids transporting the metals were generated during the intrusion of the Qôrqut granite, although the metals themselves were likely derived from nearby greenstone belts.

Tungsten

The Nuuk region hosts a major tungsten province, with scheelite occurring in virtually every greenstone enclave. The mid to late Archaean greenstones are clearly the most prospective for tungsten deposits. Channel sampling at Ivisaartoq revealed 0.44% WO_3 over 2.5 m.

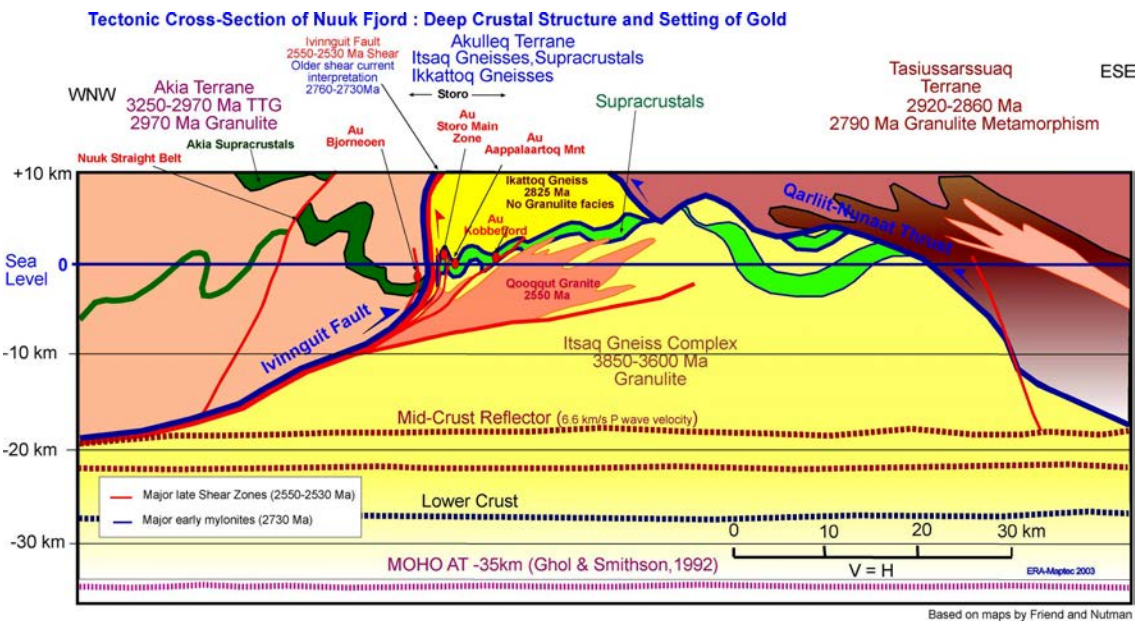

Figure 58: *Tectonic cross section across Storø: Deep crustal structure and setting of gold. (Dave Coller in NunaMinerals 2003).*

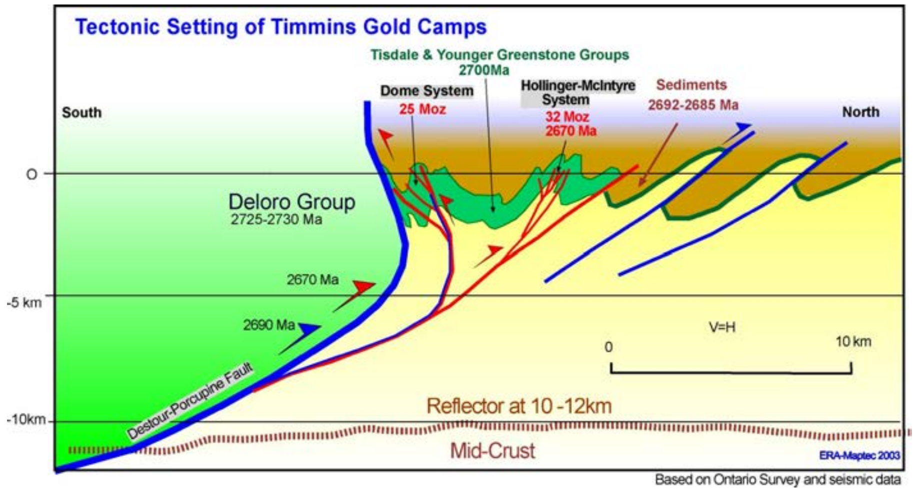

Figure 59: *Tectonic setting of Timmins gold camp (Dave Coller in NunaMinerals 2003).*

