DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2012/65

South-East Greenland, 62° - 67°N, SEGMENT workshop, February 2012

Abstract volume

Bo Møller Stensgaard

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DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

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Content

‘South-East Greenland, 62°N – 67°N, SEGMENT Workshop 2012’

The **South-East Greenland, 62°N – 67°N, SEGMENT Workshop 2012** was held at GEUS, Copenhagen, February 27-29, 2012. The programme and the abstracts of the workshop is presented below.

The workshop was organised as part of the performance contract with the Ministry (activity 4.1 and 4.2) and the project co-operation agreement between GEUS and the Bureau of Minerals and Petroleum about the project SEGMENT: **S**outh-**E**ast **G**reenland **M**apping and Mineral **EN**dowment **T**ask.

The workshop provided the possibility to discuss and report results and observations from fieldwork that was carried out in 2011; and also provided the possibility to discuss future research in the region, to plan new work in 2012 and to push the knowledge about the geology in South-East one step forward. The workshop was informal and was intended to have focus on constructive and fruitful discussions and exchange of ideas. The 2012 workshop focuses mainly on the area between 62°– 64°30’N, covering the North Atlantic craton in South-East Greenland.

The first two days of the workshop was devoted to presentations, whereas the last day was devoted to meetings and discussions in different working groups/topics that had been established for the work in South-East Greenland.

Participants at the workshop are from the following institutions:

- Geological Survey of Denmark and Greenland (GEUS)
- Bureau of Minerals and Petroleum, Greenland (BMP)
- Department of Geoscience, University of Aarhus
- Institute for Geography and Geology, University of Copenhagen
- Geological Museum, the Natural History Museum of Denmark
- University of Stellenbosch, South Africa
- Centre for Exploration Targeting, School of Earth and Environment, University of Western Australia
- Westfälische Wilhelms-Universität Münster, Germany
- Greenland Institute of Natural Resources, Greenland

Organiser of the workshop:
Bo Møller Stensgaard, bmst@geus.dk

Workshop programme

Monday 27 February:
Chaired/facilitated by Jochen Kolb and Bo Møller Stensgaard

08.30 – 09.00	Registration
09.00 – 09.05	Welcome – Day 1. Karen Hanghøj and Bo Møller Stensgaard (GEUS)
09.05 – 09.35	Tectonometamorphic evolution in the North Atlantic Craton of South-East Greenland. By Kolb *et al*.
09.35 – 10.00	Update from the age dating program in South-East Greenland. By Thrane.
10.00 – 10.20	*Coffee break*
10.20 – 10.45	ASTER multispectral satellite imagery – mapping the lithological features in South East Greenland. By Tukianien & Sørensen.
10.45 – 11.10	Observations of Mesoarchean melt formation and migration in Langenæs and Helge Halvø, southeast Greenland. By Reno *et al.*
11.10 – 11.35	Field observations and geochemical characteristics of "supracrustal rocks" at Helges Halvø and Langenæs. By Næraa *et al.*
11.35 – 12.00	The geochemistry of mafic and ultramafic basement rocks in the Skjoldungen area SE Greenland. By Ulrich *et al.*
12.00 – 13.00	*Lunch break*
13.00 – 13.25	Characterisation of the nickel sulphide mineralisation between Graah Fjord and Bernstorff Isfjord, South-East Greenland. By Owen.
13.25 – 13.50	Adakitic nature of the lower crust in southeastern Greenland. By Bagas.
13.50 – 14.15	Intrusions of the Archaean Skjoldungen Alkaline Province, South East Greenland: Observations from the 2011 field season and preliminary geochemical results. By Kokfelt & Klausen.
14.15 – 14.40	Some remarks on the country rocks for the Skjoldungen alkaline intrusions and their comparison. By Berger *et al.*

14.40 – 15.05	Archaean subduction in Greenland shown by diamonds from kimberlite (West Greenland) and the oldest carbonatite in the world (South-East Greenland). By Wiewióra**.**
15.05 – 15.20	*Coffee break*
15.20 – 15.45	Upper crustal exhumation rates of the Ruinnæsset intrusion: Indications for the transition from Archaean mountain belt to a cratonic stage. By Berger *et al.*
15.45 – 16.10	Kimberlite emplacement patterns in Canada and West Greenland: expectations for the East. By Tappe.
16.10 – 16.35	Age dating program of mafic dykes in South-East Greenland: introduction to project. By Kokfelt on behalf of Nilsson and Söderlund
16.35 – 17.00	Polar bear studies in East Greenland. By Born *et al.*
17.00 – 17.10	Day 1 - Closing remarks.

Tuesday 28 February:
Chaired/facilitated by Troels F.D. Nielsen & Bo M. Stensgaard

09.00 – 09.05	Welcome – Day 2. By Bo M. Stensgaard
09.05 – 09.30	Reconnaissance of the economic potential of the Timmiarmiut region – field observations and results from the 2011 SEG field season. By Tukianien & Sørensen.
09.30 – 09.45	Mineralising systems in SE-Greenland: Methods of investigating mineralization processes and formation conditions. By Katerinopoulou.
09.45 – 09.55	Post-Proterozoic tectonics in the Skjoldungen area. By Post-Archaean Tectonics Working Group (Guarnieri *et al.*)
09.55 – 10.05	*Coffee break*
10.05 – 10.30	Deformation in South-East Greenland. By Bagas *et al.*
10.30 – 10.55	Ages and kinematics of brittle deformation along the South East Greenland margin (Skjoldungen area). By Guarnieri & Berger.
10.55 – 11.20	Deciphering the burial, uplift and exhumation history of South-East Greenland using geological data, landscape analysis and palaeothermal data. Fixpoints and unknowns between 62 and 71°N. By Japsen *et al.*
11.20 – 11.45	Mineral systems in the North Atlantic Craton of South-East Greenland. By Kolb & Stensgaard.
11.45 – 12.10	Review and interpretations of geophysical from Southeast Greenland. By Rasmussen & Thorning.
12.35 – 13.30	*Lunch break*

13.30 – 15.00 Plenum discussion:

- What should we call the rocks in South-East Greenland?
- How should a new GIS-based 1:500 000 scale map look for South-East Greenland? Which data should it contain?
- Mineralising systems in South-East Greenland: what is there and what is not? And the why's? – What have we overlooked?
- What do we presently know about the Post-Archaean evolution in South-East Greenland? – Palaeoproterozoic, Palaeozoic and Palaeogene events affecting 62° to 64°30'N – and the implications/effects of these events.
- "Supracrustal rocks" – to be or not to be? Different or similar successions from north to South?
- Intrusions of the SAP – the main scientific questions and how to answer them best!?
- Timmiarmiut intrusions – what do we know and what remains?
- *More…*

Wednesday 29 February:

09.00 – 09.15 3rd Day Welcome – introduction to individual meetings. By Stensgaard.

09.00 – 13.00 Individual meetings within the different work groups/topics that have been defined for the work in South-East Greenland.

Key questions for the work groups to be answered:

- What is the status for the work topic?
- Are the defined questions for the work topic still the same, or do they need to be reformulated/changed?
- What are the next steps? Who is taking care of what?
- Which critical information/data are we missing?
- What are our plans for publishing/reporting of the results?
- What are our plans for fieldwork in 2012?

13.00 – 14.00 Working lunch in the Auditorium 'Theodor Sorgenfrei' – with reports from the various work groups / continued plenum discussion

14.00 – 14.30 Plans and setup of fieldwork in 2012. By Stensgaard

14.30 – 14.45 End of workshop – closing remarks.

Maps of South-East Greenland

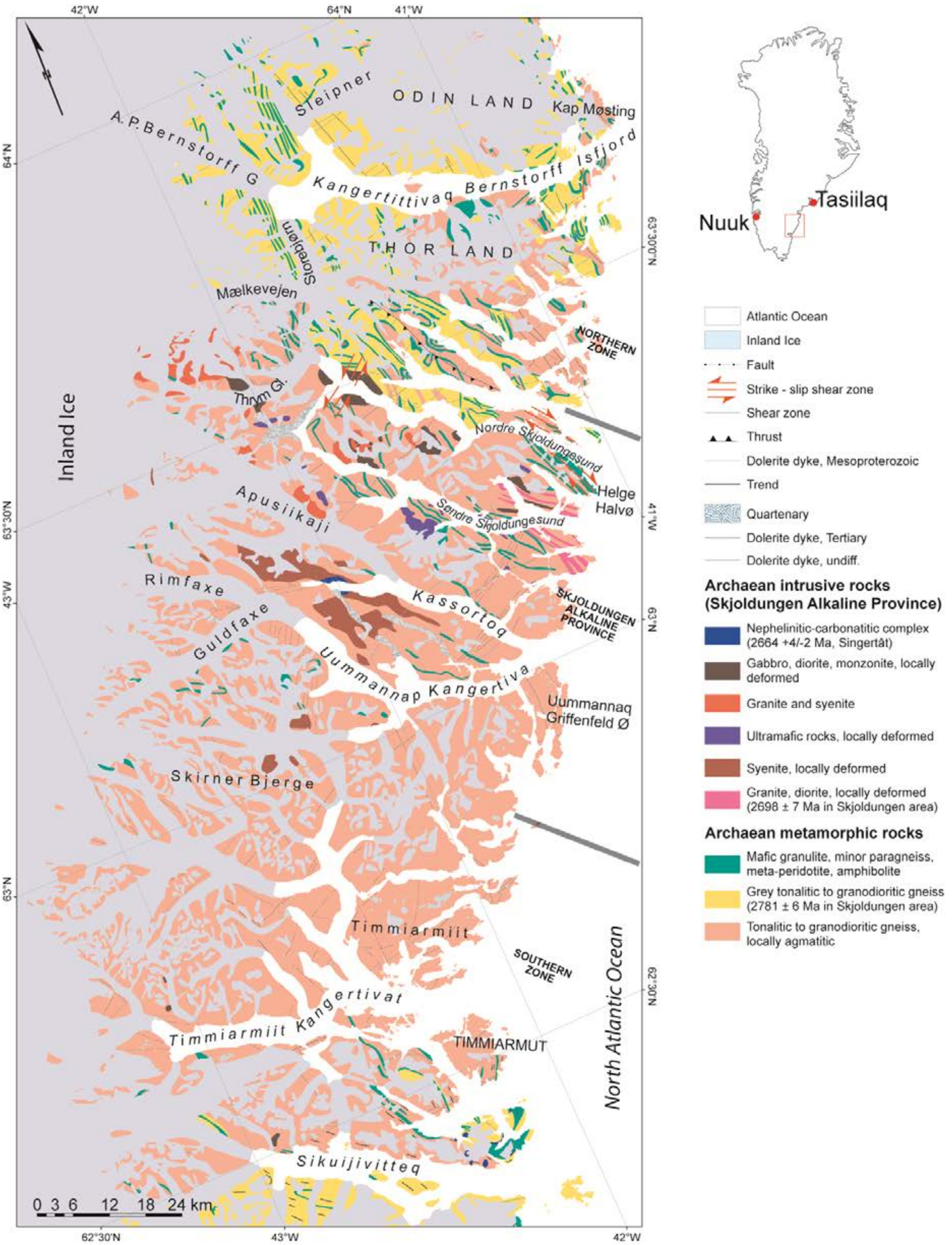

Figure 1. *Simplified geological map of the Skjoldungen focus area for the 2011 field work. The northernmost part of the region, the Gyldenløve Fjord area, that also was covered by the fieldwork is not included in the map (only limited work was carried out in this area).*

