DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2000/50

Mineral resource potential of South Greenland: review of new digital data sets

Agnete Steenfelt, Troels F. D. Nielsen
and Henrik Stendal

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MINISTRY OF ENVIRONMENT AND ENERGY

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Contents

Abstract

Comprehensive geoscientific data sets for South Greenland have been compiled in ArcView format on CD-ROM. The data include topographical, geological, geochemical and geophysical maps, rock analyses, descriptions of mineral occurrences, and bibliographies. The aim is to provide scientific and commercial interests with all available digital information in one place. This report presents extracts from the total data set to review the geology and mineral potential of South Greenland.

Most of South Greenland is underlain by rocks of the Palaeoproterozoic Ketilidian orogen, in the north bounded by Archaean basement. An alkaline igneous province, the Mesoproterozoic Gardar province, covers a large region within the Ketilidian and the basement.

The Archaean basement is dominated by orthogneiss but contains a small greenstone assemblage with iron formations and gold mineralisation. The Ketilidian orogen is composed of (1) a Border zone, the southernmost part of the Archaean basement, where Ketilidian supracrustals were deposited and Ketilidian granites have intruded, (2) a Batholith zone with predominance of juvenile calc-alkaline granite-diorite complexes (c. 1850 to 1800 Ma of age), and (3) a zone of metasediments intruded by a post-kinematic, crustally derived, granite-monzonite-norite suite (c. 1755 to 1725 Ma). The Ketilidian orogen hosts mineralisation with gold, arsenic, uranium, copper and graphite. Sulphide mineralised zones with low zinc and copper concentrations are common in the Ketilidian supracrustals. Evolved magmas and hydrothermal alteration zones of the Gardar intrusive complexes constitute large, low-grade deposits of uranium, thorium, speciality metals (zirconium, yttrium, niobium, tantalum, rare earth elements), fluorine, lithium and zinc. A high-grade cryolite deposit has been mined.

A potential for economic deposits of gold, uranium and speciality metals are outlined by geochemical data of stream sediments (both fine fraction and heavy mineral concentrates) and rock samples together with known occurrences of mineralisation with these metals. Discovery of mineralisation within bodies of a Ketilidian gabbro suite suggests a potential for deposits of titanium, vanadium, nickel, chromium and platinum group elements. A diamond potential is indicated by the occurrence of kimberlite sheets in the Archaean basement.

The compiled data demonstrates significant geochemical and geophysical variations within South Greenland, which must be taken into account in geological modelling. The current geological model for the Ketilidian orogen does not explain these variations and a revision, therefore, seems appropriate. Any alternative plate-tectonic model will obviously have implications for mineral deposit modelling within the region.

Introduction

The GEUS project “South Greenland mineral resource evaluation” was carried out 1997 to 1999 with the aim of compiling as much as possible of geoscientific information about South Greenland in digital form, and make the data publicly available. In addition, a re-evaluation of the mineral potential of South Greenland has been made using integrated data sets and geological modelling. The present report contains an overview of the data, examples of the many data sets and a summary of current ideas about the mineral potential. All compiled data, maps and detailed information are presented in ArcView format on a CD-ROM issued by GEUS (Schjøth et al. 2000), the content of which is listed in Appendix 1 of this report.

Records of mineral occurrences and other geoscience data of South Greenland have been presented and discussed earlier by the Geological Survey of Greenland (Ady & Tukiainen 1994; Thorning et al. 1994), and an overview of the mineral potential was given by Mosher (1995). The present evaluation is, however, well justified as much new information from South Greenland has been acquired or made digitally available since 1995. The new information and data comprise:

- Airborne geophysical surveys of South-West Greenland (Aeromag 1995 and 1996, Thorning & Stemp 1997; AEM Greenland 1996 (incl. Radiometry), Stemp 1997)
- Recently released gravity data from the National Survey and Cadastre (KMS)
- Geological field observations during the SUPRASYD project 1992–1996, resulting in geological mapping of two map sheets at scale 1:100 000 (Garde & Chadwick 1996; Garde et al. 1998b) and revision of the geological map in other areas, age dating and chemical analyses of rock samples.
- Discovery of mineral occurrences (Stendal & Schønwandt 1997) and results from exploration by companies holding exploration licences (only non-confidential/released results are quoted from the latter).
- Articles and reports published 1994 to 1999: see bibliography on CD-ROM

In addition the following has been produced as part of the project:

- A digital geological map at the nominal scale of 1:500 000
- A bibliography with qualifiers on subject, area, locality, methods and commodities
- Summary descriptions of more than 100 known mineral occurrences
- Calibration and statistical analysis of regional stream sediment data (Nielsen et al. 1997; Steenfelt 1999)
- A metadatabase of archived sample location maps
- Transformation of sample locations to a new topographical reference: G/250 Vector, Copyright Kort & Matrikelstyrelsen 1997
- Database for chemically analysed rock samples (location, description, analytical data)

Personnel

The "South Greenland mineral resource evaluation" project has been a key project for the Department for Economic Geology with participation of many persons from this department and from the Department of Geological Mapping. The following persons (in alphabetical order) have spent most time and effort with the production of the CD-ROM: Adam A. Garde, Mette S. Jørgensen, Mogens Lind, Else Moberg, Troels F. D. Nielsen, Thorkild M. Rasmussen, Frands Schjøth, Karsten Secher, Agnete Steenfelt, Henrik Stendal, Leif Thorning, Tapani Tukiainen.

Topography, climate, land use and infrastructure

The region encompasses the southern part of Greenland from its southernmost point, Uummannarsuak (Kap Farvel; 59°47′N, 43°55′W, see Fig. 1), to 62°N. The CD-ROM contains a base map, a digital elevation model and Landsat TM image to illustrate physiographic features.

The landscape of South Greenland comprises four elements: an archipelagic coastal zone, a fjord zone, a glacier and nunatak zone, and the Inland Ice. The coastal zone with thousands of islands and skerries has low topography, but inland through the fjord zone the terrain raises to an alpine topography with many peaks above 1500 m and up to 2700 m above sea level in the innermost glacier and nunatak zone. The highest point of the Inland Ice in South Greenland is about 2500 m above sea level.

The climate is arctic to sub-arctic with a mean temperature for the warmest month slightly below +10°C. The climate is influenced by the north-western branch of the warm Golf Stream running northwards into Labrador Sea and preventing the formation of sea ice along the south-west coast of Greenland. However, local sea currents and wind carry drift ice from the seas east of South Greenland round Kap Farvel and northwards on the west side, sometimes blocking the entrances to fjords from Nanortalik to Narsaq. South Greenland lies on the path of many low-pressure systems moving from North America towards Iceland and the Atlantic Ocean. This causes unstable and unpredictable weather conditions, with the risk of rain, snow, and severe storms even during the summer; there may also be quite long periods of calm, sunny and warm weather. Several fjords and valleys experience strong katabatic winds (foehn storms). Snow usually disappears during June and returns during September.

Only low-altitude terrain supports any significant vegetation comprising herbs, low bushes and scrubs including arctic creeping species of trees. However, the vegetation may get dense and trees reach heights of three to four metres in sheltered valleys and along the shores of the inner parts of south-west oriented fjords. Here, Greenland's only farming takes place. The sheep farming involves growing of grass for production of hey.

Administratively, the region is divided between the municipalities of Nanortalik, Qaqortoq/Julianehåb, Narsaq, Ivittuut, Paamiut/Frederikshåb and Tasiilaq/Ammassalik, which hosts approximately 20% of the 55 000 inhabitants in Greenland. The larger settlements, towns, comprise Qaqortoq (3100 inhabitants), Paamiut (1950 inhabitants), Nanortalik (1300 inhabitants), and Narsaq (1800 inhabitants). The location of the towns is shown in Appendix 2. In addition, there are many small settlements, but only along the southwest coast. The only permanent habitation on the east coast is the telecommunication station of Prins Christiansund, usually manned by a crew of four to six technicians. Main trades in South Greenland are fishery, services and education, tourism, and sheep farming. A Danish naval base is located at Grønnedal.

Most passenger traffic into the area today takes place through the airport of Narsarsuaq, which has regular connections to Copenhagen in Denmark, Reykjavik in Iceland, and the capital of Greenland, Nuuk, some 500 km further north on the west coast. Local transport is by scheduled helicopter flight or by boat. There are also connections by coastal ship along the west coast of Greenland. Freight into the area is by air or by transatlantic shipping from Denmark. Inland areas can only be reached by helicopter or by foot.

South Greenland has a long history of mineral exploration activities and geological investigations, much of which were carried out by the Geological Survey of Greenland GGU (in 1995 merged with the Geological Survey of Denmark to form GEUS). This is documented in the bibliography on the CD-ROM, which has more than 2000 entries including published articles, internal Survey reports and field notes. The CD-ROM also lists 204 company reports on mineral exploration conducted within the region. The reports are available upon request from the archives of GEUS.

Outline of the geology

South Greenland comprises three major chrono-stratigraphic units: (1) the southern part of an Archaean craton, (2) the Palaeoproterozoic Ketilidian orogen, and (3) the Mesoproterozoic Gardar igneous province. Phanerozoic events are volumetrically insignificant and comprise intrusions of Mesozoic, coast-parallel dolerite and carbonatitic lamprophyre dykes, and a few kimberlite dykes. The Quaternary glaciation covered the region, possibly with the exception of the highest peaks. The ice cap, the Inland Ice, still remains over most of Greenland with glaciers extending towards the coast trough valleys and fjords. Holocene marine terraces, common along the coasts, testify to Holocene uplift.

Fig. 1 shows the geological map of the region with a division of the Ketilidian orogen introduced by Chadwick & Garde (1996). An article by Garde et al. (1998a) contains the latest age dates quoted in the following. In the Border zone Ketilidian supracrustal rocks (deposited around 2000 Ma ago) rest unconformably on Archaean basement, and the zone is variably influenced by Ketilidian deformation. The Batholith zone is dominated by granitoid complexes of the Julianehåb Batholith intruded in the period 1855 to 1800 Ma ago. The Psammite and Pelite zones are dominated by strongly deformed metasediments with minor intercalated metavolcanic units. A post-Ketilidian intrusive suite of mafic and felsic rocks (c. 1755 to 1725 Ma of age), the rapakivi suite, is emplaced into the latter two zones and the southern part of the Batholith. In Mesoproterozoic times continental rifting with associated sedimentation, volcanism and alkaline igneous activity (c. 1330 to 1120 Ma; Paslick et al.

1993) took place in the Gardar igneous province, which affected both the Archaean and Ketilidian parts of South Greenland.

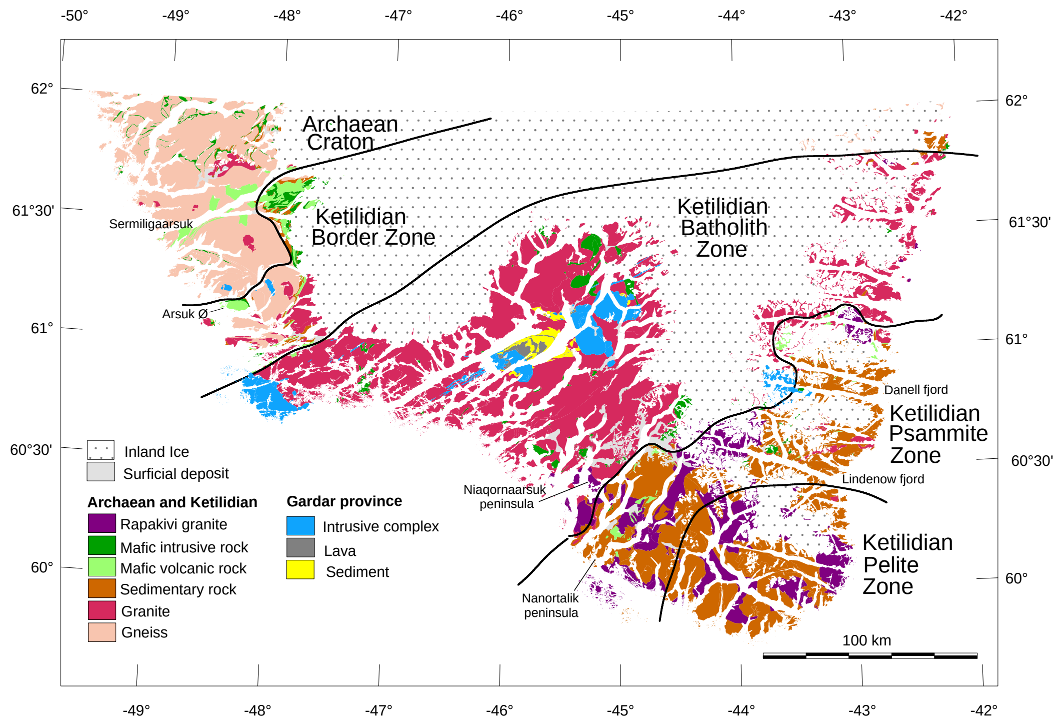

Figure 1. *Simplified geological map of South Greenland. Division of the Ketilidian orogen after Chadwick & Garde (1996). The map is a simplified version of the digital geological map on the CD-ROM.*

Geological mapping and summaries

The geology of the region has been mapped at scale 1:500 000 (Allaart 1975; Weidick 1987). There are nine 1:100 000 geological maps and a number of published, more detailed geological maps of e.g. the Gardar igneous complexes. Unpublished field-maps are archived at GEUS, a list is included on the CD-ROM. The geological map on the CD-ROM is based on digitisation of the 1:500 000 map by Allaart (1975) with revisions and updated legend reflecting the results of recent mapping and radiometric age determinations.

A useful introduction to the entire region is found in Kalsbeek et al. (1990). The Archaean part is described by Bridgwater et al. (1976), while the Ketilidian orogen is described by Allaart (1976) and re-appraised by Chadwick & Garde (1996). An introduction to the Gardar province is given by Upton & Emeleus (1987). There are numerous publications on the geology of smaller areas and of specific rock types within the region (see bibliography on the CD-ROM). Geochemical and geophysical maps were published in the Thematic Map Series of GGU (Ady & Tukiainen 1994; Thorning et al. 1994). Summaries of mineral occurrences in South Greenland are included in Kalsbeek et al. (1990), in the Thematic Map Series, and in Mosher (1995).

Geochemical and aeromagnetic variation within South Greenland

The CD-ROM contains more than 100 spatial data sets illustrating the variation in lithological, geochemical and geophysical properties within the region. Statistical parameters for the stream sediment geochemical data set are listed in Appendix 3.

South Greenland has previously been shown to be chemically distinct from the rest of Greenland. The first geochemical stream sediment and air-borne radiometric surveys of South Greenland demonstrated that South Greenland may be termed a uranium province (Armour-Brown et al. 1983). Steenfelt (1994) shows that the region also stands out from the remaining part of southern West Greenland as a potassium rich province. Two provinces characterised by high arsenic (As) concentrations have been recognised, and the highest density and magnitude of stream sediment gold (Au) anomalies within Greenland have been recorded in South Greenland (Steenfelt 1990; Steenfelt 1996).