Recommendations

The Nuuk region has potential for economic deposits of gold, base metals and tungsten.

Gold

The gold potential of the Nuuk region is promising. However, very little is known about how and when the gold showings were formed. If the gold showings all were formed more or less at the same time by one major event, then we probably have a major gold province in the Nuuk region. This province could match gold provinces in Australia and Canada, which produce millions of ounces of gold. If the gold showings were formed locally by different processes, then the outlook for finding one or more gold mines near Nuuk is less favourable.

The following facts are established

Nuuk region has high-grade gold showings on Storø and Isukasia and gold anomalies on Sermitsiaq, Store Malene, Bjørneøen and Ivisaartoq. Most of the gold occurs in or near to greenstone belts and close to a regional terrane boundary.

The following problems need to be addressed in order to discover whether the Nuuk region hosts a gold province with possible economic gold deposits.

- Is the proximity of the gold showings to the terrane boundary a coincidence or has the boundary played a role in forming the gold showings?
- Does the close association between the gold showings and the greenstone belt prove that the gold was mobilised from greenstone belts?
- When were the gold showings formed and by which processes?
- Which types of alteration were developed during the gold mineralising event and under which temperature and pressure conditions?

The following studies should be undertaken in order to solve these problems.

- Detailed structural analyses on Storø and regional structural work along the terrane boundary, major faults and shear zones.
- Ore geological investigations and fluid inclusion studies of the gold showings on Storø.
- Investigations of the alteration zones around the gold occurrences on Storø.
- Isotope work on the gold showings on Storø in order to determine the timing of the gold mineralising events.
- Detailed geological mapping and geochemical sampling of the greenstone belts on Storø, Bjørneøen, Sermitsiaq, Store Malene and Ivisaartoq.
- Regional study of the late thermal regime of the Nuuk region.
- Geochemical investigations along the main structural features in the Nuuk region.

Base metals

Copper

Copper is found stratabound in the early Archaean Isua greenstone belt, but the most promising copper potential is probably in VMS occurrences in the mid to late Archaean greenstone belts.
Detailed mapping of the greenstone belts in Godthåbsfjorden and on the islands south of Nuuk is the best way to find new copper occurrences.

Lead and zinc

Lead is found together with zinc and silver in intrusive tonalite sheets in the Isukasia area. The genesis of these occurrences is unknown. There are probably possibilities for more and larger occurrences of this type, but it will be very difficult to find them, since they do not respond to any geophysical investigations and they are not rusty.

Zinc is found together with copper and small amounts of tin in VMS showings in the mid to late Archaean greenstone belts. Detailed mapping is probably the only way of proving whether there are economically interesting VMS deposits of this type.

Tungsten

Tungsten is found stratabound in banded amphibolites, in altered ultrabasic rocks and in tourmalinites in the mid to late Archaean greenstone belts The best tungsten occurrences are seen in the Ivisaartoq area. These are extensive and rather high grade. More detailed studies of the Ivisaartoq area may prove the presence of further prospective tungsten ore-bodies.

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Appendix A: Explanatory notes to the DVD

(Frands Schjøth & Mette S. Jørgensen)

Introduction

The DVD contains the hitherto most comprehensive, quality controlled, digital geo-data set from the Nuuk Region gathered by the Geological Survey of Denmark and Greenland (GEUS). In agreement with the stated strategy of the Greenland Home Rule Government, the DVD has been compiled with the basic philosophy in mind that quality controlled digital data should be released for general use in order to promote their use in mineral exploration.