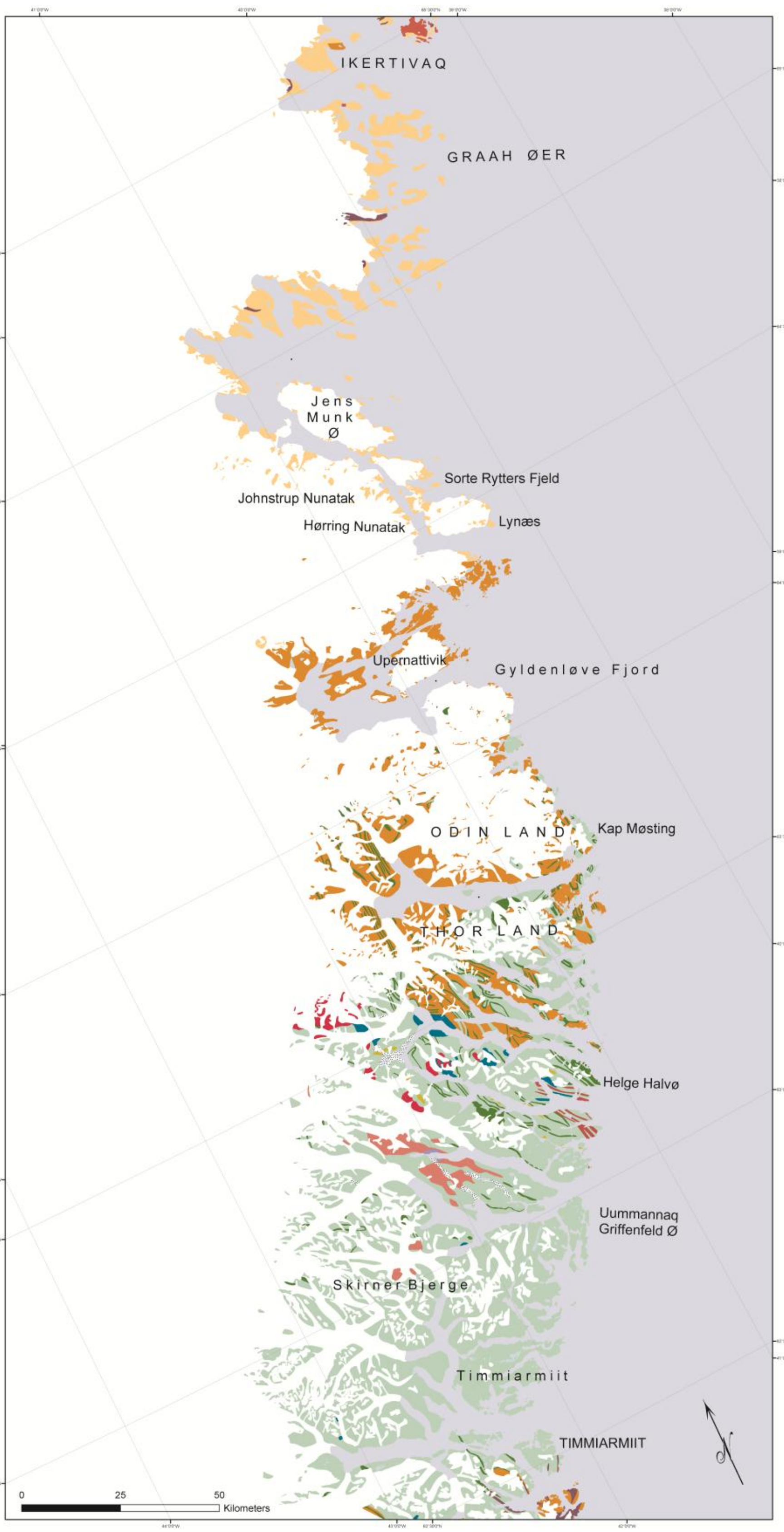

Figure 2. *Simplified geology of the southern part of the region covered by the SEGMENT 2011–2014 project.*

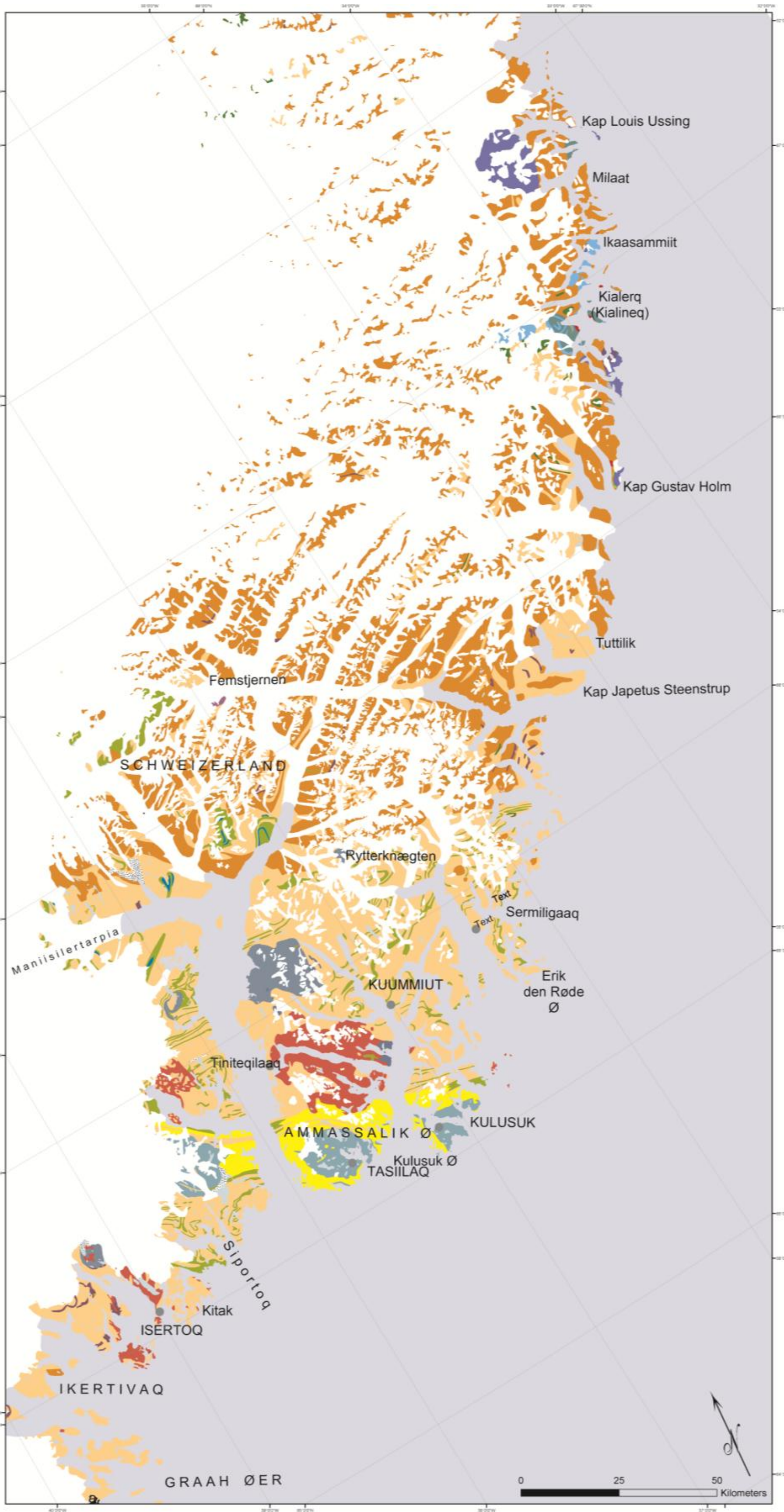

Figure 3. *Simplified geology of the northern part of the region covered by the SEGMENT 2011–2014 project.*