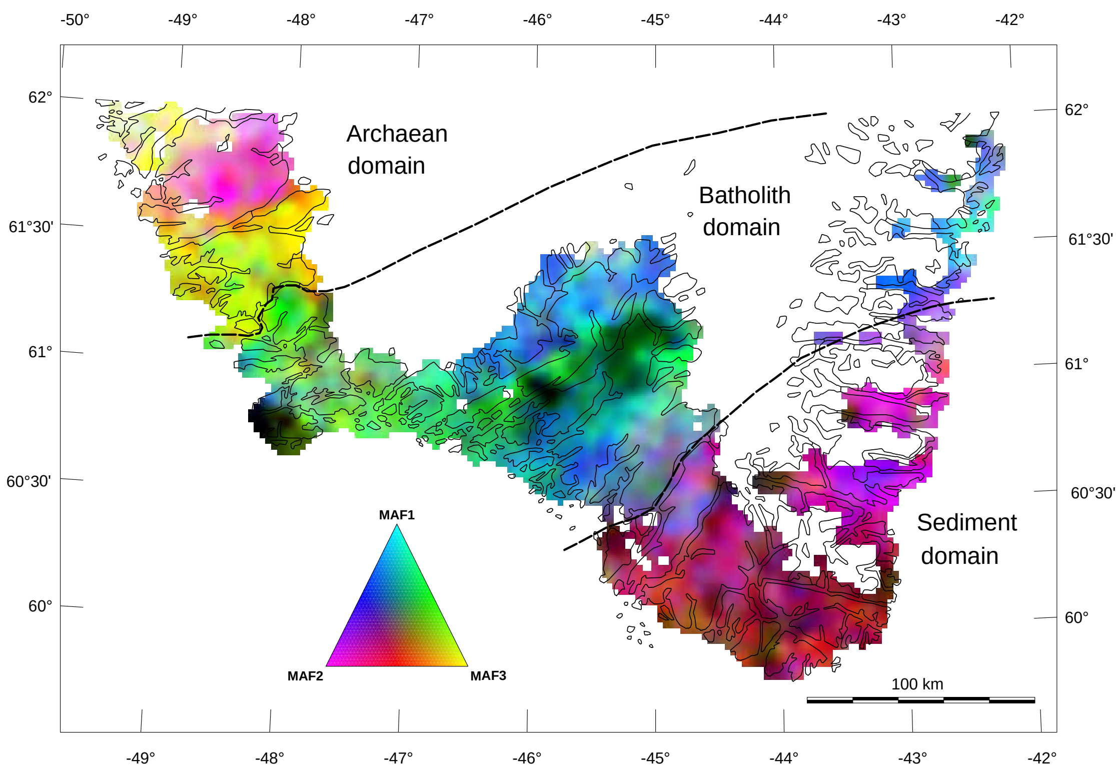

Figure 2. *Geochemical domains of South Greenland, defined by multi-element spatial analysis of chemical data for the < 0.1 mm grain size fraction of stream sediment samples (MAF: maximum autocorrelation factorial kriging, Nielsen et al. 1997). The ternary image is composed of grids of the first three factors. Grid cell size: 2500 m. The domains are named after the predominating litho-stratigraphical units. Sample location is shown in Appendix 2.*

In Thorning et al. (1994) the chemical characteristics of South Greenland and the chemical differences between various litho-tectonic regions were demonstrated qualitatively. More recently, a multi-element statistical spatial analysis (termed MAF – maximum autocorrelation spatial factor analysis; (Nielsen et al. 1997)) has been applied to the stream sediment geochemical data and grids of the first three factors (MAF1,MAF2, MAF3) have been combined to display the major features of the spatial information within the data set. The composite grid map (Fig. 2) shows the existence of three geochemically distinct domains with well-defined boundaries. The domains largely correspond to the main division of the Ketilidian orogen, see Fig. 1.

In Fig. 2 the Archaean domain is displayed in shades of yellow and pink. It comprises the Archaean craton together with the northern part of the Palaeoproterozoic sequences of the Border zone (Fig. 1). The Batholith domain in blue comprises the Batholith Zone together with the southern part of the Border Zone in which the chemistry is much influenced by the intrusion of Ketilidian granites and Gardar syenites, carbonatites and doleritic dykes. Greenish or green-brown to black colours within the Batholith domain are influenced by intrusions of the Gardar event. The sediment domain, in purple colours, comprises the Ketilidian Psammite and Pelite Zones. These two zones are chemically indistinguishable from each other. The rapakivi suite within this domain is reflected by red-orange to brownish hues.

The diagram Fig. 3 illustrates the chemical differences between the main geochemical domains element by element. The means of measured element concentrations in stream sediments for each domain are normalised against estimated average composition of the upper crust (Taylor & McLennan 1985). Summary statistical data for the entire data set are shown in Appendix 3.

Measured by the stream sediment concentrations, South Greenland is enriched in most elements relative to average upper crust. There is, however, an effect of differential weathering reflected in the stream sediment compositions in comparison with rock compositions. The reason is that feldspars decompose more readily than hornblende, pyroxene and many accessory minerals during weathering. As a result, the stream sediments become poorer in Si, Ca, Sr, Na, K, Rb than the rocks they are derived from, and richer in elements like Cr, Ti, Y, Zr, Th, REE, contained in spinel, apatite, zircon, rutile, monazite, garnet etc. It is estimated that this process is responsible for enrichment by a factor of 1.5 to 2. In the case of U there is some enhancement of U concentrations in organic-rich surface environments in lowlands of the south-western Batholith domain. This process, however, cannot be the only cause of the very high average uranium concentration in the stream sediments. Consequently, where elements are enriched by more than a factor two it must reflect an enrichment in the source of the stream sediments, and all or parts of the South Greenland crust is found to be particularly enriched in P, As, Hf, U and REE.

It is further observed that the geochemical differences between the domains concern almost all elements. The Archaean domain is the poorer in most elements except Co, Cr, Cu and Ni. The chemistry of the Batholith domain is much influenced by the Gardar rocks and is richer in Fe, Ti, Mn, Na, P, Mo, Nb, Sr, Ta, U, Y, Zn and REE relative to the other two domains. The Sediment domain is particularly enriched in As, Au, Sb, Hf and Zr, but also has higher K, Rb and Cs. These differences will be discussed in the following detailed description of each domain.

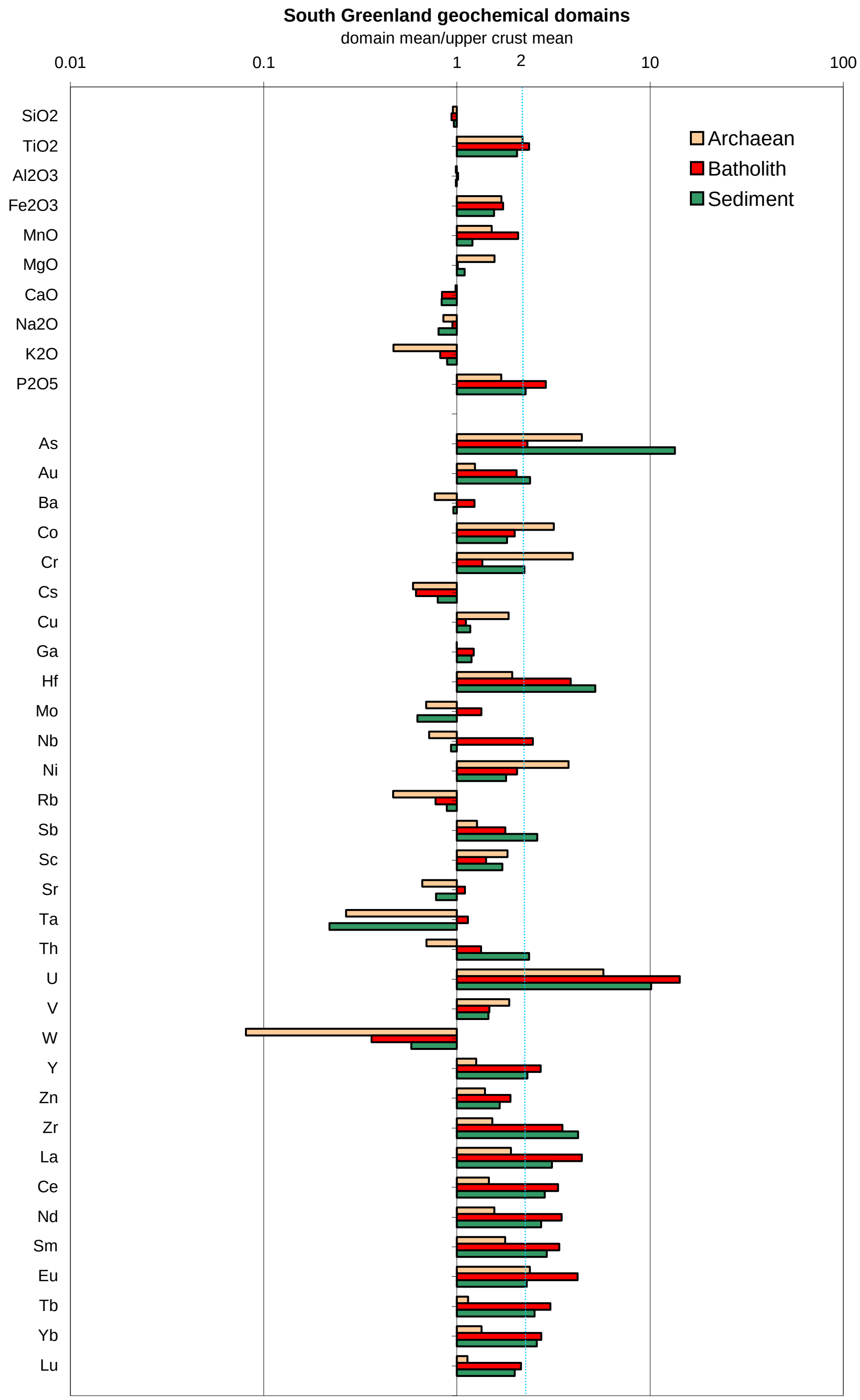

Figure 3. *Element variation between the three geochemical domains of South Greenland. The means of element concentrations in stream sediments from within each domain is normalised against the estimated average composition for the upper crust (Taylor & McLennan 1985).*

The maps of the magnetic field (Figs 4 and 5) result from recent aeromagnetic surveys (Stemp 1997; Thorning & Stemp 1997). The map shows a prominent large-scale variation in the magnetic field strength. Areas of low magnetic background flank an ENE-trending zone of elevated magnetic background with many elongated anomalies conformable to the zone. A smaller area of high magnetic response south of the main zone is parallel to the main zone. The main high-magnetic zone corresponds almost, but not entirely, to the geochemical Batholith domain, while the second high area lies within the Sediment domain.

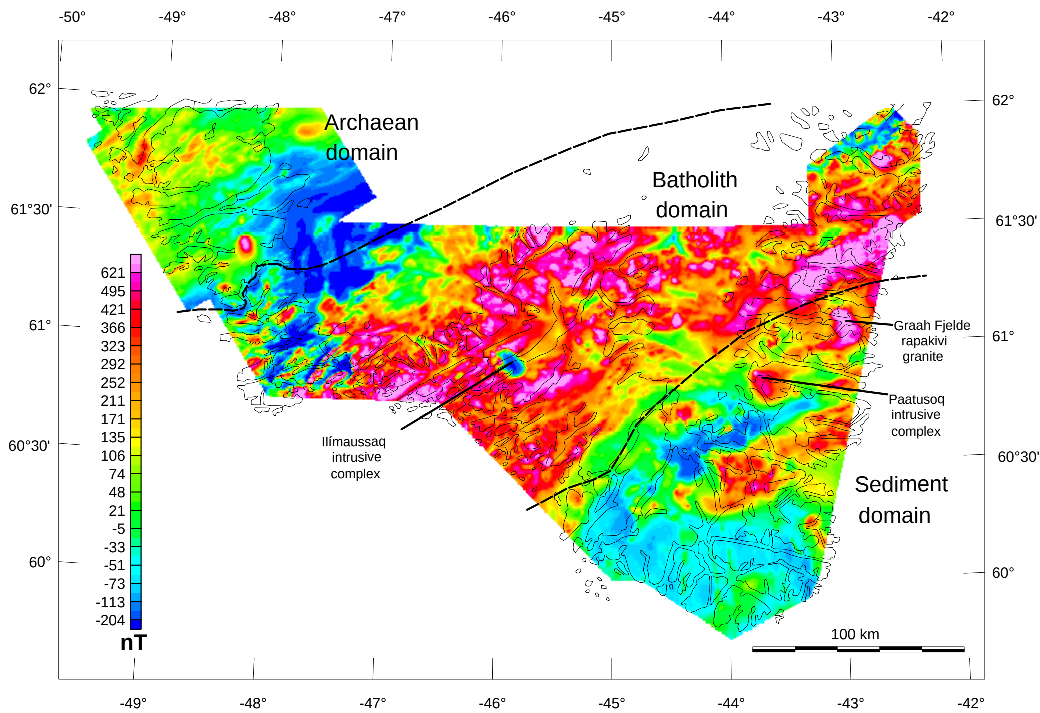

Figure 4. *Aeromagnetic map of South Greenland. Total magnetic field. Grid cell size: 100 m. nT: nanotesla. The domains are defined by stream sediment geochemistry (see Fig. 2).*

In the map of vertical magnetic gradient (Fig. 5) the Archaean domain is characterised by a strongly banded, ENE-directed pattern. A wobbly, high-frequency pattern with preferred ENE and ESE structures is seen over the Batholith domain and half of the Sediment domain. By contrast, the pattern is steady with narrow N-S linear features in the southern part of the Sediment domain. The almost E-W-trending boundary between the two types of patterns does not coincide with neither the litho-tectonic division of the Ketilidian orogen (Fig. 1) nor the geochemical domains (Fig. 2).

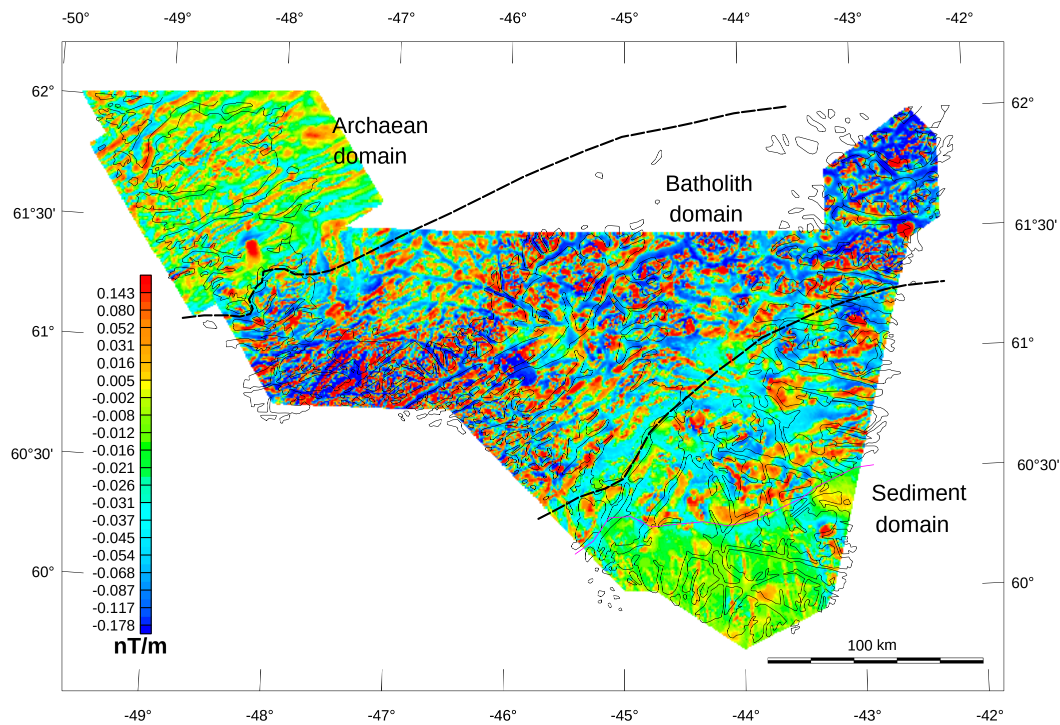

Figure 5. *Aeromagnetic map of South Greenland. Vertical magnetic gradient. Grid cell size: 100 m. nT: nanotesla. The purple line separates different patterns within the Sediment domain.*

Geochemical differences between and within the domains are further visualised in Figs 6 to 12 showing examples of single element distribution, composite images and a combination of aeromagnetic data and geochemistry. The maps illustrate the important differences in the character of the geological entities, differences that must be accounted for in geological modelling.