The presentation of the data on the DVD follows a standard for sharing of data with the public (see Schjøth & Thorning 1998; Pedersen 1999; Schjøth *et al*. 2000; Rasmussen *et al.* 2001; Jensen *et al.* 2003).

The present document describes the content and use of the DVD. In addition, the acquisition of data for individual views of the ArcView project termed NuukRegion is documented.

General information

It is anticipated that the user has basic knowledge of ArcView GIS and its use.

The Nuuk Region project file has been constructed using ArcView GIS version 3.3 and makes full use of many of the facilities in this version of the program. The project has been designed and tested in Windows 2000, NT 4.0 and 98. The screen layout of views has been optimised for a 17” screen size.

The digital topographic data set is in decimal degrees with the geodetic reference WGS84 and copyright as follow:

Topographic base: G/250 Vector, Copyright Kort & Matrikelstyrelsen, 1998

The projection parameters for the whole data set, is:

UTM-zone:	22 (*i.e.* the central meridian is 51° West)
False Easting:	500 000 metres
Geodetic reference:	WGS84

Some information is provided as PDF-files for use in the Adobe Acrobat Reader program. A free installation kit for Acrobat Reader, version 5.1, is included on the DVD for those users who do not already have access to this program. The PDF-files can be reached via hot-links from certain themes in the Nuuk Region Project File.

Place names follow the new Greenlandic orthography, changing the spelling of most place names. However, geological formations named by a nearby place *before* the introduction of the new orthography retain the old spelling.

Directory structure of the DVD

The directory structure of the DVD is visualised in Figure A1 and A2. Figure A1 shown the top level and Figure A2 shows the sub levels.

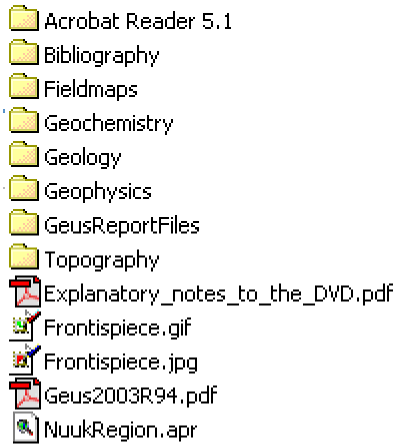


Figure A1. *Top level directory of the DVD. The 'NuukRegion.apr' file is the ArcView GIS Project File and 'Geus2003R94.pdf' file is the accompanying report as a PDF-file.*

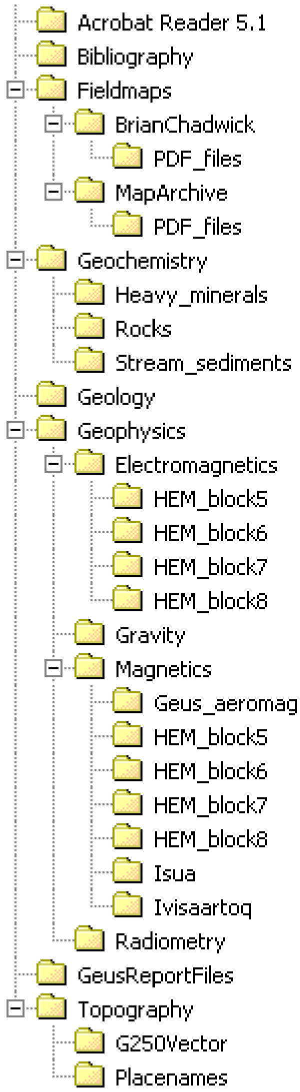


Figure A2. *Directory structures showing the sublevels of the DVD. The top level is shown in Figure A1.*

Use of the DVD

1. Place the Nuuk Region DVD in the slot
2. Start ArcView 3.3 on your computer
3. Open the Nuuk Region Project File; it will probably take some time to load
4. The Nuuk Region Project file will open on a view (1.1), which only contains the location of the Nuuk Region on the Greenland index map. When this is closed, a list of views will become visible. Choose the desired view and start exploring the data

If desired, the entire directory structure of the DVD with all the files can be copied to your hard disk as long as the same structure is maintained.