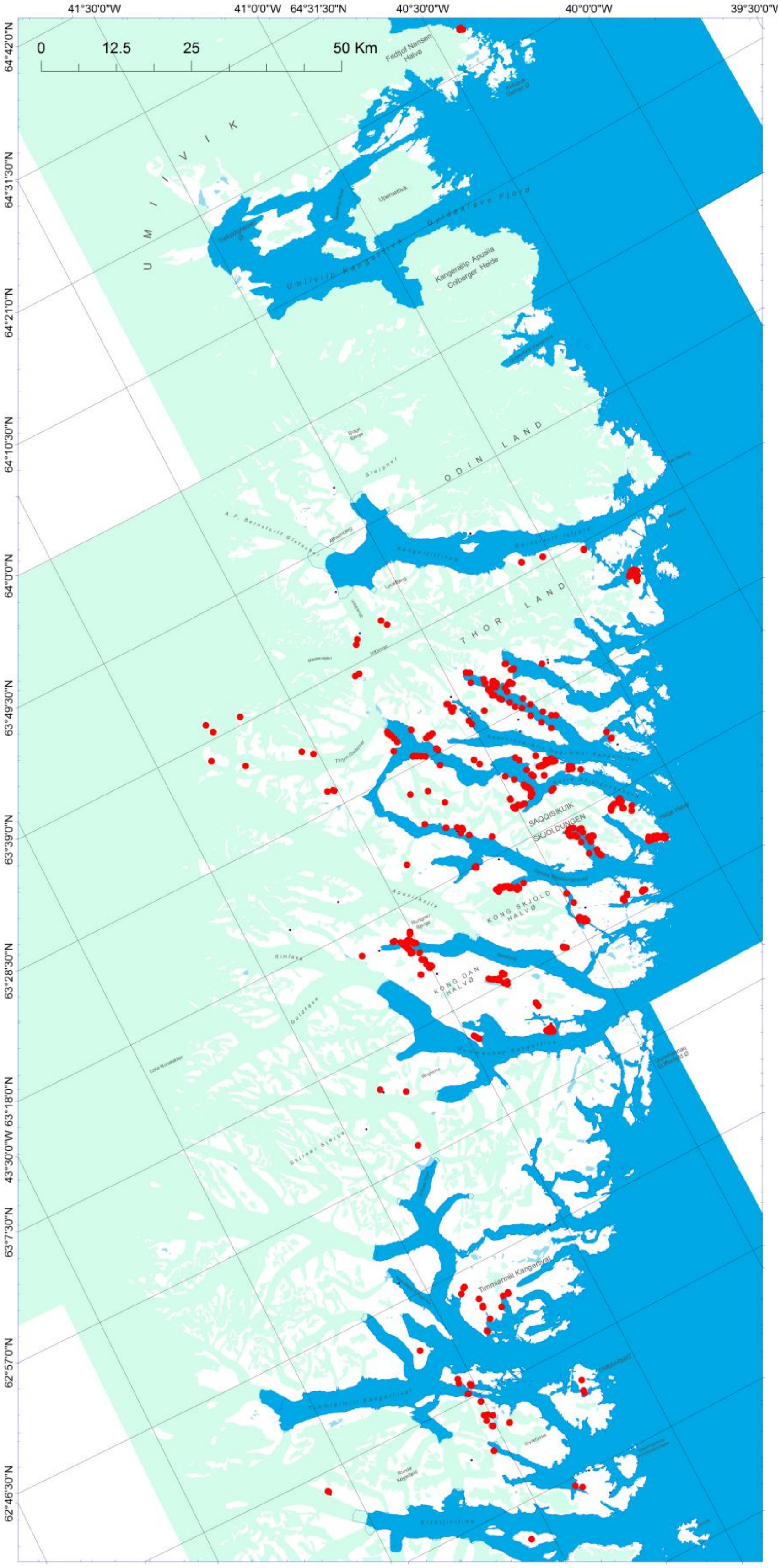

Figure 4. *Map showing the localities (red circles) visited during the fieldwork in 2011.*

List of abstracts

Lower crustal Archaean rocks in South-East Greenland

L. Bagas[1], T. Næraa[2] & B.L. Reno[2]

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Gneisses representing major multiphase plutonic batholiths (or complexes) that include felsic, intermediate, mafic, and ultramafic rocks characterize the remote and sparsely populated south-eastern part of Greenland. These rocks are located in a high-alpine terrain reaching altitudes of around 3500 m above sea level. The CET has commenced a study of this remote and pristine region in collaboration with the Geological Survey of Denmark and Greenland.

Many plutonic complexes are located in throughout the world, including Cenozoic to Cretaceous complexes (e.g. Tepper et al., 1993). Archaean granitic complexes older than 2.7 Ga throughout the world consist of tonalite to granodiorite plutons (TTGs) that are interpreted to originate from the partial melting of mafic lower crust, such as in the Palaeo- to Mesoachaean northern Pilbara Craton in Western Australia where metamorphism is generally at the greenschist facies or lower (e.g. Smithies, 2000). In contrast, southeastern Greenland is unique in that it exposes contemporarily aged granulite-facies gneisses and migmatites, and dissected layered ultramafic to intermediate orthogneisses representative of the Archaean lower crust (Fig. 1).

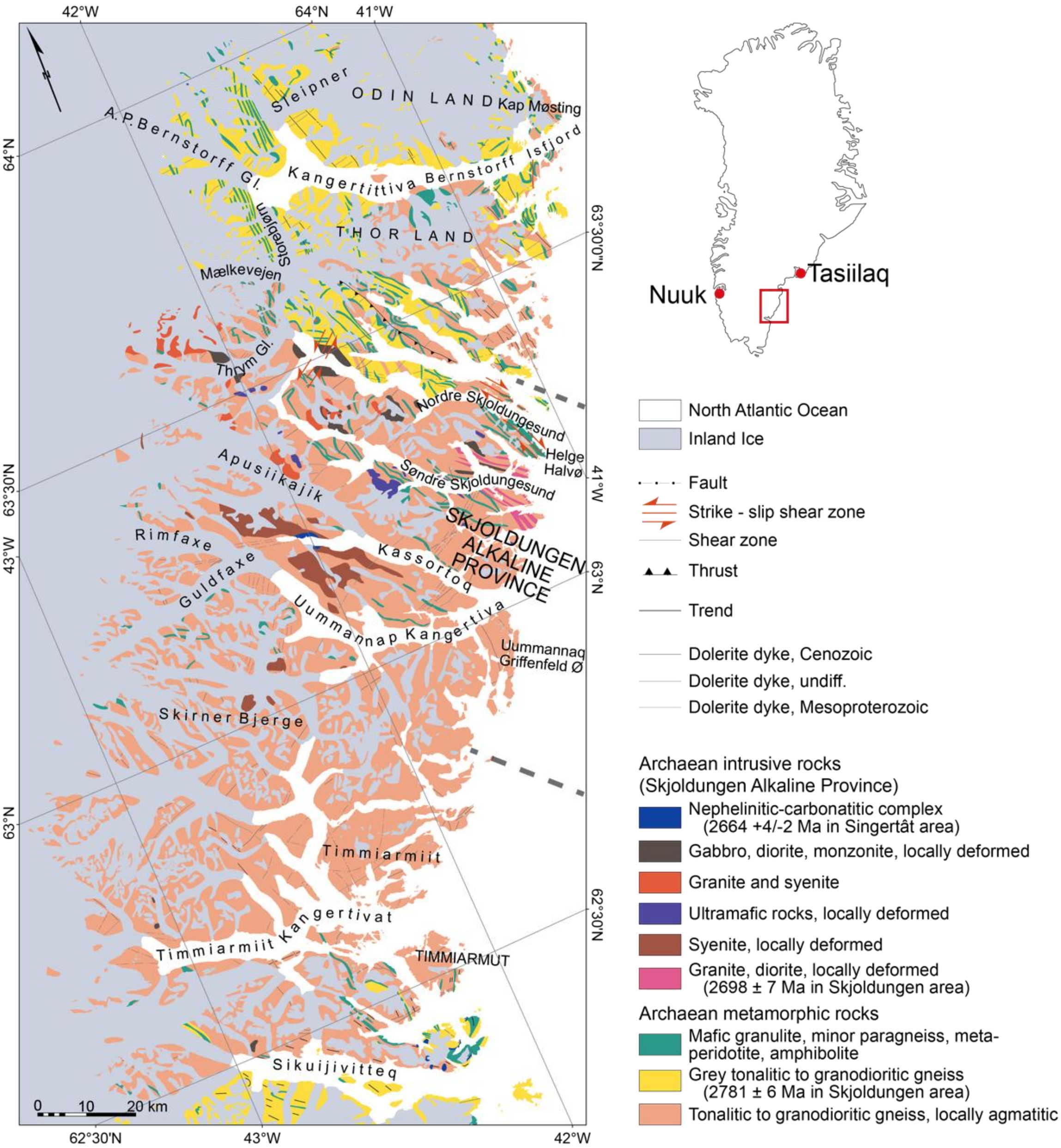

Figure. 1. *Simplified geology of southeastern Greenland (modified after Kolb et al., in press).*

Collisional tectonics

Igneous rocks are extensively studied because they present petrogenetic windows into the evolution of the deeper crust, because they have distinctive geochemical characteristics indicative of their tectonic setting during their formation (e.g. Pearce et al., 1984). Numerous studies have temporally and spatially associated magmatism to convergent margins, and syn- to post-collision extensional settings (e.g. Bonin, 2007). Under the high-pressure (~10 kbar) and temperature (800° - 1000° C) conditions present during collisional events, many mafic rocks will develop a garnet and/or Fe-rich pyroxene dominated mineral assemblage that is denser than the underlying mantle (Jull and Kelemen, 2001). The result is a gravitationally unstable lower-crust that delaminates and sinks into the mantle resulting in elevated temperatures at the base of the crust where magmatic arc develop (Kay and Kay, 1993).

General classification of gneisses

Southeastern Greenland is characterised by granulite-facies felsic, mafic and ultramafic gneisses that are commonly migmatitic indicative of partial melting. Using the chemical classifications of Miyashiro (1974), at least two gneissic suites are present in the region, one is tholeiitic and the other is calc-alkaline (Fig. 2). Tholeiitic to calc-alkaline arc magmas are commonly interpreted to be derived from partial melting of hydrated peridotite in the asthenospheric mantle wedge above a dehydrating subducting slab (e.g. Gaetani and Grove, 2003).

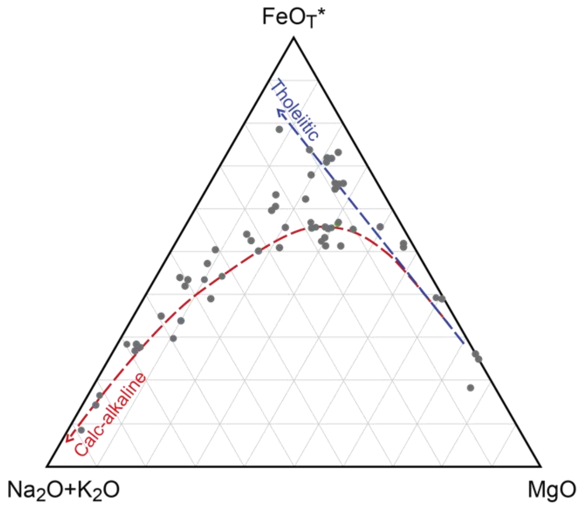

Figure 2. *AFM diagram of Miyashiro (1974) indicating that there are at least two suites of mafic gneisses in the study area.*

Harker diagrams for the gneisses in the region reveal the following trends evident with increasing SiO_2 (Fig. 3), and suggest the presence of strong geochemical associations:

- Cao, TiO_2 and K_2O decrease proportionally, although K_2O appears to define two separate trends.
- Fe_2O_{3T}, MnO and CaO decrease proportionally.
- Al_2O_3 and Na_2O exponentially increase.
- MgO and Mg# exponentially decreases.