Geological, geochemical and geophysical characterisation of the domains

The Archaean domain

The Archaean craton is composed of tonalitic orthogneiss with mafic igneous enclaves and slivers of supracrustal rocks. According to existing age determinations most of the gneiss precursors formed between 2800 and 3000 Ma ago (Kalsbeek et al. 1990). A major supracrustal unit, the Tartoq Group, comprises a greenstone association of mafic metavolcanic rocks and metasediments, which have been intruded by a granite dated at 2940 Ma (Nutman & Kalsbeek 1994). North of Sermiligaarsuk a radioactive granite (Steenfelt et al. 1994; Stemp 1997) gives high concentrations of K, Rb, Th, LREE, Y and Zr in the stream sediments and is the reason for the pink area in Fig. 2. North-east of the granite metasediments and many pegmatites contribute to the anomalies in lithophile elements, Y and Zr (Steenfelt et al. 1994).

The Palaeoproterozoic supracrustal successions of the Ketilidian Border Zone unconformably overlie the basement in a belt along the Inland Ice and in scattered exposures in the extreme northeastern corner of the geological map. In the west, the supracrustal rocks reach a stratigraphical thickness of several kilometres in the area at the head of Sermiligaarsuk and on Arsuk Ø. A lower sequence of shales and greywackes with subordinate conglomerate, quartzite and carbonate rocks are overlain by a volcanic sequence largely consisting of pillow-lavas. Mafic sills and dykes intrude the volcanic pile. The depositional environment has been interpreted to be a shallow basin and the plate-tectonic setting a back-arc basin (McCaffrey et al. 1998).

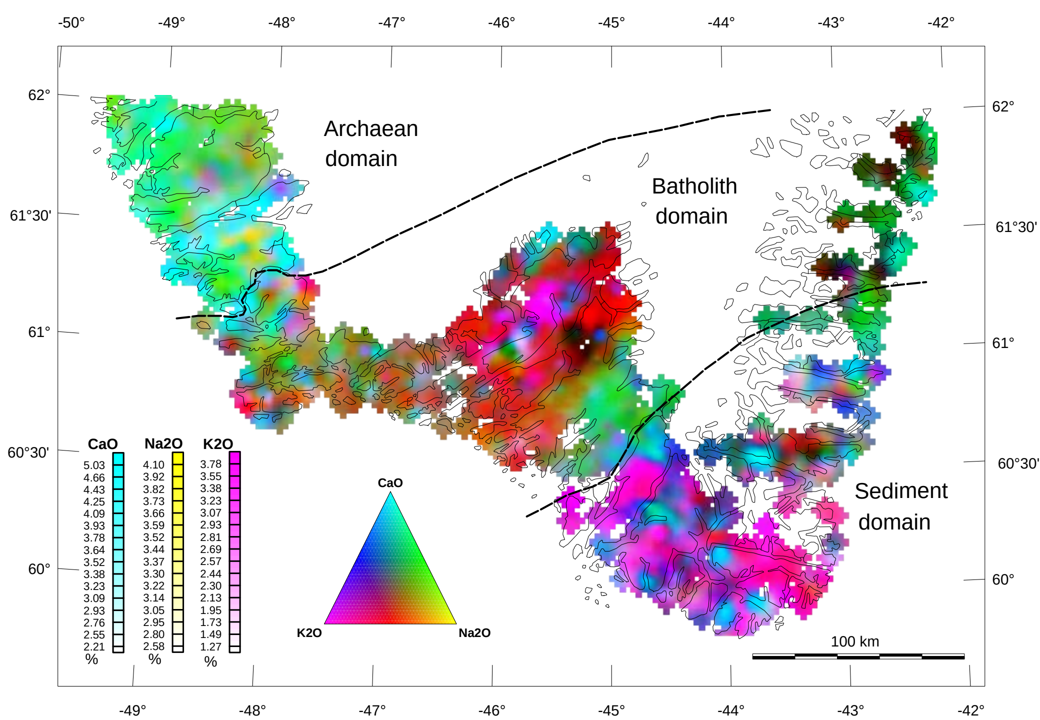

Figure 6. *Composite grid image of CaO, Na_2O and K_2O in stream sediment. Grid cell size: 2500 m. The ternary legend shows mixing-colours of the three components. High values for all three elements give brown to black colours. The bars show that the intensity of the colour is proportional to the element concentration. Sample location is shown in Appendix 2.*

The stream sediment maps combining CaO-Na_2O-K_2O (Fig. 6) and Sr-Ba-Rb (Fig. 7) show that the Archaean domain is characterised by a high proportion of Ca, but low concentrations of Sr, Rb and Ba compared to the two other domains. This reflects the predominance of tonalitic and quartz dioritic gneisses and the relatively high proportion of mafic metavolcanic rocks intercalated with the gneisses. The enrichment in Co, Cu, Cr and Ni (Fig. 3) reflects the abundance of mafic rock enclaves in the gneisses, the metavolcanics of the Ketilidian foreland deposits, and in particular, the presence of numerous dolerite dykes of

Ketilidian and Gardar ages. High concentrations of Sc (Fig. 8) and As (Fig. 11) characterise both the Archaean and Ketilidian metavolcanic rocks. The southern part of the Archaean craton is intruded by Ketilidian and Gardar magmas and is included into the Batholith domain in the chemical division of Figs 2 and 3.
The low number of stream sediment samples collected in the northernmost part of the east coast (see Appendix 1) does not permit a geochemical characterisation of the terrain north of the Batholith.

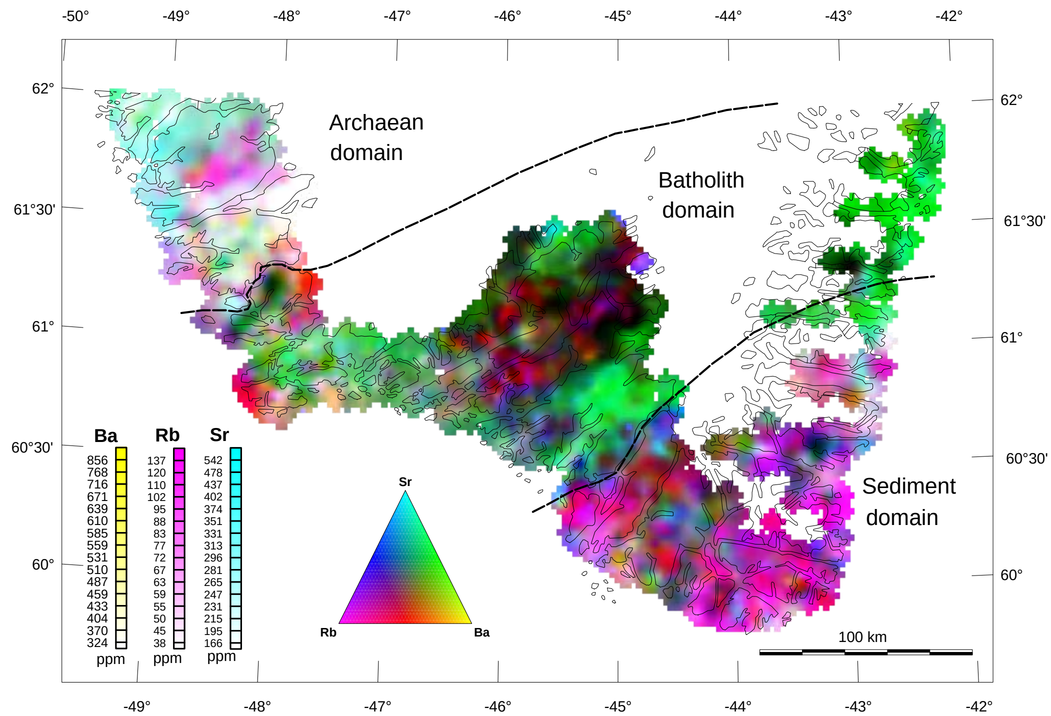

Figure 7. *Composite grid image of Sr, Ba and Rb in stream sediment. Grid cell size: 2500 m. The ternary legend shows mixing-colours of the three components. High values for all three elements give brown to black colours. The bars show that the intensity of the colour is proportional to the element concentration. Sample location is shown in Appendix 2.*

Domains of the Ketilidian orogen

The Ketilidian orogeny took place over a period from c. 2000 to 1750 Ma (Garde et al. 1998a). It is envisaged to have developed in response to northward directed subduction of an oceanic plate below the Archaean craton with subsequent oblique convergence of a volcanic arc against the craton (Chadwick & Garde 1996). The main rock complexes formed during the orogeny comprise (see Fig. 1): 1) sediments and volcanic extrusives deposited on the Archaean foreland; 2) intrusion of large volumes of granitoid rocks and minor volumes of basic rocks into a volcanic arc environment (the Julianehåb Batholith) as well as into the Archaean foreland; 3) deposition of erosion products from the Batholith together with minor volumes of mafic volcanic lavas and pyroclastics in a fore-arc environment (the Psammite and Pelite Zones described here as the Sediment domain).

The first major post-Ketilidian geological event, i.e. the intrusion of rapakivi granites and associated basic rocks around 1740 Ma, is mainly confined to and is described here as a part of the Sediment domain. The second major event, the Gardar event from 1330 to 1120 Ma (Paslick et al. 1993), affects both the Ketilidian Batholith and the Archaean craton, but is largely within the geochemically defined Batholith domain.

Batholith domain

The Batholith domain is dominated by intrusive complexes. A small part of the Archaean craton, which is intruded by Ketilidian granites, as well as a narrow belt of Ketilidian foreland supracrustals are included in the chemically defined domain. Ages of intrusive units within the Batholith domain span the period from 1855 to c.1800 Ma. The older units within the Batholith are strongly deformed while many younger (around 1800 Ma) granites, monzonites and diorites (appinites), show little or no deformation. The major phases of the deformation formed several NNE or NE trending, sinistral shear zones through the Batholith. The general trend of the deformation is clearly reflected in the pattern of magnetic anomalies (Figs 4 and 5).

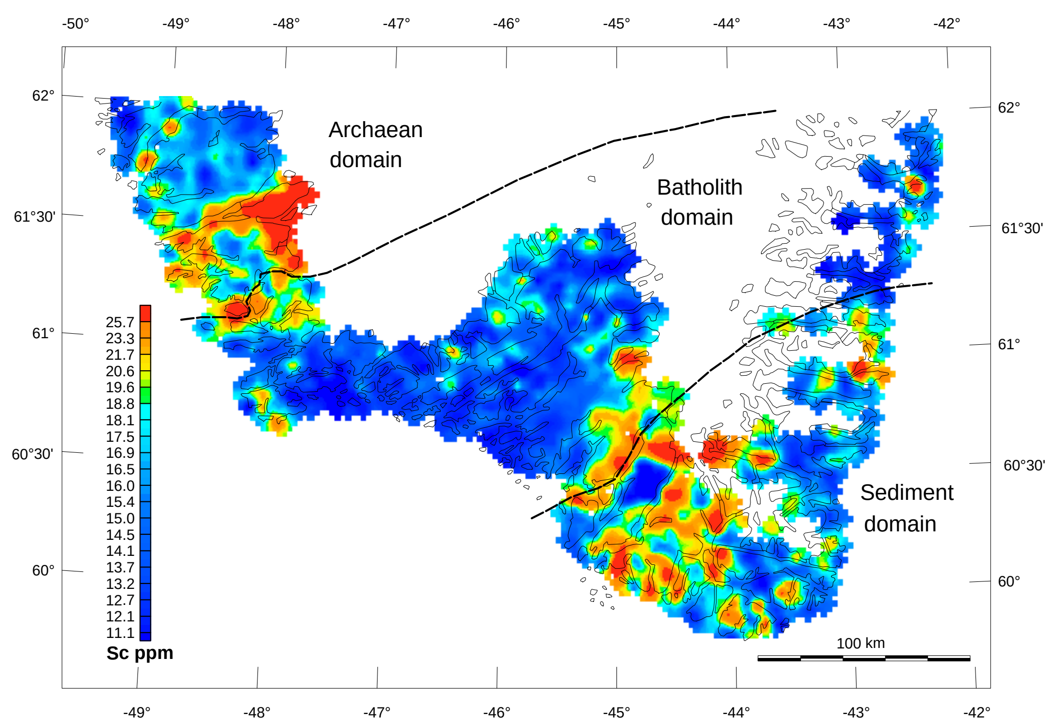

Figure 8. *Geochemical map of Sc based on stream sediment data. Grid cell size: 2500 m. Grid values obtained by kriging. Sample location is shown in Appendix 2.*

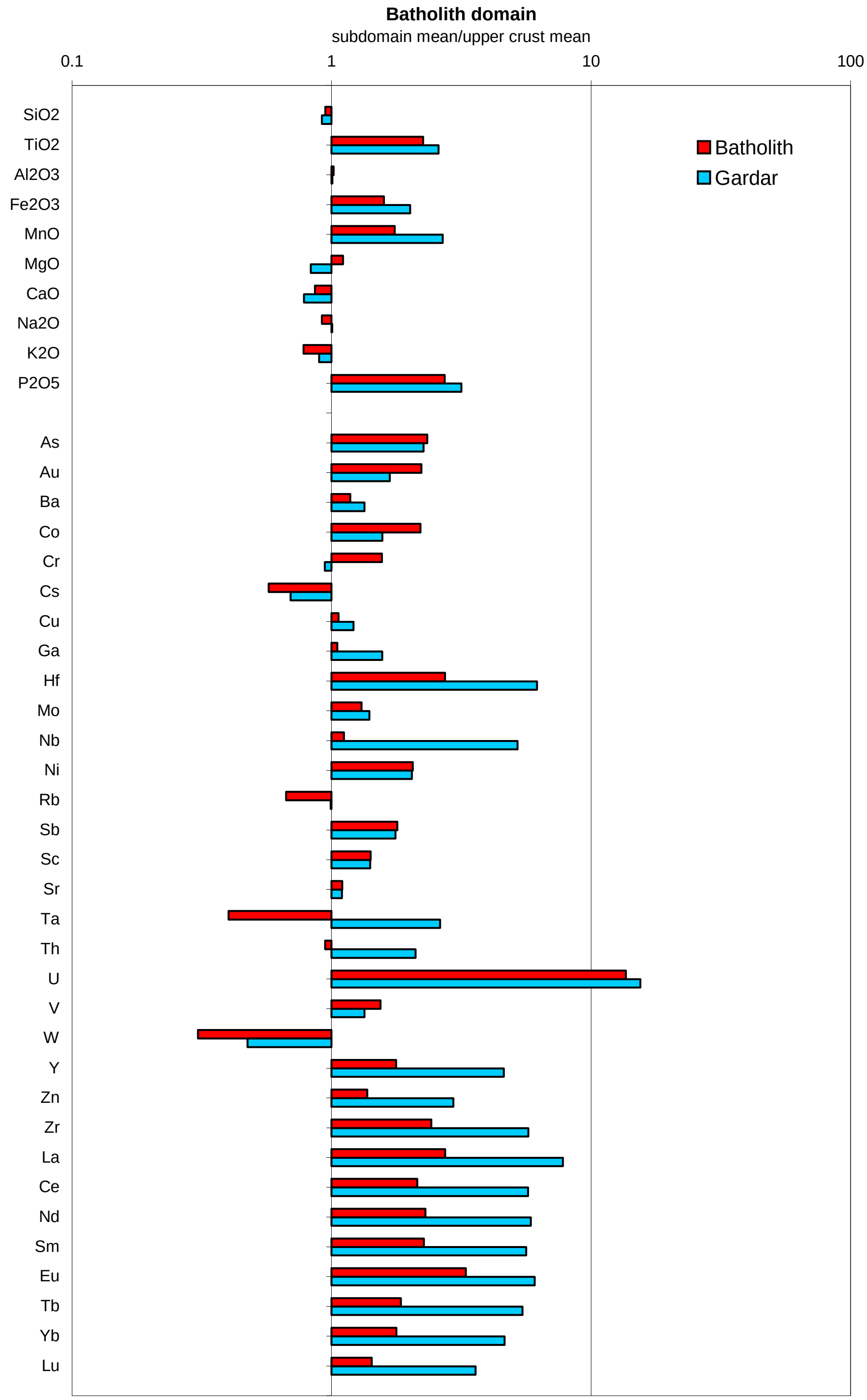

Figure 9. *Element variation between two geochemical subdomains of the Batholith domain, South Greenland. The means of stream sediment concentrations within each subdomain is normalised against the estimated average composition for the upper crust (Taylor & McLennan 1985).*

The intrusions are calc-alkaline or slightly alkaline in character and are interpreted to have formed from juvenile Proterozoic magmas (Kalsbeek & Taylor 1985). The Ketilidian granites intruding the Archaean basement are enriched in large-ion lithophile elements (LILE).