ArcView GIS views of compiled data

The different types of digital data sets are arranged as views in the ArcView GIS project file (*NuukRegion.apr*). The following table gives a list of the views in the ArcView GIS project file including the name of the data compiler:

ArcView GIS view	Compiled by
0.1 Frontispiece	Frands Schjøth
1.1 Location of Nuuk Region	Mette S. Jørgensen
1.2 Digital topographic map	Mette S. Jørgensen
2.1 Geological map 1:500 000	Frands Schjøth
2.2 Geological maps 1:100 000	Frands Schjøth and Mette S. Jørgensen
3.1 Field maps	Frands Schjøth
4.1 Heavy Mineral Concentrate Chemistry	Else Moberg
4.2 Rock chemistry	Else Moberg
4.3 Stream Sediment Chemical Anomalies	Else Moberg
5.1 Magnetic GEUS aeromag	Thorkild M. Rasmussen
5.2 Magnetic data – Aerodat survey block 5	Thorkild M. Rasmussen
5.3 Magnetic data – Aerodat survey block 6	Thorkild M. Rasmussen
5.4 Magnetic data – Aerodat survey block 7	Thorkild M. Rasmussen
5.5 Magnetic data – Aerodat survey block 8	Thorkild M. Rasmussen
5.6 Magnetic Isua	Thorkild M. Rasmussen
5.7 Magnetic Ivisaartoq	Thorkild M. Rasmussen
5.8 Electromagnetic data – Aerodat survey block 5	Thorkild M. Rasmussen
5.9 Electromagnetic data – Aerodat survey block 6	Thorkild M. Rasmussen
5.10 Electromagnetic data – Aerodat survey block 7	Thorkild M. Rasmussen
5.11 Electromagnetic data – Aerodat survey block 8	Thorkild M. Rasmussen
5.12 Gravity data from KMS	Thorkild M. Rasmussen
5.13 Radiometry	Agnete Steenfelt

Description of the views

This DVD contains many different data types with the main file extensions shown here:

ArcView GIS shapefiles as .SHP
Textfiles as .TXT
Images as GIF, TIF and .JPG
Adobe as .PDF

To extent the functionality of the ArcView GIS project file some customised Avenue scripts (ArcView GIS internal macro language) has been added to the project. The Avenue scripts have been well tested and they work as long as the data on the DVD keeps the same relation to each other.

The customised Avenue script for linking to PDF-files uses the location of the file 'Frontispiece.jpg' (Figure A1) which is read from the first view ('0.1 Frontispiece') in the ArcView GIS project file. If the user saves a version of ArcView GIS project file it should be noticed that if the linking to the PDF-files should still work then keep the ArcView GIS view '0.1 Frontispiece' in the ArcView GIS project file.

In Adobe Acrobat Reader it is recommended to open cross-document links in a separate window. This is done as follows in Adobe Acrobat Reader:

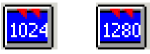
Adobe Acrobat Reader 5.0 and 5.1:

Edit > Preference > Options
uncheck Open Cross-Document Links in Same Window

Adobe Reader 6.0 :

Edit > Preference > General
uncheck Open cross-document links in same window

Added buttons in ArcView GIS project file



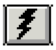
The two blue tool buttons marked ‘1024’ and ‘1280’ serve two purposes:

‘

1. In the Project window, press one of the buttons to resize the project window to fit a screen with 1024 × 768 or 1280 × 1024 pixels, respectively

2. In any View, press one of the buttons to select and make active one from a list of Views. Selecting a View also resizes it to a screen with 1024 × 768 or 1280 × 1024 pixels, respectively

In the ArcView GIS view, the button marked ‘Bib’ opens the bibliography for the Nuuk region.



The above buttons is clear (not dimmed) when a GIS theme has links.

View 0.1 Frontispiece

Photo showing rusty mid to late Archaean greenstones with promising gold showings on Aappalaartoq mountain on Storø.