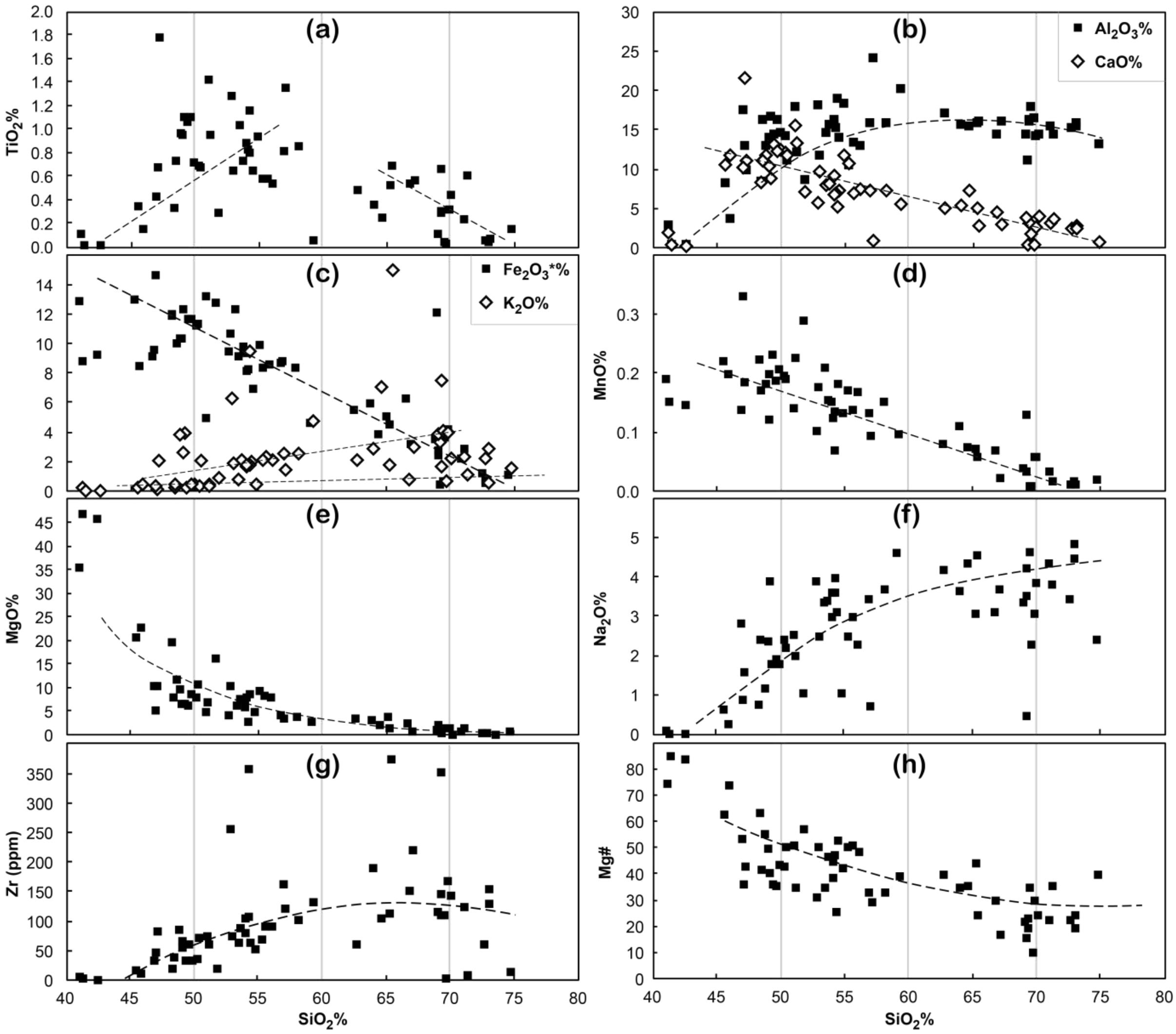

Figure 3. *Harker variation diagrams and Zr and Mg# vs SiO_2 plots (a-h) for samples of gneiss from southeastern Greenland (plots are combined where scales are the same).*

On plots versus MgO, trends are evident for at least SiO_2 (see Fig. 3), Al_2O_3, TiO_2, K_2O, CaO, Ni, Cr, and Fe_2O_{3T}, whereas there are no obvious trends for La and Rb (Fig. 4). The higher MgO samples corresponding to the more mafic gneisses theoretically represent the more primitive magmas, and the lower MgO samples being the result of fractionation where mineral phases enter a melt, or partial melting where minerals are left behind (Fig. 4).

Using Ce as an index of fractionation (Fig. 5), there are curved trends with the incompatible and compatible elements Th and Nb, and collinear trends with Yb, Zr, La/Sm_n and Gd/ Yb_n, whereas the Ce versus Yb, La/Sm_n and Gd/ Yb_n plots appears to define two linear relationships.

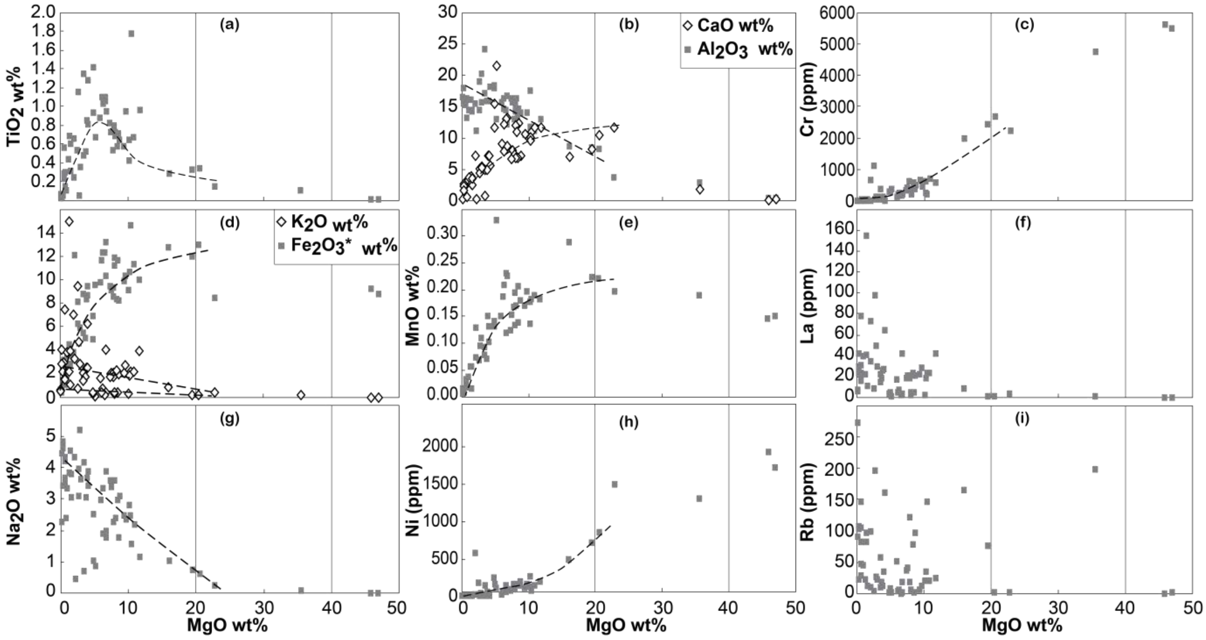

Figure 4. *Selected elements versus MgO plots illustrating possible fractionation trends of samples collected in southeastern Greenland (plots are combined where scales are the same).*

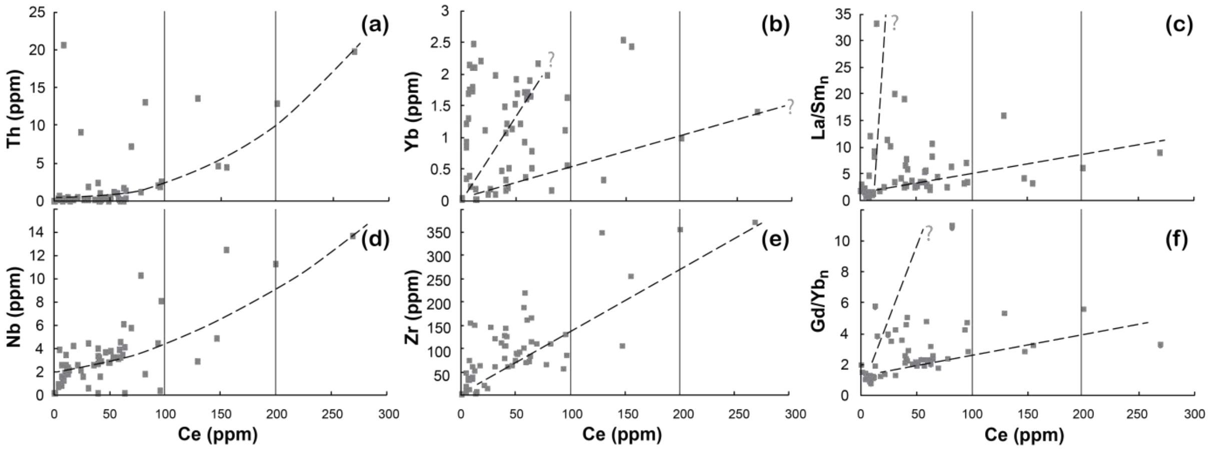

Figure 5. *Plots of Ce versus selected elements and ratios for rocks in southeastern Greenland.*

Fractionation or partial melting?

Some trace element associations, such as the positive correlation between Ni and MgO in Figure 4(h), might be fractionation related, although many of the incompatible elements do not show the negative correlations predicted by crystal fractionation. La and Sr do not show major correlations with MgO, although individual sections of the plots could be interpreted as positive or negative correlations, or are relatively constant over small ranges of MgO (Fig. 4f,i). These relationships suggest that there are regional variations in the source and degree of melting (rather than just fractionation).