The stream sediment geochemistry shows that the Batholith domain is highly influenced by the Gardar magmas, Gardar dykes and fenitisation phenomena, which makes it difficult to isolate the geochemical signature of the Batholith itself. An attempt has been made assuming that stream sediments with high Nb concentrations belong to the Gardar province. The signatures of the Gardar and non-Gardar subdomains of the Batholith domain are illustrated in Fig. 9.

The stream sediment grid map of combined Sr-Ba-Rb (Fig. 7) show that high Sr and Ba, and low Rb distinguishes the Batholith from the other domains and from the Gardar province. Low Sc values characterise the Batholith and Gardar province (Fig. 8). Analyses of rock samples from the Batholith (granodiorites and quartz diorites) confirm that they are high in Sr and Ba. The highest Sr concentrations occur in the north-eastern part of the Batholith, where also high Ba grid values appear to characterise some of the Batholith intrusions. The magnetic response is generally high over most of the Batholith domain, but the elongated magnetic anomalies can only partly be attributed to individual mapped intrusive members by their distribution and size. However, north of Narsarsuaq the strongest magnetic anomalies coincide with occurrences of composite intrusions of diorite and pyroxene-biotite monzonite. The older intrusive units of the Batholith at the southern and northern margins of the domain are only weakly magnetic, while a stronger magnetic response is found centrally in the domain, dominated by younger members. It is a general observation in the Archaean and Proterozoic basement of Greenland that granitic, granodioritic and tonalitic rocks give low magnetic response whereas quartz dioritic, dioritic and monzonitic rocks are often more magnetic. It is, therefore, suggested that gabbroic-dioritic-(appinitic)-monzonitic intrusions, some of which only partly outcrop, are the main source of the magnetic highs within the Batholith domain.

Sediment domain

This domain comprises moderately to strongly folded and thrusted sequences of metasediments with subordinate occurrences of basic metavolcanic rocks. (Allaart 1976) described the domain as composed of a folded migmatite zone (now the psammite zone) and a flat-lying migmatite complex (now pelite zone) alluding to the difference in tectonic style and ubiquitous presence of migmatitic veins in the metasediments. However, there is no compelling lithological or geochemical reason for subdividing the domain. The aeromagnetic map (Fig. 4), and particularly the map of vertical magnetic gradient (Fig. 5) show a change in pattern over the southernmost part of the domain which agrees with a change from steep to flat-lying structures.

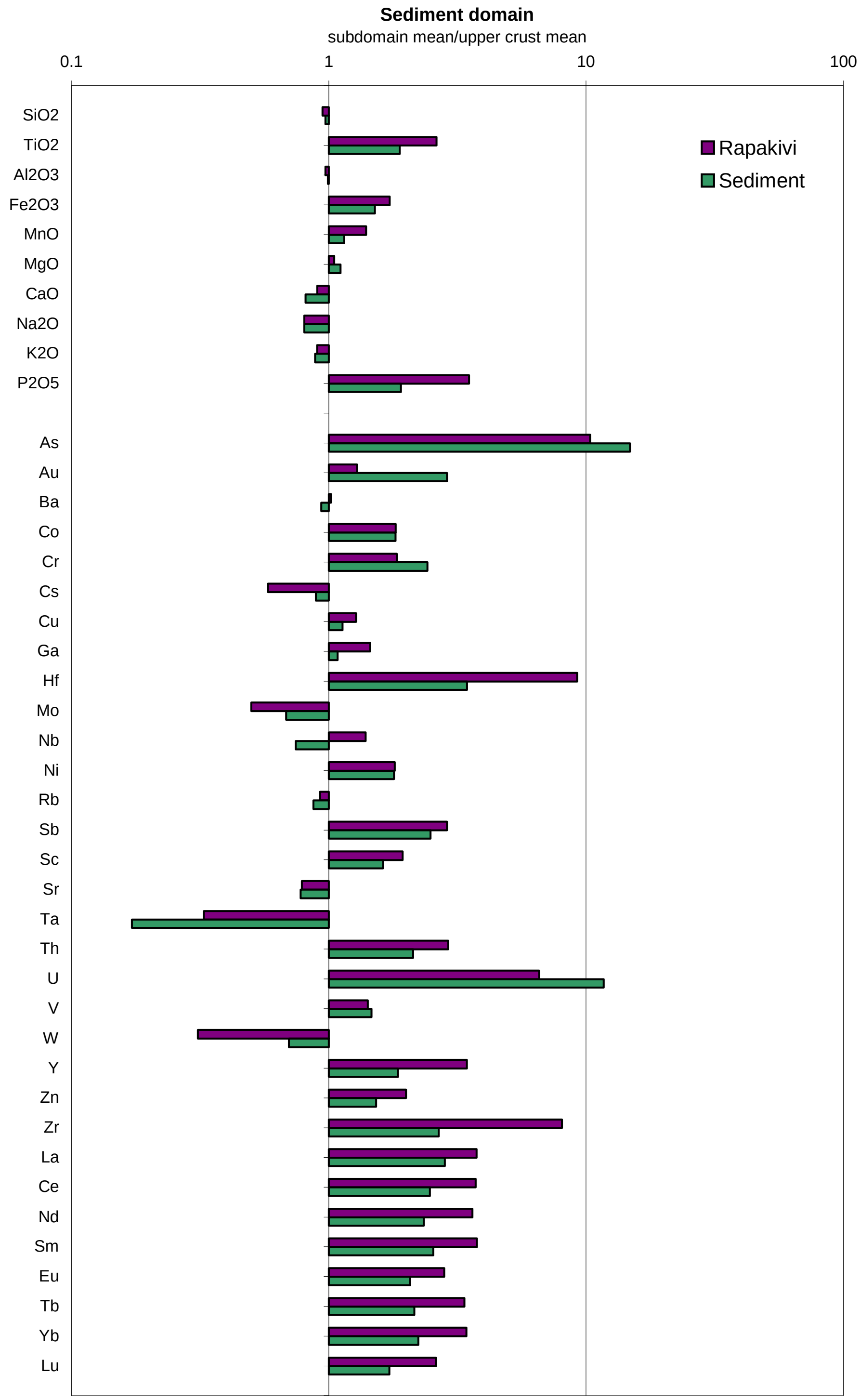

Figure 10. *Element variation between two geochemical subdomains of the Sediment domain, South Greenland. The means of stream sediment concentrations within each subdomain is normalised against the estimated average composition for the upper crust (Taylor & McLennan 1985).*

The metasediments represent fluvial and near shore sediments dominated by psammite as well as basinal facies dominated by pelites and interpreted to represent turbidites. Both facies occur together at many sites where they are mapped as undifferentiated metasediments in the geological map on the CD-ROM. The metavolcanic rocks comprise lavas and pyroclastic rocks of mainly basaltic composition interpreted to represent both submarine and subareal settings. The main deformation took place around 1790 Ma ago. The metasediments contain detrital zircons with ages spanning the period 2100 to 1790 Ma.

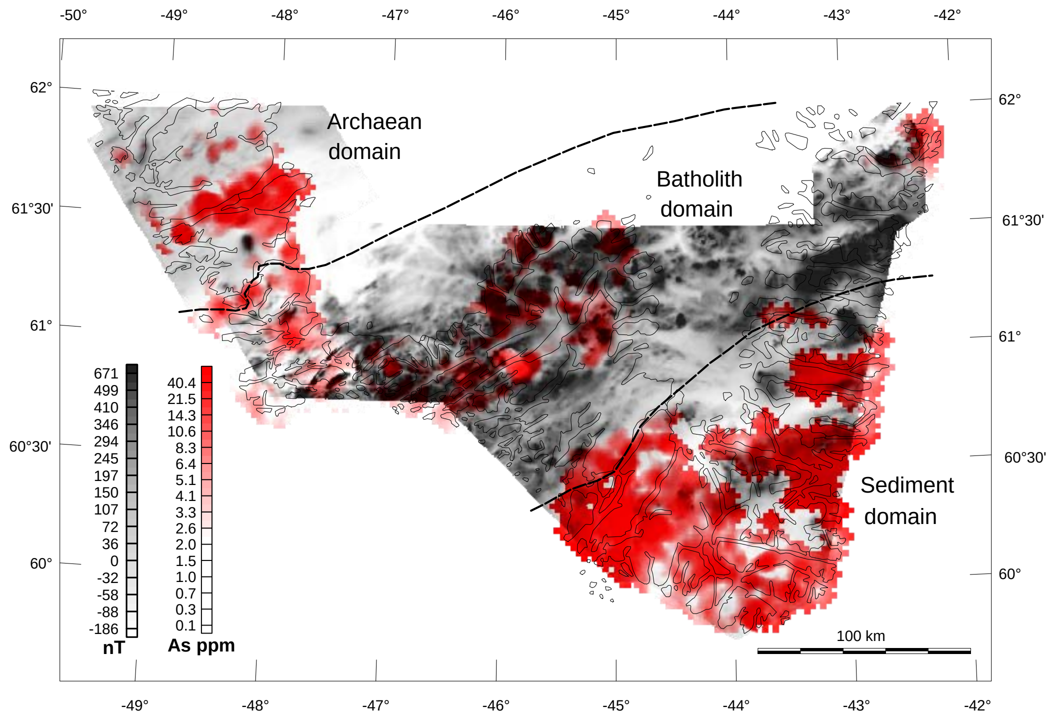

Figure 11. *Composite grid image of aeromagnetic total field (nT = nanotesla) and concentrations of arsenic (As) in stream sediments from South Greenland. Grid cell size for As grid: 2500 m. Grid values obtained by kriging. Sample location is shown in Appendix 2. Grid cell size for total magnetic field: 100 m.*

There is a NE-elongated area of high magnetic response in the eastern part of the Sediment domain (Figs 4 and 11). This is not matched in shape by mapped units of intrusive rocks, and the anomaly is at present not fully explained. The most likely explanation is that there is a ridge or zone of a magnetite bearing intrusive rock such as diorite, monzonite or appinite or hornblende granite. A swarm of appinite dykes occurs in this area. A hornblende granite is exposed in the outer, near-coastal part of the magnetic anomaly and is believed to be part of the Batholith (Swager et al. 1995). It therefore seems possible that the Batholith underlies at least part of the supracrustal domain.

Members of the intrusive rapakivi suite, dominated by rapakivi granites but also comprising intermediate and mafic rocks (norite), occupy an estimated 10 % of the exposed surface. The rapakivi suite intruded from 1750 Ma to 1720 Ma, after the peak of metamorphism and deformation, and form massive sheets interpreted to be lopoliths by (Grocott et al. 1999). The rapakivi granites have low magnetic response with the exception of one northerly body, Graah Fjelde.

The geochemical signature of the rapakivis has been isolated from the surrounding mixture of variably migmatised and granite-intruded metasediments and metavolcanics of the sediment domain (Fig. 10). It is observed that the rapakivis are richer in most elements and that the sedimentary rocks are only significantly higher in Mg, As, Au, Cr, Cs, Mo, U and W.

The geochemical signature of the Sediment domain differs considerably from that of the Batholith domain Fig. 2 and 3. A distinguishing feature of the entire domain is high As (Fig. 11), and it is also richer in Sb and Th, somewhat richer in lithophile elements and also in Zr, Hf, and Y. In the regional scale of Fig. 2 it appears as a geochemically uniform domain but on the local scale the two main components, the metasediments and the rapakivi suite are different. Although it may seem difficult to separate the signature of the sedimentary rocks from that of the rapakivi granites, because they are so intimately associated spatially, some

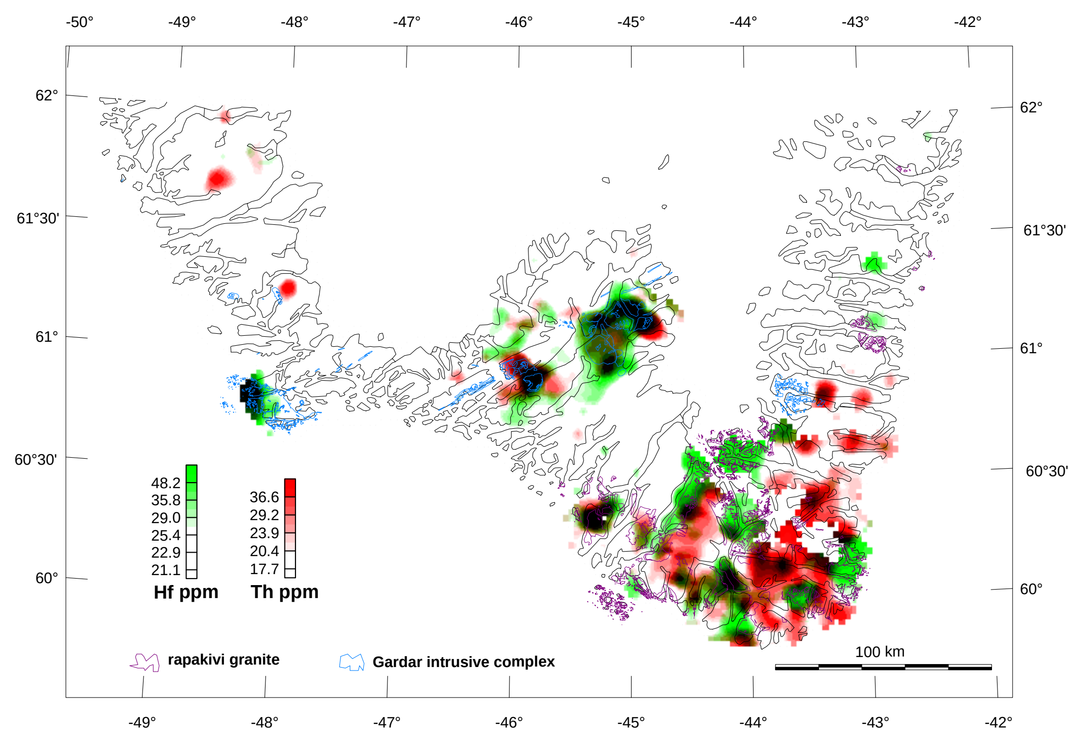

Figure 12. *Composite grid image of hafnium (Hf) and thorium (Th) in stream sediments from South Greenland. Grid cell size: 2500 m. Grid values obtained by kriging. Sample location is shown in Appendix 2. The outlines of occurrences of rapakivi granite suite and of Gardar intrusive complexes are shown (compare with Fig. 1).*

element plots outline the differences. The rapakivi granites are unusually rich in Hf and Zr, as noticed by previous investigators (Gulson & Krogh 1975), and also have high concentrations of HREE (and Y). The map of Hf combined with Th (Fig. 12) shows that the high Hf areas coincide with most of the mapped rapakivi granites, whereas high Th is mostly found in the metasediments and in microcline granites within them.