View 1.1 Location of Nuuk region

Location of the Nuuk Region in Greenland.

View 1.2 Digital topographic map

The digital topographic data set is in decimal degrees with the geodetic reference WGS84 and projection UTM zone 22. The map is limited by latitude 63º30’ N and 65º15’ N and longitude 49º00’ W and 52º30’ W.

The digitised topographical data are contained in a number of themes as ArcView shapefiles. The shapefiles are found in the directory ‘Topography’ (Figures A1 and A2). The Nuuk Region is the project area.

View 2.1 Geological map 1:500 000

The geological map for the Nuuk Region is clipped from the digital version of the Geological Map 1:500 000 (Allaart 1982). The published map is in projection ‘Lambert conformal conic’, the scanning, georeferencing and the digital topographic data (1:250 000), therefore, does not fit perfectly in the ArcView GIS version.

View 2.2 Geological maps 1:100 000

Four published geological maps in scale 1:100 000 (McGregor 1983; Garde 1987, 1988; Chadwick & Coe 1988) are scanned and georeferenced for use in ArcView GIS. The published maps are in projection ‘Lambert conformal conic’, the scanning, georeferencing and the digital topographic data (1:250 000), therefore, do not fit perfectly in the ArcView GIS version.

View 3.1 Field maps

Fifty-nine field maps from GEUS map archive have been scanned to PDF-files. There are two GIS themes (BrianChadwick and MapArchive) in this view. The field maps can be viewed by pressing the hotlink button.

View 4.1 Heavy mineral concentrate chemistry

Samples collected were plotted on 1:100 000 topographic maps enlarged from 1:250 000 topographic maps from Kort & Matrikelstyrelsen. These samples do not plot correctly on the new digital maps and some of the sample sites have manually been moved to the correct positions.

Panned stream gravel has been collected from 345 sites within the Nuuk region. About 10 kg (~4 litres) of coarse gravel was collected and passed through a ~2 mm screen. The fines were panned and the concentrate was inspected under UV-light in the field for scheelite. The scheelite grains were counted and their colours noted. Seventy-six of the heavy mineral concentrates were analysed, and the results are listed on the DVD, in the table ‘Attributes of All_analyses’. The view contains distribution maps for a selected number of elements only. The analytical methods can be seen in a table named 'lab_method'.

View 4.2 Rock chemistry

Samples collected during the last few years were located by GPS position. Samples collected previously were plotted on 1:100 000 topographic maps enlarged from 1:250 000 topographic maps from Kort & Matrikelstyrelsen. These samples do not plot correctly on the new digital maps and some of the sample sites have manually been moved to the correct positions.

The analytical data for rock samples are extracted from a GEUS database comprising samples collected during fieldwork in GGU (Geological Survey of Greenland) or GEUS regie. All extracted data are contained in the table 'Attributes of All_analyses' assigned to the theme. The theme 'Sample location' contains information on sample location and sample collector. The samples have been analysed by a variety of methods, see table 'lab_method'. Element distribution maps are presented for a selected number of the elements.

The data are not quality controlled, and it is known that a bias exists between analytical methods and the time of analysis (Steenfelt 1999). Also the concentrations measured in samples of mineralised rock are commonly beyond the calibration range for the method where the accuracy is low, and very high concentrations of some elements may influence the determined concentrations of other elements. In the tables, negative values indicate that the concentration is below the detection limit of the analytical method.

The element distribution maps are designed to emphasise the location and character of the mineralised sites or sites with concentrations above the range for non-mineralised rocks, and the problems with accuracy are not important for this kind of use. Not all elements have been plotted on maps.

View 4.3 Stream sediment chemical anomalies

Samples collected were plotted on 1:100 000 topographic maps enlarged from 1:250 000 topographic maps from Kort & Matrikelstyrelsen. These samples do not plot correctly on the new digital maps.