The La/Yb ratios are high and variable, and increase with both La and Yb abundances (Fig. 6). Low HREE abundances reflect the presence of garnet in the source region at high temperatures and pressures (as discussed above), and this is illustrated in the La/Yb versus La plot of Fig. 6(b). The samples appear to plot in distinct parts of this diagram defining two partial melting (adakitic-like and tholeiitic) trends and a possible fractionation trend. Furthermore, the steep (adakitic-like) trend in which La/ Yb varies from 10 to ~180 (left side of the graph), can only be produced in the presence of residual or metamorphic garnet. Subsequent fractionation increases La abundance whereas La/Yb remains constant resulting in a subhorizontal fractionation trend.

The shallower tholeiitic trend in Fig. 6(b) suggests that the tholeiitic and calc-alkaline trends delineated in Fig. 2 do not have the same provenance. Thus Fig. 6 indicates that partial melting of the provenance is due to metamorphism and source compositions and the differences in the gneisses is not due to mineral fractionation in their provenance (Fig. 7). In addition, the high Ti/Y and low Rb/Ba ratios shown in Fig. 6(a) for most of the gneisses are features not generally ascribed to the continental crust, and the protoliths for the gneisses are not the product of simple mixing lines between crust and asthenospheric magma.

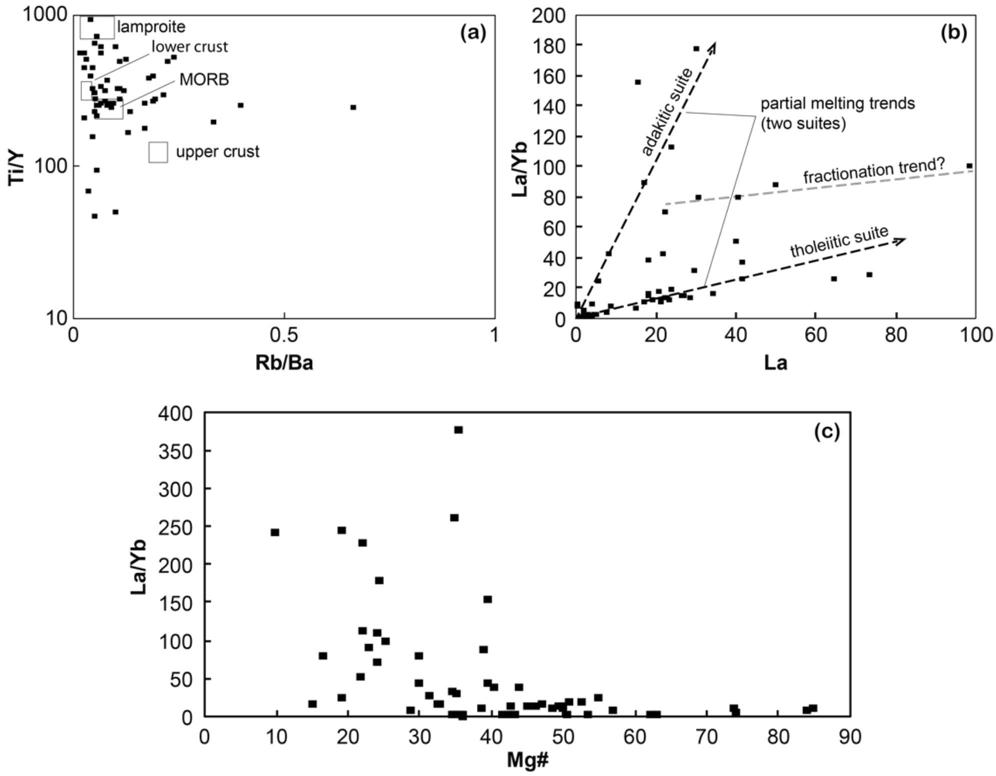

Figure 6. *(a) Ti/Y vs Rb/Ba plot showing that the gneisses are probably derived from small degree mantle melts in equilibrium with residual garnet (represented by lamproites), as opposed to being derived from crust-contaminated asthenosphere-derived magma; (b) La/Yb vs La plot. Positive correlations between La/Yb and La are indicative of partial melting (black dashed lines), and fractionation (grey dashed line) played a minor role; and (c) La/Yb vs Mg# plot indicating that there was no significant fractionation.*

Using the La/Yb ratio as a general measure of the incompatible element enrichment, asthenospheric mineralogy and composition would have La/Yb <9 as the degree of melting increases from say 1 to 15%, yet La/ Yb ranges from between 1 to 380, which, again, suggests multiple sources. This range of La/Yb ratios do not appear to correlate with Mg# (Fig. 6c), and suggests that the high La/Yb values does not reflect significant fractionation or combined fractionation and assimilation.

Figure 7. *Migmatised garnetiferous mafic gneiss from southeastern Greenland illustrating partial melting.*

Partial melting: adakitic and gabbroic gneisses

As discussed above, the gneisses in southeastern Greenland can be grouped into calc-alkaline or tholeiitic suites. The suites formed in a provenance containing residual garnet and minor plagioclase, such as expected from garnet amphibolite or eclogite-facies rocks present at the base of continental crust (>40 km), in eclogitized subducting oceanic crust, or the base of a delaminated crust.

Various plots are used to recognise products of lower crustal adakitic melts from others (Fig. 8; after Defant and Drummond, 1993). The combination of the curves in Fig. 8 (a,d,i,j) and the sub-horizontal trend in Fig. 8b indicate partial melting took place was accompanied by amphibole fractionation in the absence of garnet fractionation. This means that garnet present in the gneisses of southeastern Greenland are metamorphic and not associated with fractionation during partial melting. These plots also indicate that there are at least two suites (gabbroic or tholeiitic, and adakite-like).

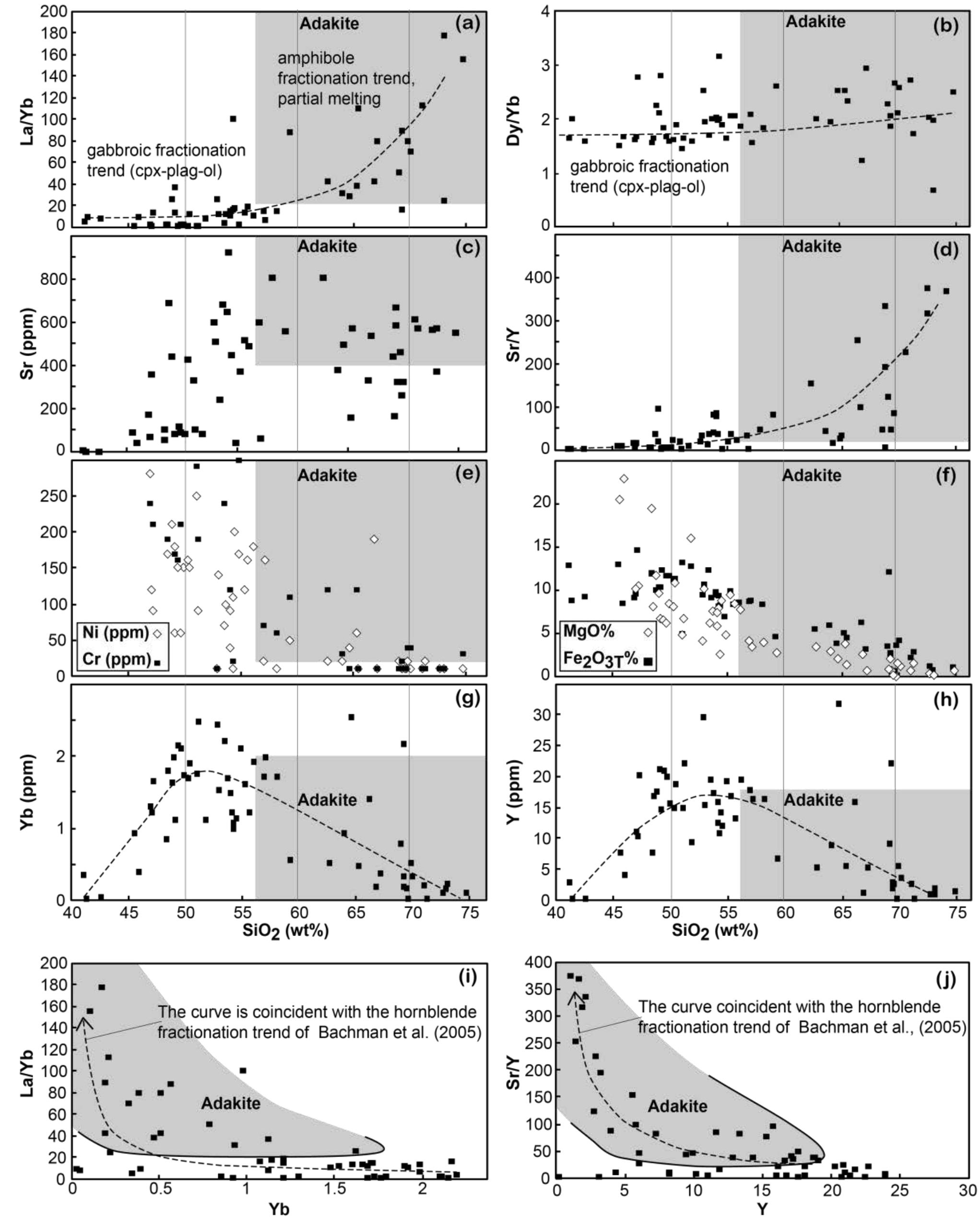

Figure 8. *Geochemical data for gneisses from southeastern GR. Plots show fields and limits for adakitic compositions; dashed lines = amphibole fractionation trends.*

Using Figure 8, the adakite-like samples were separated and chondrite-normalised (Fig. 9). The positive and negative Eu anomalies shown in Figure 9 suggest that the source for the gneisses was plagioclase free for some samples and had residual plagioclase for other samples. The plagioclase free source is probably the mantle, and the degree of LREE (La-Eu) enrichment is too significant for the source magmas to have been generated from a depleted mantle by a single melting episode. The fractionation of hornblende during partial melting is confirmed by the characteristic listric-shaped REE profile in Figure 9, as observed in many arc volcanic and plutonic suites (e.g. Richards et al., 2001). Furthermore, the plot also indicates that no garnet fractionation took place; if so, the HREE would increase rather than decrease from left to right in the plot.