The highest concentrations of lithophile elements (Cs, Rb, U) and of As occur in a zone that follows the boundary to the Batholith. Many Au anomalies and many of the occurrences of gold mineralisation are known from this same zone. The enrichment in lithophile elements is caused by "migmatitic veins" and syn-tectonic intrusion of granites interpreted to be S-type granites. These have given ages from 1795 to 1785 Ma (Garde et al. 1998a).

Gardar province

The Gardar event involved three main phases of rifting and associated intrusion of alkaline magmas (Upton & Emeleus 1987). The first two phases developed along fault zones with directions between E-W and ENE-WSW. Stretches of these faults are discernible in the maps of aeromagnetic data. The third rifting episode formed an ENE graben in which lavas and sediments are still preserved, see Fig. 1. Four large and six minor Gardar intrusive complexes have been known since the first geological mapping by the Geological Survey of Greenland (Emeleus & Upton 1976). The SUPRASYD project has shown that one fairly large syenite-monzonite complex on the east coast probably also belong to the Gardar province (Grocott et al. 1999). This body was previously believed to be a member of the rapakivi suite. In addition to the emplacement of the major complexes, the Gardar event resulted in the intrusion of several generations of dyke swarms of alkali basalt to trachyte or comendite in composition. Altogether, the Gardar event has brought large volumes of differentiated alkaline magma into the crust.

The magmas of the Gardar province comprise a range from silica over- to strongly undersaturated compositions. They are variably enriched in LILE, rare earth elements (REE), Ti, Hf, U, Th, Y, Zr and Zn, and they are in strong chemical contrast to the surrounding Batholith granitoids or Archaean gneisses. The Gardar province therefore creates very strong anomaly patterns in the stream sediment chemical maps for most of the elements determined (Figs 2 and 9). Relative to the Batholith subdomain, the Gardar province has higher concentrations of all major and trace elements except Mg, Ca, Co and Cr, and slightly lower concentrations of Au, As and Sb. The enrichment in Hf, Y, Nb, REE and Zn they have in common with the Rapakivi granites (Figs 10 and 12) but the most differentiated Gardar magmas have higher concentrations of these elements and additionally high Ta and Th. The La/Yb ratio is higher and the Hf/Zr ratio is much lower in the samples from the Gardar subdomain than in those from the subdomain of rapakivi granites.

The most silica-undersaturated intrusive complexes, Ilímaussaq in particular, create magnetic minima while the saturated seem not to differ much in magnetic response from the Batholith rocks (Fig. 4). There is a magnetic high over the Paatusoq intrusion, or in fact displaced slightly to the southwest of the body as it is mapped. The location of the intrusive complexes is shown in Fig. 16.

There are geochemical differences between individual Gardar intrusive complexes which are expressed in the stream sediment data. The TMS 94/1 (Thorning et al. 1994) contains a geochemical characterisation of the complexes based on inspection of the geochemical data. This is reproduced here in slightly modified form to emphasise the differences (Table 1).

	Ti	Fe	Mn	Na	K	Ba	Ga	Hf	Mo	Nb	Pb	Rb	Sb	Sr	Ta	Th	U	Y	Zn	Zr	REE
Igaliko			x	x		x	x	x		**x**	x	x	x		**x**	x	x	x	x	x	x
Ilimaussaq			x	x			x	x		**x**	x	x	x		**x**	x	**x**	x	x	**x**	**x**
Nunarssuit	x	x	x				x	x			x	x			x	x		x	x		x
Grønnedal-Ika		x	x	x					x	x		x		x	x	x		x			x
Qassiarsuk			x		x	x								x					x		

Table 1. *Stream sediment geochemical characterisation of major intrusive complexes of the Gardar province, South Greenland. High concentrations are marked with an x. Where the x is in bold the concentrations are of economic interest*.

Mineral occurrences

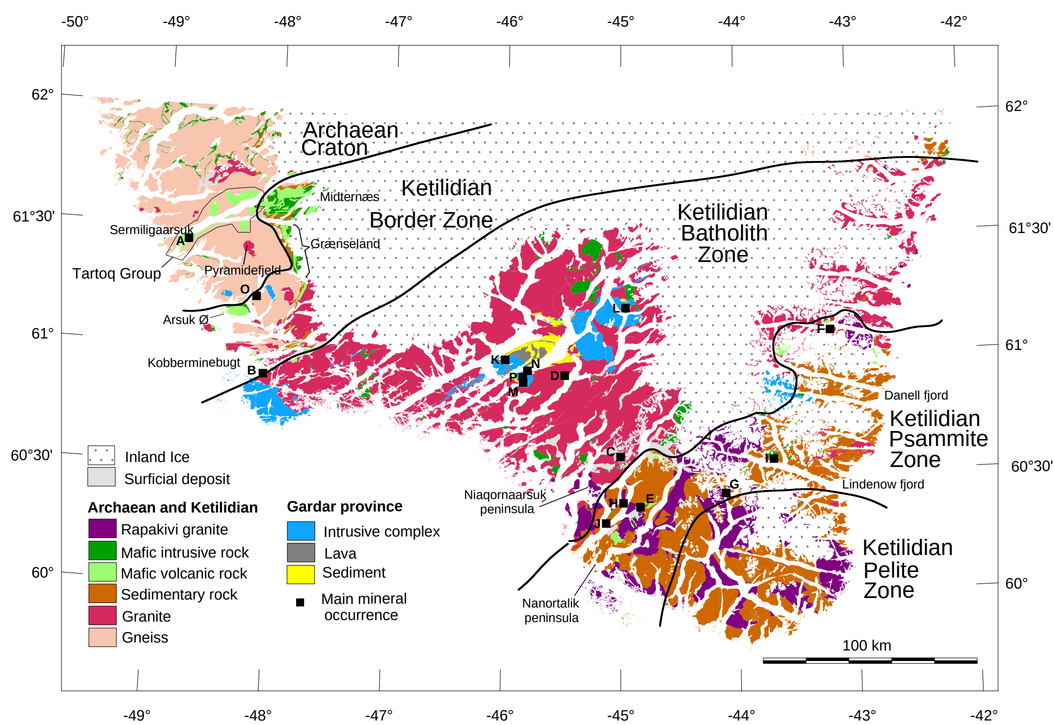

Figure 13. *Simplified geological map of South Greenland with location of main mineral occurrences (see table 2). A: Nuuluk (Au), B: Josva (Cu), C: Niaqornaarsuk (Au), D: Puisattaq (U), E: Nalunaq (Au), F: Kangerluluk (Au), G: Illorsuit (U), H: Amitsoq (PGE), I: Stendalen (Ti, V), J: Amitsoq (graphite), K: Kvanefjeld (U), L: Motzfeldt (Nb, Ta), M: Kringlerne (Zr, Nb), N: (Zr, Y), O: Ivittuut (cryolite), P: Tupersuatsiaat (sodalite).*

Presently, there is no production of metals or industrial minerals in South Greenland, but a few mines have been operated in the past. The most important one was the world-class cryolite mine at Ivittuut, which produced 3.7 mill tons of ore with 58 % cryolite from 1856 to 1987, at which time the ore body was exhausted (Bondam 1991).

Summaries of the mineral occurrences of South Greenland have been given by Kalsbeek et al. (1990), Mosher (1995) and Thorning et al. (1994). Summaries of the gold occurrences are found in Steenfelt (in press) Stendal & Schønwandt (1997). The CD-ROM contains short descriptions with literature references for each of 107 known mineral occurrences. In this report the main mineral occurrences are listed in Table 2 together with estimates on size and ore grades.

Id# in fig. 13	Commodity	Name	Estimates of resource or dimension of mineralised occurrence	Estimates of ore grades or max assay value of grab or chip sample	Remarks and references
Archaean Craton					
	Tartoq greenstones				
	GOLD				
A		Nuuluk	several sulphide lenses up to 1 m wide and 30 m long over 4 km	5-15 ppm Au; grab max 50 ppm Au	(Petersen & Madsen 1995)
Ketilidian orogen					
	Border Zone supracrustals				
	COPPER				
B		Josva	2200 t mined	3.5% Cu, 250 ppm Ag, 1.5 ppm Au	(Ball 1923; (Amdrup *et al.* 1921))
	Batholith				
	GOLD				
C		Niaqornaarsuk, (Qoorormiut Valley)	0.5 to 5 m wide and up to 10 m long quartz veins along 200 m shear zone	chip (6 m) 114 ppm Au	additional showings along shear zones. (Olsen & Petersen 1995)
	URANIUM				
D		Puisattaq	11 m long, 1-10 cm wide vein	1-10 % U	many pitchblende vein showings in Narsarsuaq to Qaqortoq district. (Nyegaard & Armour-Brown 1986; Steenfelt & Armour-Brown 1988)
	Sediment Zones				
	GOLD				
E		Nalunaq	413 000 t ore	32 ppm Au	gold mineralisation at two additional sites at Nanortalik peninsula. (Northern Miner 2000)
F		Kangerluluk	400 m wide, 800 m long shear system with c. 1 m wide mineralised zones	chip max 7.5 ppm Au, grab max 118 ppm Au	(Stendal 1997)
	URANIUM				
G		Illorsuit	1-2 m wide, 150 m long zone	0.01 to 2.5 % U	(Steenfelt & Armour-Brown 1988)
	PGE				
H		Amitsoq	1.5 km long ultramafic body	grab max 0.3 ppm Pt, 0.3 ppm Pd	one of four known ultramafic bodies. (Schønwandt 1971)
	TITANIUM-VANADIUM				
I		Stendalen	20 m thick ilmenite-magnetite layer in gabbro covering 2 km^2	0.26 % V_2O_5	(Birkedal 1998)
	GRAPHITE				
J		Amitsoq	6000 t ore mined, 250 000 t reserves	21 % graphite	(Lindaas 1911)

Id# in fig. 13	Commodity	Name	Estimates of ressource or dimension of mineralised occurrence	Estimates of ore grades or max assay value of grab or chip sample	Remarks and references
Gardar province					
	URANIUM-(THORIUM-LITHIUM-FLUORINE)				
K		Kvanefjeld	56 mill t ore (~20440 t U) 235 000 t Li 470 000 t F	365 ppm U 1900 ppm Li 9600 ppm F	(Kalvig 1983) (Kunzendorf et al. 1982)
	NIOBIUM-TANTALUM				
L		Motzfeldt	600 mill t ore	1400 ppm Nb, 120 ppm Ta	high grade zones exist (3770 ppm Nb, 426 ppm Ta) (Thomassen 1989)
	Zr (Nb-Y-REE)				
M		Kringlerne	+2 mill t ore	3% ZrO_2	high grade zones up to 6% ZrO_2, 0.2% Nb_2O_5, 3% REE2O3, 0.2% Y2O3, 400 ppm Ta (Sørensen 1992)
N		Appat	3.2 mill t ore	1.2% ZrO_2, 0.1 % Y_2O_3	(LeCouteur 1989)
	CRYOLITE-FLUORITE-(SIDERITE)				
O		Ivittuut	3.723 mill t ore mined remaining in-situ reserves: 141 000 t ore 321 000 t ore 675 000 t ore 16 500 t ore c. 500 000 t ore	58 % cryolite 8% cryolite 18.2 % fluorite 38.3 % siderite 0.9 % sphalerite 34.6 % quartz	(Keto 1988; Bondam 1991)
	SODALITE				
P		Tupersuatsiaat	1600 mill t ore	50 % sodalite	(Kalvig & Appel 1994)

Table 2. *Main mineral occurrences of South Greenland. The list includes abandoned mines, potentially economic prospects, and showings of economic interest.*

Archaean Craton

Archaean formations: gold, banded iron formation

The supracrustal Tartoq group hosts extensive sulphide and magnetite banded iron formations with low but persistent gold values (Appel 1974; Evans & King 1993). Higher, but more erratic gold grades (up to 19.5 g/t over 2.5 m) are found in epigenetic mineralisation associated with quartz-ankerite and arsenopyrite-pyrite-chalcopyrite lenses within a system of carbonated shear zones (Evans & King 1993). Occurrences at Nuuluk (A in Fig. 13 and Table 2) have been drilled (Petersen 1993; Petersen & Madsen 1995). The formation of the high-grade vein gold is explained as the result of a multi-stage process beginning with low-grade syn-sedimentary exhalative type of mineralisation with Au, As and S in chemical sediments (Evans & King 1993).

Ketilidian orogen

Border Zone supracrustals: copper, (gold)
Ketilidian supracrustal rocks (Ilordleq Group, Watterson 1965) occur in a thin belt on the south shore of Kobberminebugt. The sequence comprises mafic and felsic metavolcanic rocks mixed with metasediments. The package is generally strongly sheared. Amphibolite units have abundant disseminated chalcopyrite (Secher & Kalvig 1987). The copper mineralisation mined from 1905 to 1914 at the Josva and mine comprises bornite, chalcocite and chalcopyrite as fracture filling of faulted and brecciated structures (Ghisler 1968; Harry & Oen 1964) in metavolcanic rocks. The grades of gold and silver recorded in the mined ore are noteworthy (Table 2) and have attracted gold exploration in the area. As a result, gold mineralisation was recorded in sulphide-rich and quartz-veined metavolcanics at several localities in the Kobberminebugt region (Erfurt & Lind 1990).

Batholith granites: gold, uranium
Mesothermal gold mineralisation has occurred in second order structures associated with major shear zones at Niaqornaarsuk peninsula. Gold is located in quartz veins in zones of shearing, aplite veining and alteration transecting granodiorite and amphibolite dykes within the batholith. Chip samples with up to about 3 ppm are not unusual and very high concentrations have been found (Table 2). The mineralisation can be characterised as an Au-Bi-association. Lead isotope data suggest that the mineralisation is associated with late stage intrusions of aplites into the Batholith.

Uranium mineralisation is common in the fracture systems developed in the granite Batholith both within and outside the late ENE rifted zone of the Gardar province. Many small occurrences of uraninite(-brannerite) veinlets associated with fluorite in hydrothermally altered fracture zones have been located (Nyegaard & Armour-Brown 1986). The pitchblende has a mid-Proterozoic age contemporaneous with Gardar magmatism, and the mineralisation is considered to have formed by remobilisation of uranium from a Palaeoproterozoic supracrustal source by hydrothermal activity related to Gardar magmatism (Steenfelt & Armour-Brown 1988). The highest grades of uranium were found at Puissataq (D in Table 2 and Fig. 13).

Sediment Zones

Metavolcanics: gold
Mesothermal gold mineralisation occurs at several localities within the Psammite Zone (Stendal & Schønwandt 1997). The gold is found in quartz or aplite veins hosted by mafic metavolcanic rocks. The most important occurrence is Nalunaq (E in Table 2 and fig. 13), which has been investigated at a prospect scale (Petersen et al. 1997; Petersen & Olsen 1995) and is presently (June 2000) undergoing test mining.
There are two gold occurrences north and south of Nalunaq of the same type as Nalunaq. The mineralisation is considered to have resulted from several episodes of hydrothermal activity in connection with intrusions of granitic magmas (Stendal & Frei in press). A mineralisation at Kutseq (between Danell and Lindenow fjords) on the east coast is hosted in silicified metavolcanics and is similar to Nalunaq in mineral paragenesis and temperature of formation. The accompanying sulphides are dominated by pyrrhotite, löllingite and arsenopyrite and the mineralisation can be described as an Au-As association.

The gold mineralisation at Kangerluluk (F in Table 2 and fig. 13) is associated with copper mineralisation and is located in zones of alteration and quartz veining through a small volcano-sedimentary complex (Stendal 1997; Mueller et al. in press;). The lavas have calc-alkaline affinities and the complex is interpreted to represent remnants of a volcanic arc. The mineralisation history involves one syn-volcanic alteration stage and two post-volcanic stages spatially associated with faulting and shearing. The last remobilisation and upgrading of the Cu-Au mineralisation is ascribed to hydrothermal activity driven by intrusion of the nearby Graah Fjelde rapakivi granite.