Stream sediment samples have been collected in the Nuuk region by the Geological Survey of Greenland in several campaigns: Uranium exploration in 1979 and 1981, tungsten exploration in 1985 and low density geochemical mapping in 1986 and 1993 (see Steenfelt 1999). The stream sediment view on the DVD shows the location of all stream sediment samples. Sample preparation has been the same for all sample batches, and the less than 0.1 mm grain size fraction has been used for analysis. However, the analytical methods and determined elements vary among the campaigns, see the theme-tables in the view.

Analytical raw data are not included in the present DVD. Such data are available at cost from GEUS. In stead, the stream sediment view contains a number of maps showing the distribution of anomalously high values of gold and other elements of importance for recognising gold mineralisation.

The tables accompanying the 'Stream Sediment Chemical Anomalies' view show the sample numbers, location, analytical method and two classes of anomaly level shown in the legend. Some of the samples with anomalous concentrations appear twice or thrice in the table because they have been analysed by more than one method.

View 5.1 – 5.7 Magnetic data

Seven views based on magnetic data with themes corresponding to figures displayed in the report are included on the DVD. The views are named as follows:

- View 5.1 Magnetic GEUS aeromag
- View 5.2 Magnetic data – Aerodat survey block 5
- View 5.3 Magnetic data – Aerodat survey block 6
- View 5.4 Magnetic data – Aerodat survey block 7
- View 5.5 Magnetic data – Aerodat survey block 8
- View 5.6 Magnetic Isua
- View 5.7 Magnetic Ivisaartoq

View 5.1 includes images based on data from the regional airborne surveys 'Aeromag 1996' and 'Aeromag 1998' carried out by GEUS and BMP. The views 5.2-5.5 include images from four areas surveyed with the combined helicopterborne electromagnetic and magnetic system by Aerodat Inc for Fjordland Minerals Ltd. View 5.6 and 5.7 include data from two surveys carried out by Sander Geophysics Ltd for NunaMinerals A/S.

View 5.8 – 5.11 Electromagnetic data

- View 5.8 Electromagnetic data – Aerodat survey block 5
- View 5.9 Electromagnetic data – Aerodat survey block 6
- View 5.10 Electromagnetic data – Aerodat survey block 7
- View 5.11 Electromagnetic data – Aerodat survey block 8

The views 5.8-5.11 include images from four areas surveyed with the combined helicopterborne electromagnetic and magnetic system by Aerodat Inc. for Fjordland Minerals Ltd. The themes include apparent resistivities for the 900 Hz and 4500 Hz co-planar horizontal loops.

View 5.12 Gravity data from KMS

View 5.12 contains one image merging Bouguer anomalies for on-shore areas and free-air anomalies for offshore areas.

The gravity data are from Kort- og Matrikelstyrelsen (Strykowski & Forsberg 1998; Kenyon & Forsberg 2000; Andersen, Knudsen & Trimmer 2001; Forsberg 2002). The spacing of the gravity measurements does not allow detailed description of the gravity field.

View 5.13 Radiometry

The view contains four themes based on airborne surveys and one based on ground measurements.

Airborne survey

A four-channel gamma-ray spectrometer with a detector-volume of 11 litres installed in a fixed-wing aircraft was used to measure the gamma-radiation at a height of about 90m above the ground. Flight lines followed the topographical contours. Further technical details of the survey and data treatment are given in Tukiainen et al. (2003). The data were corrected for background radiation, and counts recorded in the K, U and Th channels were corrected for contributions from decay series of the other radioelements (stripping). The measurements were not corrected for variation in ground clearance, but the data were screened to include only those obtained within an interval of 75 to 105 metres above terrain. Furthermore, all negative values in the data sets were removed before gridding. Negative values result from the stripping in situations where conditions are not ideal.

The screened data are presented as contoured grid images. The total gamma-radiation is given in the international unit Ur (Unit of radioelement concentration), and the data from the other channels as equivalent concentrations of the overflown ground, K in %, eq. U and eq. Th in ppm. The grids and contoured images were produced using software from Geosoft Inc.

Ground measurements

During the systematic stream sediment sampling for geochemical mapping the total gamma-radiation was measured at each sampling site with a scintillometer. The measurements are recorded as counts per second. The data are shown as colour-scaled dots.

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