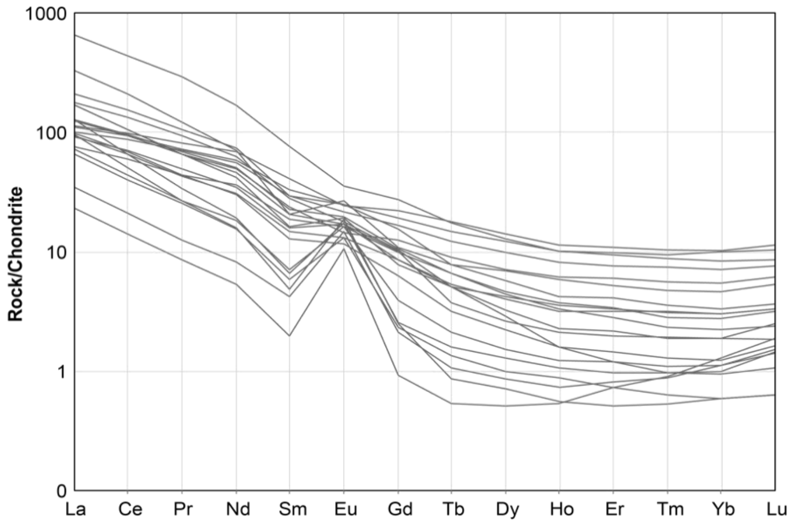

Figure 9. *Chondrite-normalized REE patterns for samples of gneisses from southeastern Greenland. Normalization values of Sun and McDonough (1989).*

Possible tectonic setting and conclusion

From the Hf/3 – Ta – Th classification of Wood (1980), the tectonic setting for the gneisses in southeastern Greenland ranges from a magmatic-arc to the mid-ocean ridge setting (Fig. 10). The figure also confirms the presence of calc-alkaline and tholeiitic suites, and suggest that there is a combined mid-ocean and island-arc setting that might have involved the root zone of a magmatic arc at the base of the crust (Fig. 11).

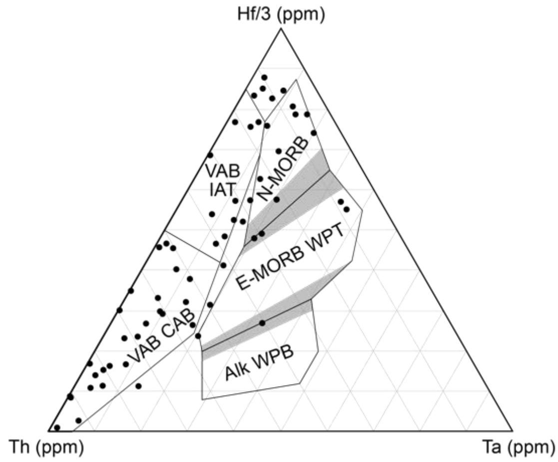

Figure 10. *Hf/3 – Ta – Th plot (after Wood, 1980) for gneisses in southeastern Greenland.*

In conclusion, the mafic (gabbroic) rocks were emplaced during arc magmatism whereas the adakitic rocks represent the product of partial melting of precursors containing restitic garnet(-plagioclase). This and the observations outlined above are summarised in Figure 11.

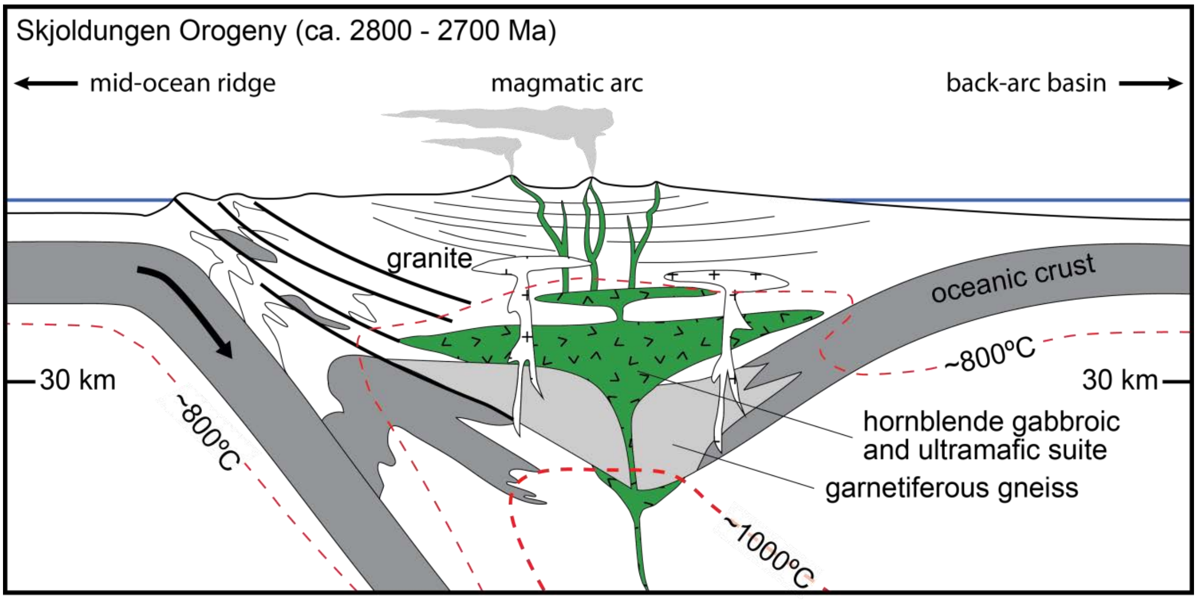

Figure 11. *Model for the formation of the protoliths for gneisses in southeastern Greenland.*

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Some remarks on the country rocks for the Skjoldungen alkaline intrusions and the comparison of different series

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The Skjoldungen alkaline province comprises several intrusions that are emplaced into a complex basement of migmatites, granulites and gneisses. Some of the gneisses are characterized by large volumes of inclusions ("agmatitic gneiss"), whereas in other areas the gneisses occur as homogeneous former plutonic rocks ("orthogneiss" Fig. 1c). The distinction between later intruding plutonic rocks and the country rock is based on structural field criteria (e.g., deformation, amount of inclusions, etc). However, locally strain gradients with different intensity of solid state overprint ("gneissification") occur in several areas independent of their primary magmatic origin. Therefore, the textural criteria alone may failed to distinguish different magmatic units.

The Skjoldungen alkaline province can be geochemically distinguished from the basement rocks in the area (Fig. 2). However, the alkaline rocks are also in several locations deformed at high grade conditions (e.g., monzonitic gneisses). In addition, the data indicate a difference between the Skjoldungen country rocks (basement) and the TTG units in SW-Greenland. In Skjoldungen, the basement rocks show a trend towards "real" granites, compared to the more trondhejmitic evolution in the western part of the craton (see K_2O- and Na_2O/CaO evolution in Fig. 2).

The alkaline rocks represent a magmatic evolution (e.g., Figs. 2 and 3). This include late plutonic rocks as well as some early alkaline gneisses. In contrast, the samples summarized as basement show large variety of trace element patterns and possible different magmatic origin. However, the major elements and petrology indicate a general calc-alkaline evolution. However, some samples characterized as basement rocks, overlap in chemistry with the alkaline serie and define outliers in the general trend of the basement rocks (Fig. 2). Moreover, the calc-alkaline samples are not complete comparable with TTG characteristics of SW-Greenland.

An indication to identify the alkaline rocks of the area are the (Na_2O+K_2O) versus (FeO+MgO) relationship. For a given alkaline content, the alkaline rocks are richer in FeO+MgO. This is consistent with a mantle input in the alkaline rocks, whereas most basement samples can be explained by partial melting of a crustal source.

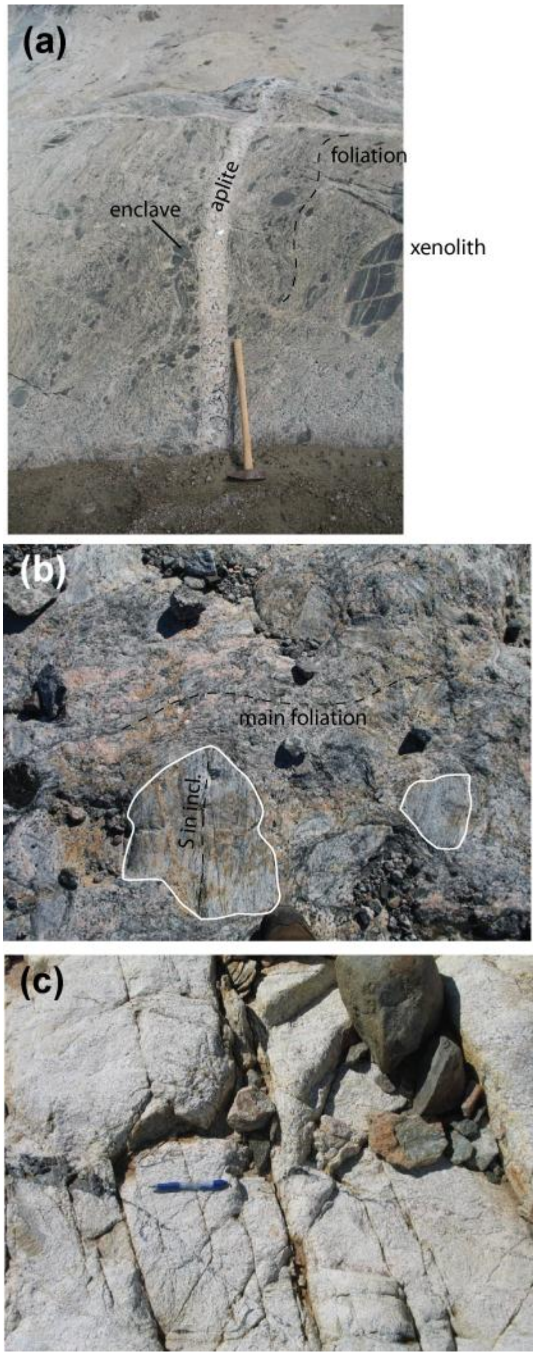

Figure 1 **(a)** *Orthogneiss with enclaves and xenoliths. These are intruded by late stage, course grained aplites.;* ***(b)*** *orthogneis xenoliths in a deformed country rock;* ***(c)*** *homogeneous orthogneiss*