South-west of Kangerluluk there is a poorly known occurrence of a volcano-sedimentary sequence with signs of gold mineralisation of a similar type to that at Kangerluluk. Boulder samples of quartz and carbonate veined, epidotised volcanic and sedimentary rocks have returned up to 9 ppm gold and 4% copper (Stendal et al. 1997).

Metasediments: graphite, uranium

Graphite is common in metapelitic sequences and there are several occurrences of which one (Amitsoq, J in Table 2 and fig. 13) was mined from 1911 to 1922 (Ball 1923; see also Bondam 1992).

Occurrences of uranium mineralisation are common in the metasediments. A uranium showing at Illorsuit (G in Table 2 and fig. 13) has been investigated in some detail. Rafts of metasediment and metavolcanic rocks metamorphosed under granulite facies conditions contain strata of finely disseminated grains of uraninite with occasional concentration in fold crests and fractures. The age of the uraninite corresponds to that of the rapakivi intrusions (1740 Ma; Armour-Brown 1986), but an original synsedimentary deposition of uranium is assumed by Steenfelt & Armour-Brown (1988), who suggested acid-intermediate volcanic rocks as a source of uranium.

Mafic intrusions: titanium-vanadium, platinum

A magnetite-rich layer in a large body of gabbro, Stendalen gabbro (I in Table 2 and fig. 13), has been investigated in some detail (Birkedal 1998). The magnetic horizon covers about 2 km2 and a five metre thick zone within the layer is semi-massive with 20 vol.% ilmenite, 10 vol.% magnetite, 5 vol.% pyrrhotite. The gabbro is deformed and is correlated with late Batholith-related intrusions with ages around 1800 Ma.

Four small ultramafic plutons with disseminated sulphides at the Nanortalik peninsula and neighbouring island, Amitsoq (H in Table 2 and fig. 13), have been examined for mineralisation with platinum group elements (PGE). An induced polarisation anomaly in one pluton was drilled, but economic grades were not found in the drill cores. Grab samples have yielded concentrations of interest (Table 2). The mineralisation at Amitsoq is described by Schønwandt (1971).

Gardar province

Central intrusive complexes and carbonatites: cryolite, uranium, speciality metals
The Gardar intrusive complexes comprise alkaline silica-oversaturated to extremely undersaturated members. The cryolite body is associated with the former category while most other concentrations of metals and other commodities of economic interest are found within the latter category, and particularly in the highly differentiated magmas of, the Ilímaussaq and Igaliko complexes.

The body of cryolite (Na_3AlF_6) was formed by late stage processes in the crystallisation of a small stock of alkaline granite (Pauly & Bailey 1999). The rich cryolite ore body is now exhausted, but minor amounts of low grade cryolite ore remains in addition to fluorite, siderite, sphalerite and quartz.

The final product of magmatic differentiation in the Ilímaussaq intrusive complex was the agpaitic mafic syenite, lujavrite. It is highly enriched in lithophile, volatile and rare elements. Many aspects of the geology and chemistry of the Ilímaussaq complex are treated in Bailey et al. (1981), which also contains a comprehensive bibliography. The lujavrite at Kvanefjeld (K in Table 2 and Fig. 13) has been evaluated as a uranium (-thorium) deposit by means of drilling, ore recovery studies, resource calculations and test mining. The principal uranium mineral is a silicophosphate, steenstrupine. The Th/U ratio of the ore is 2.5. Lujavrite occurrences at Appat, in the southern part of the Ilímaussaq complex, have been investigated for their Zr-Y-REE potential. The main mineral hosting these elements is eudialyte. Eudialyte is also abundant in another nepheline syenite within the Ilímaussaq complex, the kakortokite. A particularly eudialyte-rich layer at Kringlerne has been evaluated as a zirconium ore for production of zirconia. The third mineral prospect within Ilímaussaq concerns sodalite, which is a major constituent of the nepheline syenite called naujaite. The sodalite has been evaluated as raw material for production of artificial zeolite with ion-exchange capacity.

Mineral potential of South Greenland

South Greenland is a segment of continental crust characterised by strong enrichment in U, As, REE, Zr and Hf (Fig. 3). This suggests a potential for economic concentrations of these elements. Indeed, large occurrences of all are known from the area, and there is a potential for the discovery of new occurrences with similar or higher grade, or with different composition, structure or other quality required by the production of a specific commodity. In addition, South Greenland has a high potential for gold mineralisation, and although many occurrences have been located within the last ten years, exploration has been limited and the geochemical data suggest that there are more targets, as discussed below.

In addition, South Greenland has a potential for types of mineral occurrences that are not indicated by geochemistry, either because an element have not been analysed for, e.g. platinum group elements (PGE), Li, Be, or because the commodity is an industrial mineral like cryolite or sodalite. The potential for such occurrences may be indicated by favourable geological settings. Several semi-massive sulphide occurrences are known in supracrustal sequences and more are indicated by airborne electromagnetic surveys.

The evaluation of the mineral potential is obviously influenced by commodities of present economic interest. However, by making the data compilation for South Greenland as comprehensive as possible the data will be valid for future use, when commodities in demand are be expected to change.

Gold

All data considered relevant for an evaluation of the gold potential of South Greenland is compiled in Fig. 14. The most prospective areas are around Sermiligaarsuk Fjord, at the southern margin of the Batholith domain, and large parts of the Sediment domain.

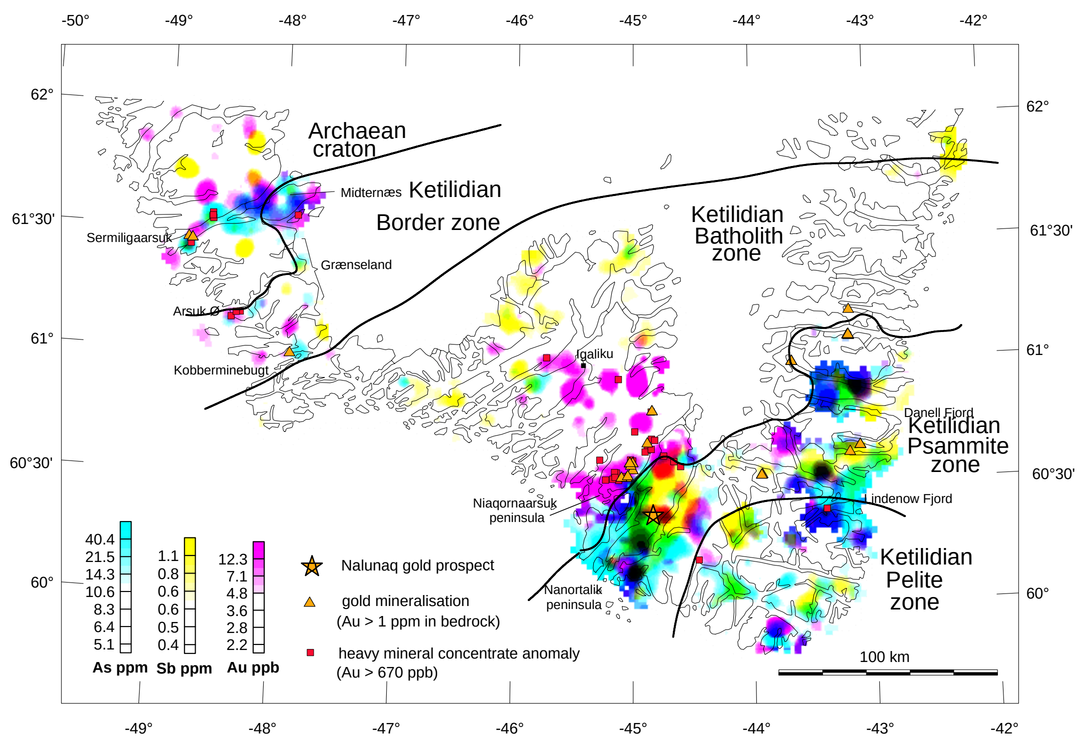

Figure 14. *Gold potential of South Greenland as indicated by the distribution of high grid values for gold (Au) and pathfinder elements arsenic (As) and antimony (Sb) in the fine fractions (< 0.1 mm) of stream sediments, together with gold anomalies in bedrock and heavy mineral concentrates of stream sediments. The anomalies are extracted from the databases behind a CD-ROM issued by GEUS (see Appendix 1). Sample location is shown in Appendix 2.*

The Archaean greenstone formation, the Tartoq Group, represents an environment of tholeiitic volcanic lavas with intercalated felsic volcanic rocks and sedimentary sequences. Occurrences of oxide and sulphide facies banded iron formation are common. Gold anomalies are registered in stream sediment and heavy mineral concentrates. The high As distinguishes the Tartoq group from other greenstone occurrences further north in West Greenland and suggest that the group has another plate-tectonic setting than the "ordinary" greenstone belts. Gold mineralisation has occurred to form low-grade as well as high-grade deposits. Detailed exploration and drilling has been carried out at Nuuluk (location on Fig. 13) and at Iterlak on the north shore of Sermiligaarsuk, but work at those sites was discontinued. Only a small part of the Tartoq group has been explored in detail and the Tartoq group holds a potential for epigenetic gold mineralisation. Apart from the anomalies at Nuuluk and Iterlak there are coinciding anomalies for As, Sb, Au at western Midternæs and the highest stream sediment gold values in the Sermiligaarsuk area (32 and 82 ppb Au) occur in the eastern outcrop of Tartoq rocks north of Sermiligaarsuk (Steenfelt et al. 1994).

The Ketilidian supracrustals at Midternæs and Grænseland and Arsuk Ø comprise shallow water sedimentary sequences and a thick volcanic section with pillow lavas, i.e. subaqueous lavas, intruded by basic sills. The environment has been suggested to represent a back-arc setting (Garde et al. 1998a; McCaffrey et al. 1998). The area is characterised by high As, and there are several anomalies for gold in stream sediment and heavy mineral concentrate.

The back-arc setting is regarded favourable for primary low-grade concentrations of gold and pathfinder elements, such as As and Sb. The scattered stream sediment and heavy mineral gold anomalies confirm the gold potential. There are a few gold showings recorded in both sedimentary and volcanic members of the Ketilidian supracrustal rocks of the Border Zone, which have hitherto been considered non-economic. The most important has been indicated by stream sediment and heavy mineral concentrate anomalies on Arsuk Ø, and has been investigated by Nunaoil Ltd. (Gowen 1992). Rusty chert horizons and quartz veins have low-grade enrichment in Cu and Au.

Gold was possibly remobilised in connection with deformation and intruding felsic magmas around 1800 Ma, particularly in the southern part of the Grænseland supracrustals, where narrow outcrops of Ketilidian supracrustals continue southwards until Kobberminebugt. There are a few gold anomalies in stream sediment, heavy mineral concentrates and there is relatively high Sb and high As along the narrow outcrop. Samples of quartz veins and sulphide veins have given gold concentrations up to 2.9 ppm Au (Erfurt & Lind 1990). The supracrustals hosting the abandoned Josva mine has a gold and silver potential. The mined ore had a grade of over 1 ppm Au and 250 ppm Ag, and up to 5 ppm Au has been recorded in samples of quartz and bornite veins collected more recently (Erfurt & Lind 1990).

Steenfelt (in press) argues that the As-rich environments in South Greenland are favourable source environments for gold mineralisation, and that high Cs in stream sediments can be used to indicate the presence of high level granitic intrusions, which may cause remobilisation of gold. Anomalies for Sb would be a sign that such remobilisation and upgrading of pathfinder elements has taken place. Thus coinciding anomalies for As, Sb and Cs in stream sediment may be used as a prospectivity criterion for epigenetic gold mineralisation. Applying this criterion, the southern part of Grænseland is outlined to have gold potential. Unfortunately, the gridded maps shown on the CD-ROM does not indicate this very clearly, because there are few samples collected within the narrow belt of supracrustals. However, the data base and dot maps do show samples with high concentrations of all three elements.

The potential for gold mineralisation in the Batholith has been strongly enhanced since the discovery of the gold occurrences in the vicinity of and related to shear zones at Niaqornaarsuk peninsula. The grades are promising and sustain a potential for economic deposits. The shear zones at Niaqornaarsuk are prominent, but there are other important shear zones within the Batholith, which may be considered as equally favourable as deposition sites for gold mineralisation. In contrast to the situation at Niaqornaarsuk, As is absent over most of the Babholith Zone, which suggest that any gold mineralisation there would be of a different type (Steenfelt & Tukiainen 1991). The gold anomalies in the district around Igaliku lie within a fracture system with vein-type uranium mineralisation (see below). This opens the possibility that gold has been mobilised together with uranium in connection with Gardar magmatism.

The gold potential is considered high within the Sediment Zones. The Au, As, Sb anomalous districts characterising the known gold occurrences also prevail in districts where exploration activities have been few. On geochemical grounds Steenfelt (in press) points at central Danell Fjord and outer Lindenow fjord as highly prospective areas for gold. Occurrences of gold have not been found within the Pelite Zone but a few coinciding anomalies for Au, As and Sb suggest that gold mineralisation has occurred also there.

Uranium

The data relevant for the evaluation of the uranium potential are compiled in Fig.15. The most anomalous areas are within the Batholith domain, in the surroundings of the major Gardar intrusive complexes. Within the Sediment domain, the southern Nanortalik peninsula and the wider surroundings of Lindenow Fjord have significant anomalies for uranium.

The governmental uranium exploration programme SYDURAN located uranium pitchblende and brannerite mineralisation in fault structures within regional stream sediment uranium anomalies in the Batholith Zone. Although no mineralisation with considerable tonnage was found, high grades were demonstrated. Exploration was discontinued for political reasons and the potential for economic vein-type uranium mineralisation still persists in the highly fractured Batholith within the most prominent ENE rift zone of the Gardar province (see Nyegaard & Armour-Brown 1986 and Steenfelt & Armour-Brown 1988). The mineralisation model presented for the uranium occurrences (Steenfelt & Armour-Brown 1988) involved primary synsedimentary concentration of U in the Ketilidian supracrustals, remobilisation during the Gardar period, and final deposition of uranium oxide (uraninite and brannerite) in faults of the rift system.

The geochemistry suggests that the Ketilidian sediments of the Sediment Zones were rich in or enriched in uranium during sedimentation. Upgrading of uranium may have taken place during metamorphism or the intrusion of rapakivi suite magmas. Illorsuit (G in Table 2 and Fig. 13) is but one of a number of radiometric U-anomalies in the metasediments of the Sediment domain. The geological setting at Illorsuit is not unique and the distribution of both the radiometric eq. U and stream sediment U (Fig. 15) show many anomalous areas in the Sediment domain. The small cluster of heavy mineral anomalies east of the Nanortalik peninsula suggests the presence of an undiscovered mineralisation.

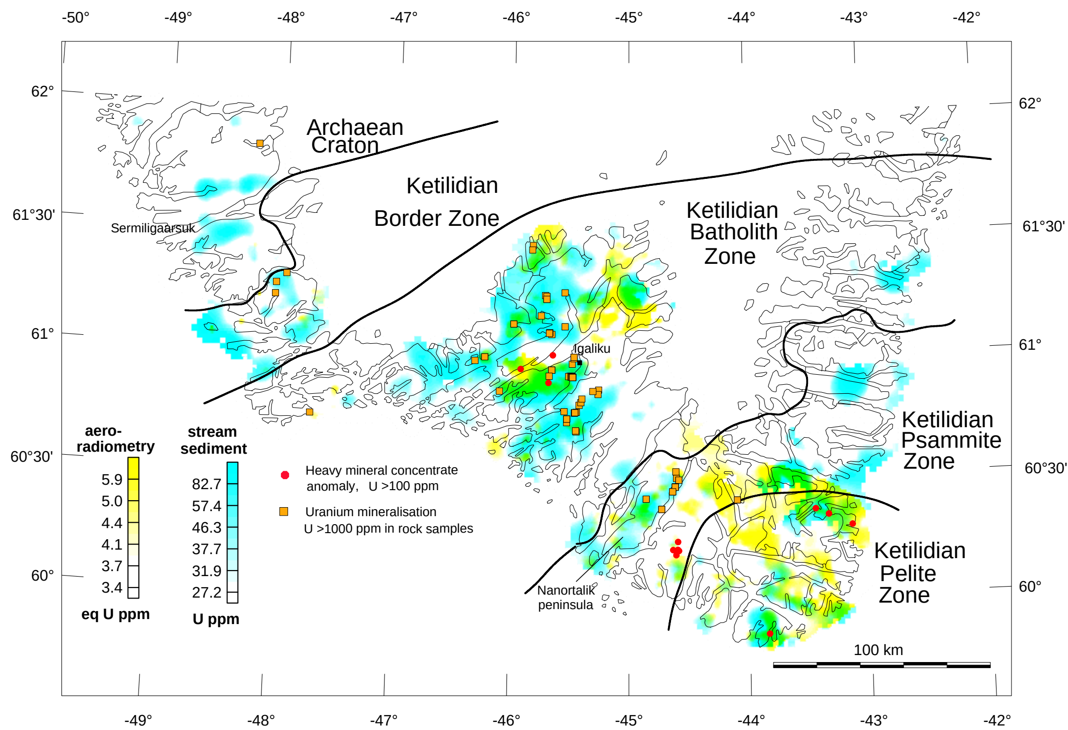

Figure 15. *Uranium (U) potential of South Greenland as indicated by the distribution of high grid values in aeroradiometrically measured U concentrations (eq U) and stream sediment U concentrations, together with anomalies for U in heavy mineral concentrates of stream sediments and bedrock. Sample location and aeroradiometric survey coverage is shown in Appendix 2.*

The potential for large, low-grade (i.e. 200-400 ppm U) deposits of uranium and thorium is found in the Ilímaussaq and Igaliko complexes of the Gardar province. The proven resource has been assessed at Kvanefjeld (Table 2). However, lujavrite with equal concentrations of U occurs elsewhere in the Ilímaussaq complex, so that the potential additional resources of U are several times larger than the present estimate.

Speciality metals (niobium, tantalum, yttrium, REE, zirconium, lithium, beryllium), cryolite, sodalite, phosphorous

Of the mineral deposits investigated within the Gardar province (Table 2), only the cryolite in Ivittuut has come to the stage of exploitation, but with changes in the mineral market or in government policies in the future, some of these deposits may be economically viable. It is a common feature of the deposits of uranium and speciality metals within the central intrusive complexes that they are large and low-grade. There are, in fact, much larger resources of these minerals/metals than those indicated by the assessments made. Cryolite, however, is an exception in that additional occurrences of cryolite ore have not been found, so far, despite extensive exploration campaigns in the surroundings of the known body (Bondam 1991; Keto 1998). However, drilling indicates a minor resource of additional cryolite below the floor of the present open pit mine.

Fig. 16 outlines additional prospective areas for Nb, Ta and Y, and also show where there are indications of high concentrations of phosphorous. A number of heavy mineral concentrate anomalies located in the southern part of the Igaliko complex suggest the existence of Ta mineralisation additional to the known deposit at Motzfeldt Sø (L in Table 2 and Fig. 13). In the Ilímaussaq complex the most eudialyte-rich parts of kakortokite and lujavrite have as high concentrations of Nb and Ta as found at the Motzfeldt Sø deposit. The resources and grades of Zr and Y have been investigated at Appat in the Ilímaussaq complex (N in Table 2 and Fig. 13). Taking other occurrences of lujavrite into account, ore reserves have been estimated in the order of 30 mill t with the same grades as at Appat (LeCouteur 1989).

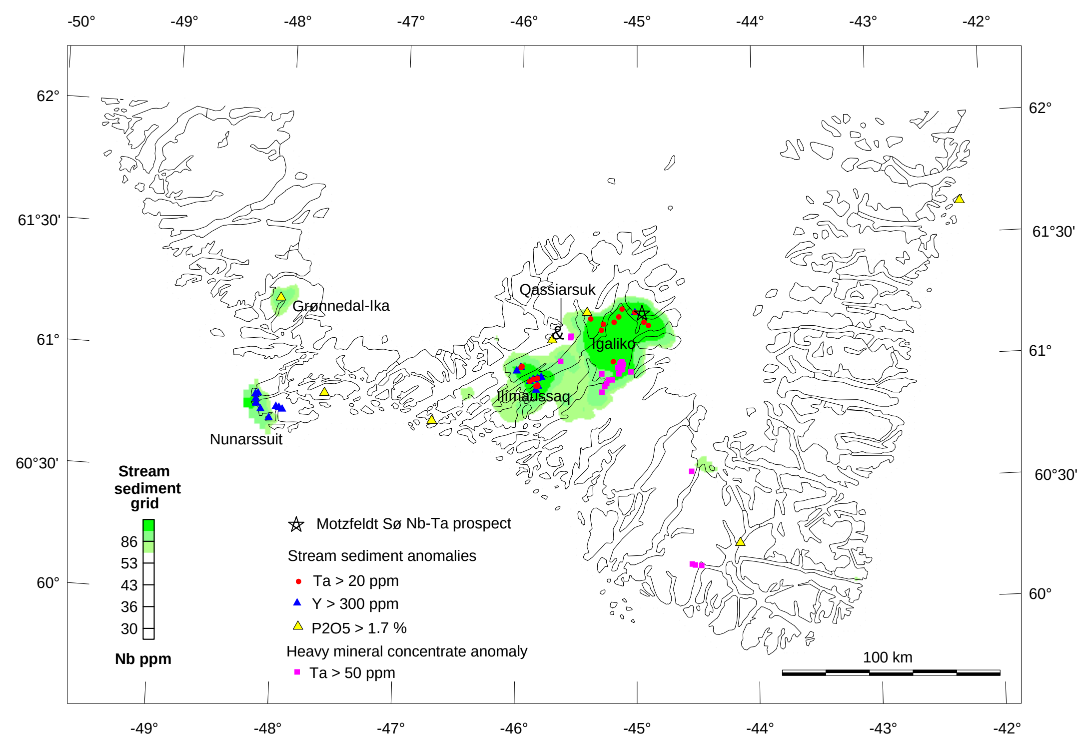

Figure 16. *Potential for deposits with niobium (Nb), tantalum (Ta), yttrium (Y) and phosphorous (P) within South Greenland as indicated by high grid values for Nb in stream sediments together with anomalies for Ta, Y and P in stream sediment (< 0.1 mm) and heavy mineral concentrates of stream sediments. Estimated mineral resources at the Motzfeldt prospect are shown in Table 2. Sample location is shown in Appendix 2.*

The stream sediment data suggest that the potential for yttrium deposits is high within the alkaline granite and augite syenite of the Nunarssuit intrusive complex (Thorning et al. 1994). Stream sediment concentrations there reach 472 ppm (10 samples have more than 300 ppm).

Lujavrites at Ilímaussaq have high concentrations of Li and F (Kunzendorf et al. 1982), but the highest concentrations of Be and Li occur in hydrothermal veins. A resource of 180 000 t of rock with 0.1 % BeO has been estimated by Engell et al. (1971).
The potential for economic concentrations of apatite has been investigated at the known occurrences of carbonatites, at Grønnedal-Ika and Qasiarsuk. At Grønnedal-Ika P2O5 concentrations of selected carbonatite profiles varied from 3.7 to 14.6 % (Morteani et al. 1986) while at Qassiarsuk carbonated lava contained around 3.5 % P2O5 (Knudsen 1985). Fig. 16 shows high P2O5 at these two localities and in addition some anomalies in the Batholith and Pelite Zones. The latter possibly reflect occurrences of phosphorite.

East of the Nanortalik peninsula there are stream sediment and heavy mineral concentrate anomalies for Ta, Th and U with an unknown source.

Copper, zinc

No particularly high concentrations of Cu are recorded in the stream sediment data (Appendix 3) and the potential for economic deposits of Cu seems small in South Greenland. Nevertheless, copper has been mined at two places in South Greenland. The copper bearing veins and breccia at the Josva deposit are too small to have a potential for present-day economic copper production. Although concentrations of stratabound chalcopyrite can be followed at kilometre scale in metavolcanic rocks adjacent to the abandoned mining site (Kalvig & Secher 1987) the mineralised horizons are thin. Production of copper was attempted, merely as a test, from veins in granite near the town of Qaqortoq in mid-19th century (Ball 1923); see also Nielsen (1973) and Schønwandt (1983), but since then the Cu mineralisation has not had any economic interest.

Geochemical data for Zn, Pb are shown in Fig. 17 together with data for Cr and V. The potential for deposits of the latter are discussed in the next section. Within the Border Zone supracrustals the potential for base metals is associated with the occurrences of massive sulphides. Several occurrences have been found during past exploration activities. In addition, airborne geophysical surveys have identified many conductors in the Border zone supracrustals, some of which are taken to indicate of massive sulphide formations (Stemp 1997). However, interpretation of conductors is difficult due to widespread graphite in the sedimentary units. A few stream sediments from Midternæs are high in Zn. A stratiform magnetite-rich conglomerate (Bondesen 1970) is outlined by a positive anomaly in the map of total magnetics, and by a V anomaly in stream sediment geochemistry.

An occurrence of massive sulphide at Iterlak, the western occurrence of the Tartoq Group on the north side of Sermiligaarsuk, was investigated by Nunaoil Ltd. (Petersen 1993). Some indications of Zn mineralisation were found at the outcrop of the Tartoq Group on the western tip of Midternæs but regarded to be without economic potential. A stream sediment

Zn anomaly (410 ppm Zn) in this area support the presence of Zn mineralisation. Concentrations of Cu in stream sediments are elevated as expected in drainages of basic lavas, but they are not sufficiently high to be considered indicative of mineralisation.

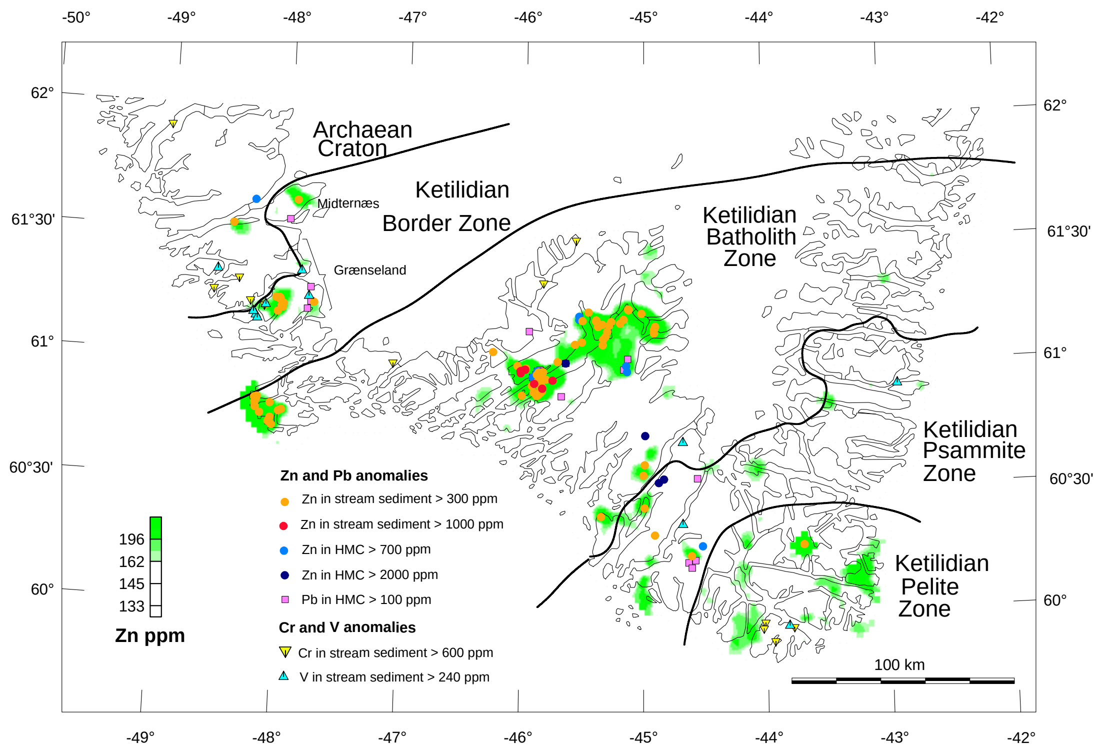

Figure 17. *Distribution of high grid values for zinc (Zn) in stream sediment together with anomalies for Zn, lead (Pb), chromium (Cr) and vanadium (V) in stream sediment (< 0.1 mm) and heavy mineral concentrates (HMC) of stream sediment. Sample location is shown in Appendix 2.*

The means of stream sediment Zn (Figs 9 and 10) and the map Fig. 17 show that Zn is very enriched in the Gardar magmas and is elevated in the rapakivi suite. This suggests that the magmas have a considerable amount of Zn in their source region or that they have been contaminated with Zn during their ascent. An estimation of the zinc resource has been made for the body of lujavrite at Kvanefjeld, the Ilímaussaq complex. A total of 225 000 t of Zn is estimated to be contained in ore grading 0.16 % Zn. (Kunzendorf et al. 1982).

Most of the high Zn values in stream sediments from the Sediment domain are derived from stream draining the rapakivi suite, but the anomalies on the Niaqornaarsuk and Nanortalik peninsulas are not within rapakivi granites and suggest mineralisation. Likewise the cluster of Zn and Pb anomalies east of Nanortalik peninsula, which is located in metasediments, attracts interest. Many sulphide-graphite-mineralised horizons have been recorded and sampled during the SUPRASYD project within the Sediment domain, but few yielded encouraging concentrations (Stendal et al. 1997); see also descriptions of mineral occurrences on the CD-ROM. The concentrations of Pb is generally low in these horizons (Swager et al. 1995). The pronounced rust zones are laterally extensive and 10 to 100 metres wide. The dominant sulphide is pyrrhotite, whereas chalcopyrite and sphalerite rarely exceed 5-10 vol. %. One occurrence of massive sulphides found in metasediments below the Stendalen gabbro has given 0.8 % Cu, 0.5 % Ni and 0.1 % Co (Birkedal 1998).

Titanium, vanadium, nickel, chromium, platinum group elements (PGE)

The suite of dioritic to ultramafic intrusions (including appinite dykes) intruded into the Batholith and Sediment domains may have a potential for metals associated with magmatic concentrations of sulphides and oxides. One such occurrence has been found in the layered Stendalen gabbro (I in Table 2 and Fig. 13). Exploration of the many similar gabbro intrusions has been very limited. It is possible that the magnetic anomalies in that area reflect the distribution of partly hidden bodies of a diorite-gabbro association.

The outcrops of ultramafic, hornblenditic, rocks at Nanortalik peninsula are small and PGE mineralisation recorded so far has not been of economic interest. There is a possibility that the weak elongated magnetic high following the west coast of Nanortalik peninsula reflects a mafic-ultramafic magmatic body at depth, much larger than the known small outcrops.

Also the norite intrusions of the rapakivi suite are potential hosts of Ni-rich sulphide mineralisation and chromite. Stream sediment anomalies for Cr are noted near an intrusion of norite on the southernmost island of South Greenland (Fig. 17).

Diamonds

A number of thin kimberlite sheets are known from Pyramidefjeld within the Archaean Craton and from Midternæs in the Ketilidian Border Zone (Andrews & Emeleus 1971; Larsen 1991). The localities are shown in Fig. 13. The kimberlites are Mesozoic (Bridgwater 1970; Larsen & Rex 1992) and have been reported to contain microdiamonds (Geisler 1972). Kimberlite indicator minerals have been found in many stream sediment samples from in the Archaean domain outside the known kimberlite occurrences (Steenfelt et al. 1999). Stemp (1997) draws the attention to circular magnetic anomalies “pipe-type features” in Grænseland, which might reflect kimberlite diatremes. Further north in West Greenland a few kimberlite dykes have been found to yield micro- as well as macrodiamonds (Bureau of Minerals and Petroleum 1999).