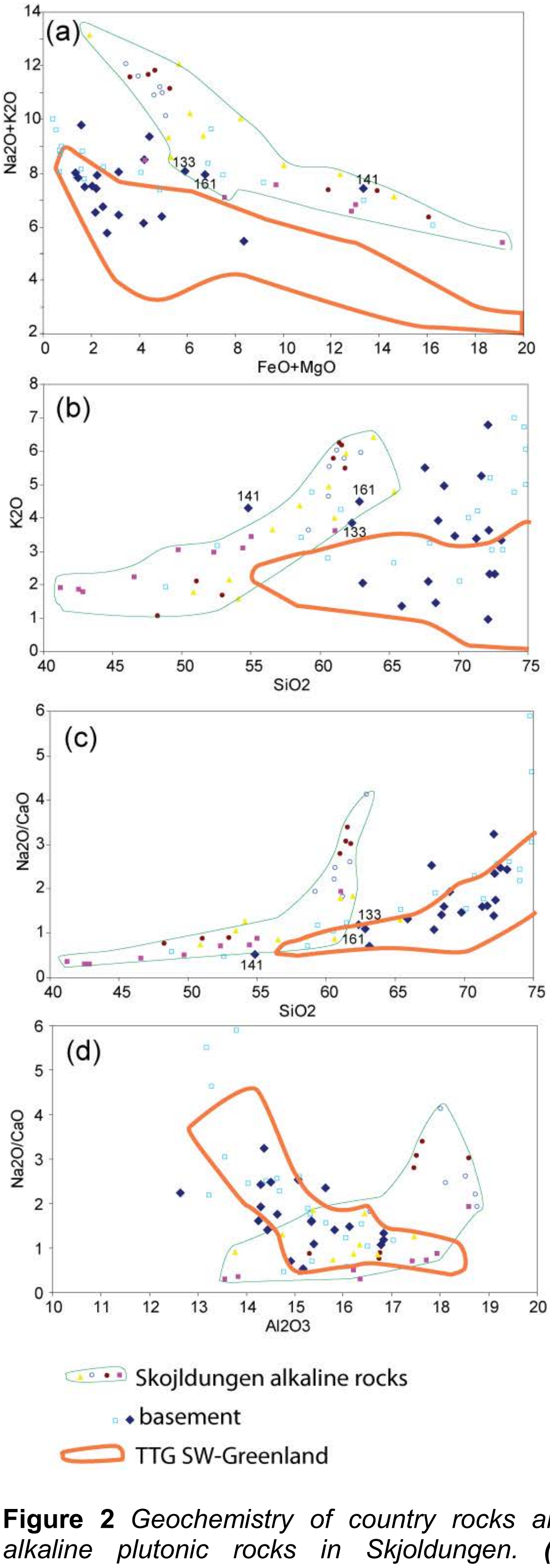

Figure 2 *Geochemistry of country rocks and alkaline plutonic rocks in Skjoldungen.* ***(a)*** *Na_2O+K_2O versus $FeO+MgO$;* ***(b)*** *K_2O versus SiO_2;* ***(c)*** *Na_2O/CaO versus SiO_2; (d)Na_2O/CaO versus SiO_2. Numbers indicate some important basement samples of the 516-Serie.*

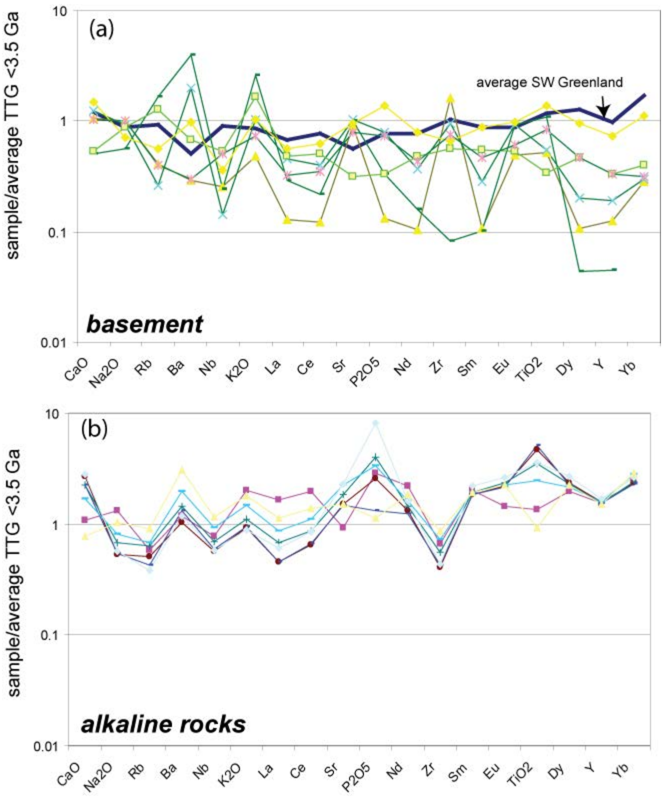

Figure 3. *Geochemistry of country rocks and alkaline plutonic rocks normalized to average TTG under 3.5 Ga of Martin et al. (2008). Note the TTG of SW Greenland fits the general TTG characteristics, whereas the Skjoldungen basement rocks differ significantly. The basement rocks show high variety of trace element pattern, whereas the alkaline rocks represent a more consistent magmatic evolution.*

In addition to the overlapping evolution of the plutonic country rocks and the alkaline plutonic rocks some differences can be listed:

- Most country rocks underwent two stages of ductile deformation
- In several places, the country rocks underwent partial melting
- On Helge Halvø different types of granulites are part of the country rocks, which are missing in the alkaline gneisses

In some places, basement units are infiltrated by new melts. The melt/basement ratio varies, which is also known from boarder zones around large batholiths. Some examples are dominated by the former basement and intruded by new melt sheets. These are often SiO_2-rich and granitic in composition. These magmas may be influenced by plagioclase fractionation. The magmas of basement rocks include different sized units of older origin. These are granitoids, mafic and ultramafic rocks between cm to km sized fragments. These are intruded by magmas of different characteristic.

Upper crustal exhumation rates of the Ruinnæsset intrusion: Indications for the transition from Archaean mountain belt to a cratonic stage

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The role of erosion and exhumation during the early Earth is key to understanding the rate of continental crust production (ratio between eroded and preserved crust).

Modern geochemical methods derive crustal production rates from resedimented zircons (Hawkesworth and Kemp, 2006), but the relation between crustal growth and erosion is less clear. This relationship is commonly inferred from modern examples. In any case, the erosion (and related sedimentation) rate depends strongly on the topographic relief. The latter is not well constrained in the Archaean, where most of the continental crust was formed (Belousova et al. 2010). In this context, the possible knowledge of near surface exhumation rates gives insights in the relief evolution, because of the close relationship between crustal thickness and relief. After thickening of the crust, the crustal thickness and relief is strongly controlled by erosion rates. Compared to the only few studies on upper crustal exhumation in the Archaean, deformation of the Archaean middle crust has been intensely investigated. Nevertheless, the effect of this deformation on crustal growth, thickening, and topographic relief is not well constrained. There is increasing evidence showing that some of the deformation during crustal growth is related to the generation and emplacement of TTG plutons, therefore the crustal thickness is not well known as well as their related isostatic equilibration.

In the case of the Skjoldungen Alkaline province the intrusion of a distinct group of magmas allows to distinguish the relative age relationships involving older TTG basement and later formed alkaline magmas (Nielsen and Rosing 1990). In addition to ongoing research on the relative timing of the different magmatic bodies in the area, we concentrate on one of the largest alkaline intrusions of the area, the Ruinnæsset intrusion. This intrusion intruded into deformed country rocks, but itself also shows evidence of some deformation. Blichert-Toft et al. (1995) recognized these field-relations and described the Ruinnæsset intrusion as a late tectonic intrusion. The Ruinnæsset intrusion is characterized by a monzonitic central part and several more primitive magmatic units at its rim. In addition, two types of pegmatitic/aplitic dykes occur. The dykes are known as “normal” pegmatite, and as “purple pegmatites”, respectively (Nielsen and Rosing 1990). They are generally subhorizontal or only slightly inclined. These dykes are in some places observed to contain miarolitic cavities (Fig. 1).