Summary

In summary, the mineral resource potential of South Greenland is primarily associated with the following settings:

1. Structurally controlled gold mineralisation in several settings in the Ketilidian Batholith, Psammite and Pelite zones.
2. Gold mineralisation in the Archaean Tartoq greenstone units.

3. REE, U and speciality metal mineralisation and deposits of industrial minerals in alkaline complexes of the Gardar province.
4. Magmatic accumulations of base metal and platinum metal sulphides and oxides in Ketilidian gabbros and ultramafics.

Comments on geological and mineral deposit modelling

The current geological model for the Ketilidian orogen (Chadwick & Garde 1996; Garde et al. 1998a) interprets the Julianehaab Batholith as the root of a volcanic arc and the Sediment domain as fore-arc deposits of material largely derived from erosion of the Batholith. The stream sediment geochemistry supports the calc-alkaline character of the Batholith domain and emphasises the predominance of granitoid rocks with high Sr and high Sr/Rb ratio. However, an implication of this model is that the metasediments of the Sediment domain should be geochemically similar to the Batholith, and this appears not to be the case.

The maps of Figs 2, 6, 7, 11 and 12 show examples of the chemical differences between the two lithotectonic units. It seems obvious that the abundance of As in the Sediment domain cannot be supplied during erosion of the Batholith granitoids, which are devoid of As (Fig. 11). It is also difficult to explain how the Sediment domain becomes so enriched in lithophile elements, Th in particular (see also Fig. 12), if the Batholith is the only source for the sediments. A volcanic arc environment has low concentrations of U and Th and cannot be the source of high Th in the metasediments or the uranium mineralisation in both the Batholith and the Sediment domains.

A detailed discussion of the origin of the chemical characteristics of the Sediment domain is beyond the scope of this report. However it is appropriate to point out that, any alternative geological model, which may be proposed to explain the chemical relations outlined here, has important implications for mineral deposit modelling. There seems to be two possibilities for the supply of the elements that are enriched in the metasediments and rapakivi suite relative to the Batholith. (1) they have been supplied by erosion of a continent, which has since disappeared; (2) they have been transported from an unexposed sedimentary package via rising magmas and associated fluids. Although the many granitic bodies in the Sediment domain with slightly younger ages that the Batholith granites are interpreted as products of local remelting of metasediments, some may, in fact, represent melting of a deeper or at least a different source, unrelated to the Batholith. Lead isotope data indicate that hydrothermal gold-arsenic mineralisation formed contemporaneously with late phases of Ketilidian magmatism (c. 1790 Ma) had a contribution of lead from a c. 2000 Ma old source (Stendal & Frei in press).

The magmas of the rapakivi suite are interpreted to have been generated by melting of a largely juvenile supracrustal source (Brown et al. 1992). The chemistry of the rapakivi suite (Fig. 7) excludes that the source could be Batholith-like sediments only, and rather suggests that the source contains both basic metavolcanic rocks – to account for elevated Nb and high Cr, Sc and Zn, – and continentally derived metasediments or felsic volcanic rocks – to account for high Zr, Hf, Th, U. The source or mixture of sources must also have been enriched in As, Sb and Au, and therefore resembles a back-arc succession like that suggested for the Ketilidian Border zone. Melting of continentally derived sediments would give magmas rich in lithophile elements.

The existence of back-arc supracrustals with syn-sedimentary mineralisation below or perhaps intercalated with metasediments of batholith provenance provide a potential for volcanogenic massive sulphides with Zn and Pb concentrations. The rise of felsic magmas generated by melting of buried sedimentary or acid volcanic rock assemblages provides the scenario and possibility for mobilisation of U, Th, As, Sb, and Au.

Conclusion

The compilation of the geochemical, geophysical and mineral resource-related data for South Greenland has provided a quantitative base which may be consulted in the debate of a range of issues varying from crustal composition, plate-tectonic modelling and petrogenesis of rock assemblages to mineral resource evaluation and environmental management.

The analysis of the compiled data in conjunction with results of recent fieldwork has resulted in the recognition that South Greenland is particularly enriched in As, Au, U, Hf, Zr and REE compared to average upper crust.

Both the Ketilidian orogen and the Gardar province feature a diversity of magmas intruding tectonically active terrain over a long period of time, which has created favourable environments for the formation of syn- and epigenetic mineralisation. Gold is the most conspicuous commodity of known mineralisation of this type.

The highly specialised magmas of the Gardar province contain concentrations of a range of rare elements, for which a future demand may be expected.

The chemical and magnetic properties of the southernmost part of the Ketilidian orogen suggest that the composition of the crust in that region is more complex than indicated by the current plate-tectonic model.

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Appendix 1: Content of the South Greenland CD-ROM

Digital data and information compiled during the evaluation of the South Greenland mineral potential is published on a CD-ROM together with a GEUS report (Schjøth *et al.* 2000).

The digital data have been compiled as an ArcView project file (*South Greenland.apr),* using ArcView version 3.2. Design and testing has been carried out in Windows NT 4.0 and Windows 98. Many different themes have been compiled into sixteen views, see below. Several views contain images in geo-referenced TIF-format based on gridded data of *e. g.* geophysical or geochemical parameters. Included are also PDF-files with summary descriptions of regional geology and descriptions of mineral occurrences with detailed maps and photos. The PDF-files can be reached by use of hot-links from certain views in the South Greenland Project File. Finally, a compilation of 206 non-confidential mineral assessment reports from the mining industry and a South Greenland General Bibliography is also available on the CD-ROM.

View 1.1 Topographic Base Map

Base map for South Greenland. Layers of names, geographical grid, and selected geographical features are available.

View 1.2 Digital Elevation Model

Approximate digital elevation model calculated from positional data from aeromagnetic survey aircraft. Included as an image in geo-referenced TIF format.

View 2.1 Mosaic of Landsat TM scenes

A composite, natural look satellite image based on seven Landsat Tm scenes.

View 3.1 Geological map (scale 1:500 000)

A new, digital geological map. The map is based on the 1:500 000 geological map (Allaart 1975) with modifications and a new legend reflecting the results of geological investigations during the SUPRASYD project.

View 4.1 Airborne magnetics

Total field and first vertical derivative magnetic anomaly maps based on several different airborne surveys. Geo-referenced TIF-files.

View 4.2 Airborne electromagnetics

Anomaly maps based on airborne electromagnetic surveys of small selected areas in the north-western part of the region. Geo-referenced TIF-files.

View 4.3 Airborne radiometrics

Radiometric anomaly maps based on airborne surveys. Geo-referenced TIF-files.

View 4.4 Gravity

Free-air and Bouguer gravity anomaly maps based on data from a number of sources compiled in a database by Kort- og Matrikelstyrelsen (KMS).

View 5.1 Sample location

Sample location for stream sediment (fine fraction), heavy mineral concentrates of stream sediments and rock samples.

View 6.1 Stream sediments

Gridded anomaly maps for 42 major and trace elements. Geo-referenced TIF-files.

View 6.2 Heavy mineral concentrates of stream sediments

Positions and analytical results as tables and coloured dot plots for 16 trace elements.

View 6.3 Rock analyses

Positions, sample descriptions and chemical analyses of c. 3400 rock samples.

View 7.1 Mineral occurrences

Map of 107 mineral occurrence sites with hot-links to descriptions in PDF-files.

View 8.1 Mineral exploration licenses 1992 – 2000

Maps of position and ownership of mineral exploration licences for each of the years 1992 – 2000.

View 9.1 Field maps and other maps

Coverage and a few basic data on field maps from GEUS' archive and published topographic and geological maps from the region.

View 10.1 Mining industry mineral assessment reports and a general bibliography

Compiled list of 204 publicly available mineral assessment reports and a geo-referenced bibliography of more than 2000 mainly geoscience titles related to South Greenland.

Appendix 2: Sample location and place names

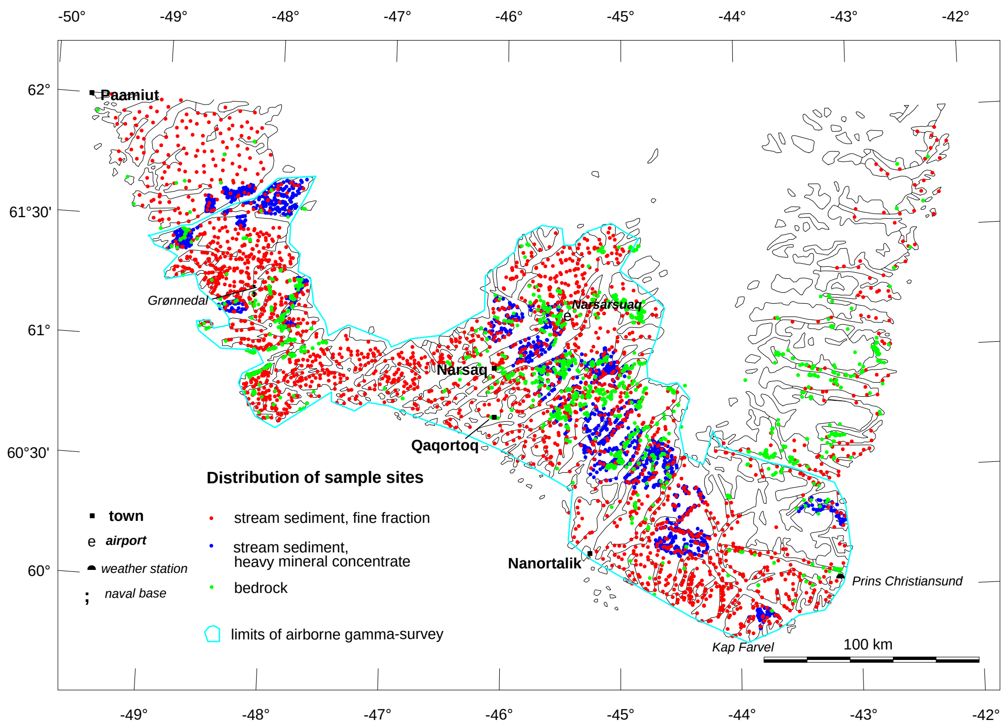

Figure Fejl! Ukendt argument for parameter.. *Location of analysed samples used in the production of the CD-ROM. Aeromagnetic and gravity data cover the entire region. The limits of the aero-radiometric survey shows the part covered by the SYDURAN uranium exploration project. The sample density for the stream sediment (fine fraction, red dots) varies from average 1 sample per 6 km^2 within the SYDURAN area to 1 per 20 km^2 in the north-west and to very irregular, low density sampling along the east coast. The samples of heavy mineral concentrate (blue dots) were collected by Nunaoil A/S at high density over selected areas. Most of the rock samples (green dots) were collected during the SYDURAN and SUPRASYD projects. The rock samples have been collected and analysed for various purposes and are not aimed to form the basis for a regional rock survey.*

Appendix 3: Statistical parameters for stream sediment data from South Greenland

	no. of samples	ana-lysis[1]	Grid values* grid min	grid max	mean	std dev	median	Sample values* mean	max	min	median
SiO_2	1346	XRF	42.23	72.73	**62.62**	3.89	62.93	62.50	74.28	37.19	63.14
TiO_2	1346	XRF	0.29	4.29	**1.11**	0.43	1.02	1.13	5.18	0.18	0.98
Al_2O_3	1346	XRF	11.17	20.27	**15.21**	0.92	15.17	15.23	24.22	9.05	15.17
Fe_2O_3	1346	XRF	2.44	28.94	**7.50**	2.42	7.10	7.63	34.60	1.58	6.90
MnO	1346	XRF	-0.95	9.03	**0.15**	0.33	0.11	0.14	9.22	0.02	0.11
MgO	1346	XRF	0.61	13.84	**2.53**	1.16	2.23	2.55	14.75	0.30	2.10
CaO	1346	XRF	1.11	11.85	**3.66**	0.91	3.61	3.63	15.98	0.58	3.46
Na_2O	1346	XRF	1.66	6.77	**3.43**	0.49	3.43	3.46	6.89	0.00	3.49
K_2O	1346	XRF	0.71	5.78	**2.63**	0.77	2.65	2.60	5.79	0.59	2.63
P_2O_5	1346	XRF	-0.02	2.00	**0.42**	0.21	0.38	0.42	2.90	0.05	0.36
As	2478	INA	-9	323	**10.6**	21.2	3.84	9.249	1100	0	3
Au	2478	INA	-29.6	331	**3.9**	12.6	1.28	3.7312	850	0	0
Ba	2443	I+X	195	1631	**582**	170	551	591.81	5223	107	557
Br	2478	INA	-3.5	439	**55.8**	47	43.3	58.49	660	0	39
Ce	2478	INA	19.8	1269	**165**	115	138	185.15	2071	16	139
Co	2478	INA	1	100	**21.2**	10.4	18.5	21.747	147	0	17
Cr	2443	I+X	-12.6	1558	**77.8**	71.5	58.9	72.28	4346	0	45
Cs	2478	INA	-0.26	13.8	**2.46**	2.11	1.95	2.4673	19	0	2
Cu	2540	XRF	5.5	170	**31.5**	17.4	27.6	31.49	220	3	25
Eu	2478	INA	0.56	21.7	**2.7**	1.4	2.31	2.958	77.3	0	2.3
Ga	2539	XRF	5.92	66.1	**20.1**	6	19.2	20	97	0	18
Hf	2478	INA	1.08	335	**22.6**	18.9	17.9	22.821	480	3	16
La	2478	INA	10	794	**97.3**	74.2	78.1	109.82	1432	8.1	78
Lu	2478	INA	0.14	4.31	**0.59**	0.38	0.5	0.6204	6.35	0.05	0.47
Mo	2314	INA	-2	41.7	**1.59**	2.53	0.75	1.5085	81	0	0
Nb	2539	XRF	-13.5	636	**35.4**	54.1	21.9	42.699	902	0	24
Nd	2478	INA	10	421	**68.5**	43.4	58	77.025	1000	0	57
Ni	2539	XRF	6.7	283	**43.8**	26.1	36.4	45.175	511	2	34
Rb	2539	XRF	19	257	**81.4**	32.6	75.5	84.916	329	15	77
Sb	2478	INA	-0.4	6.3	**0.41**	0.41	0.32	0.1295	14	0	0
Sc	2478	INA	7.7	45.8	**17.2**	4.7	16.3	17.296	52	4.4	15.5
Sm	2478	INA	0	80	**12.1**	7.42	10.25	13.459	171	2.5	10.4
Sr	2539	XRF	86	834	**330**	118	307	325.41	1224	49	301
Ta	2478	INA	-0.58	33.6	**1.31**	2.78	0.51	1.615	49	0	0
Th	2478	INA	1.38	149.8	**15.8**	12.1	12.1	16.282	270	1.1	11
U	2356	DNC	-12.4	609	**30.7**	37.7	19.9	32.733	1400	0	14.8
V	1353	XRF	24.4	310	**90.8**	27.2	86.1	93.349	513	0	84
W	2478	INA	-2.5	44	**0.95**	2.4	0.08	0.7421	64	0	0
Y	2539	XRF	9.2	402	**47**	32.2	39.2	51.703	542	8	39
Yb	2478	INA	1.5	52.4	**5.19**	3.7	4.32	5.4348	66	1.2	4
Zn	2539	XRF	19.5	1096	**111**	62.9	101	123.53	1585	16	103
Zr	2539	XRF	-269	7989	**610**	560	453	647.53	9241	90	457

*Major element oxides calculated as volatile-free percentages. Trace element values in ppm except Au, which is ppb.

[1]XRF: X-ray fluorescence spectrometry, INA: instrumental neutron activation analysis, I+X: combined XRF and INA results, DNC+I: combined delayed neutron counting and INA results.