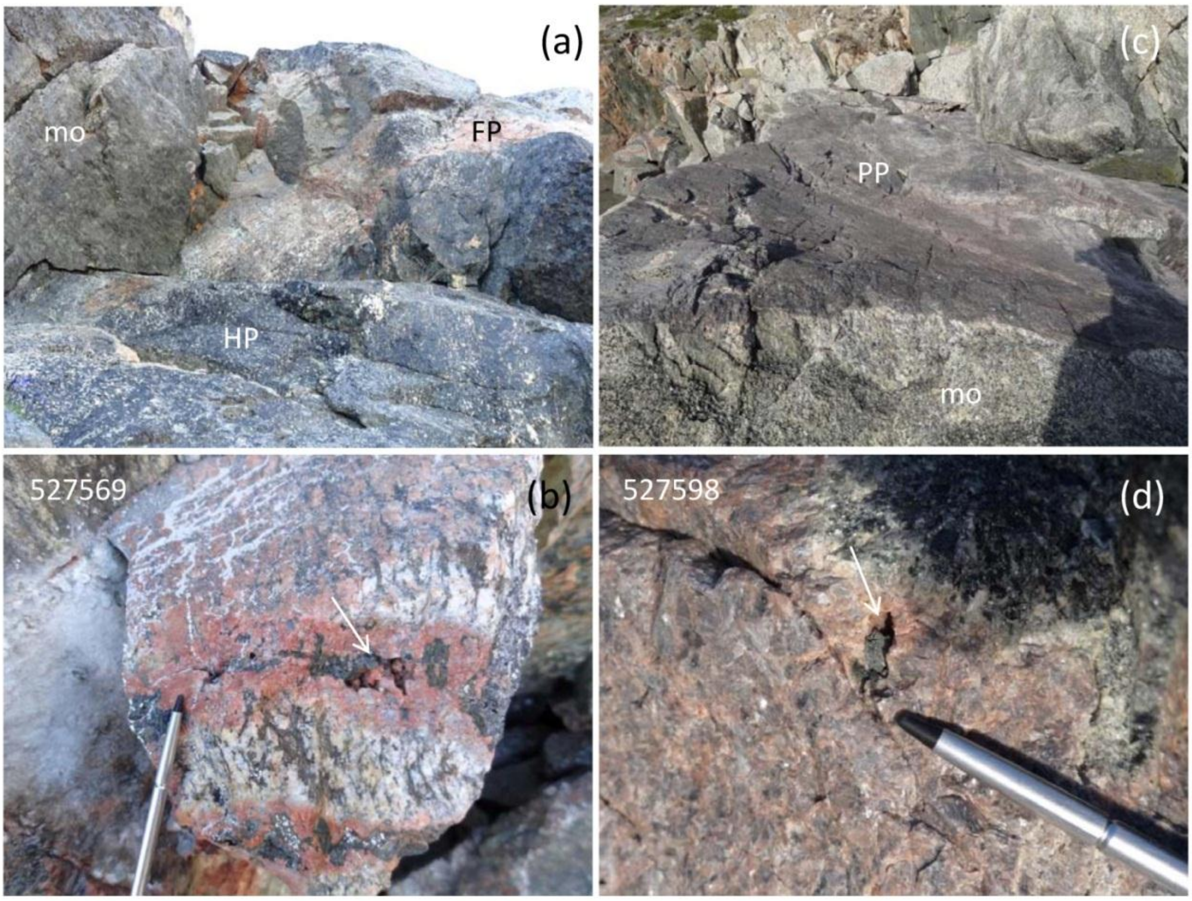

Figure 1. *Miarolitic cavities in pegmatites of the Ruinnæsset intrusion. In (a) and (b) (locality 11TFK072; N63.53300, W41.75764): The northern contact between monzonite (mo) and the gneiss basement (outside view, to the right); the contact zone contains felsic pegmatite (FP) and a marginal hornblende pegmatite (HP). Sample 527569 of felsic pegmatite contains mineral filled miarolitic cavities (white arrow in (b)). In (c) and (d) (locality 11TFK092: N63.48333, W41.64337): Gently inclined sheet of 'purple pegmatite' (PP) intruded into coarse grained monzonite (mo). Sample 527598 of 'purple pegmatite' contains crystal filled miarolitic cavities (white arrow in (d)).*

The field relations show that the main pluton of the Ruinnæsset intruded into upper amphibolite metamorphosed basement rocks during exhumation. The last stage of the Ruinnæsset intrusion contains miarolitic cavities (Fig. 1), which indicate a pressure around 1.2 kbar (e.g., Nabelek et al. 2010). The timing of metamorphism is derived from different U/Pb zircon ages of the surrounding rocks, which show an age of 2750 Ma (Kolb et al., in prep). The Ruinnæsset intrusion itself is dated to 2699±4 Ma using the $^{207}Pb/^{206}Pb$ method on zircon (Nutman and Rosing 1994).

Two samples of the Ruinnæsset intrusion containing miarolitic cavities were dated by zircon U/Pb age dating (Fig. 2 and 3). The age data were obtained by LA-ICPMS at GEUS, following the procedures outlined in Frei and Gerdes (2009). The first sample is a felsic pegmatite (represented by sample 527569), which yields a concordant ages of 2695 +3/-4 Ma, based on zircons with the highest Th/U > 1.3 (Fig. 2).This age is within error of the published age for the main part of the intrusion.

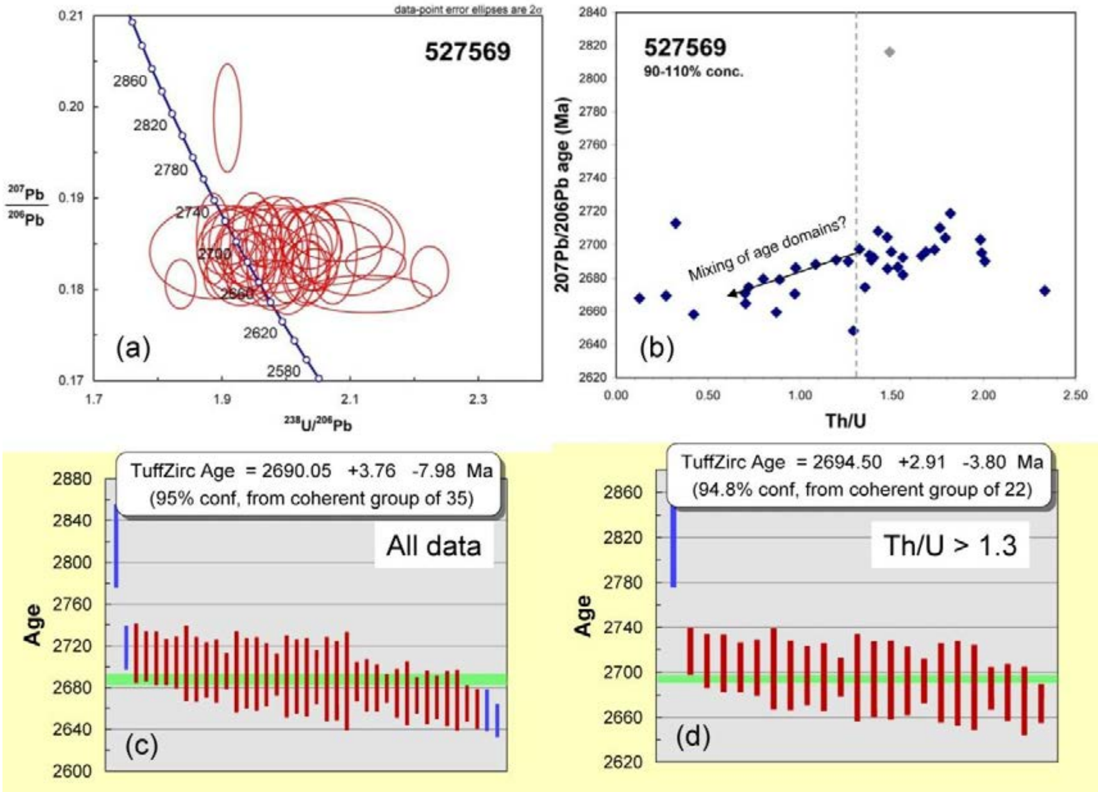

Figure 2. *Zircon U/Pb age data for felsic pegmatite sample 527569. (a) Tera-Wasserburg diagram. (b) $^{207}Pb/^{206}Pb$ age vs. Th/U; grains with lower Th/U (<1.3) appear to show effect of mixing towards a younger age component (metamorphic or ancient Pb-loss?). Calculated $^{207}Pb/^{206}Pb$ ages based on all grains (c), and on grains with Th/U > 1.3 (d), show a relatively minor difference. The age based on grains with high Th/U of 2695 +3/-4 Ma is considered the most reliable intrusion age.*

A second sample of the so-called “purple pegmatites” (527598) was dated, yielding an age of 2632 ± 7 Ma (Fig. 3). These pegmatites cross-cut all other lithologies, hence, they represent the latest magmatic activity of the area. This age indicates that the later generation of pegmatites intruded at similar crustal levels, but ~60 Ma later than the first generation. Therefore, after exhumation towards pressures around 1 kbar, the crustal section stayed on similar levels, while magmatic rocks intruded the section.

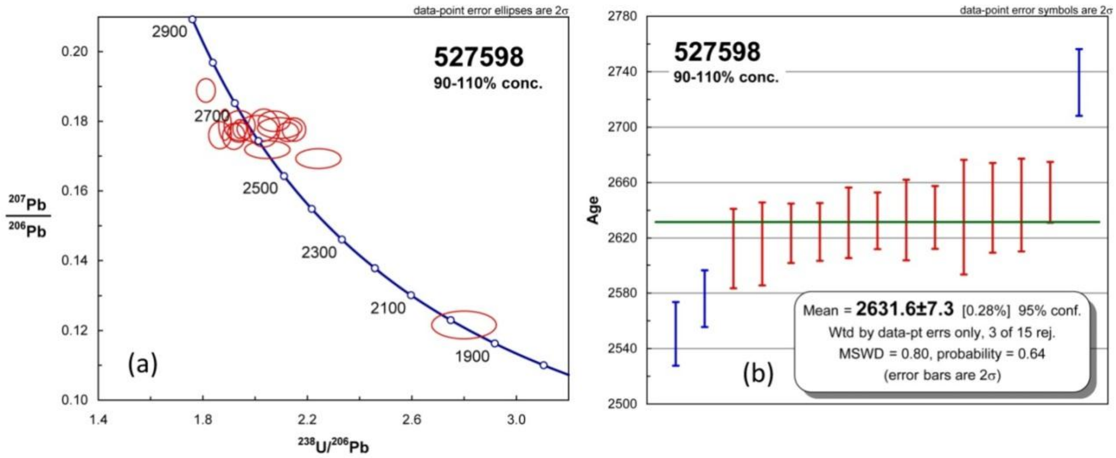

Figure 3. *Zircon U/Pb age data for ‘purple pegmatite’ sample 527598. (a) Tera-Wasserburg diagram. (b) The concordant zircon grains give an average weighted mean $^{207}Pb/^{206}Pb$ age of 2632 ± 7 Ma. One analysis is Paleoproterozoic and is not taken into account.*

Including these apparent large errors, the exhumations rates still show values, which are known from late stage evolution of modern collisional orogens (e.g., European Alps: Willet 2010).

The main change in exhumation rate occurs in the transition to the craton stage, where the area stays near the surface with no or minor exhumation and erosion. The Paleo-Proterzoic dolerite dykes that are intruded at near surface conditions are a further constrain for the exhumation history of the area. The intrusion age of these dykes encompasses a large time gap of 200-500 Ma. The late Archaean - Proterzoic stage requires nearly no erosion in order to stay in isostatic equilibrium, which requires low relief areas. Using these data, a conservative view of the time interval between the metamorphism of the basement rocks and the intrusion of the purple pegmatites is derived and indicates an exhumation rate of 0.5±0.25 km/Ma. In addition, the monzonite contains amphiboles (Thomsen 1998), which can be used as geobarometer. These amphiboles indicate crystallisation pressures of ~6 kbar. Considering the emplacement depth of the monzonite at an intermediate stage during exhumation, the average value of 0.5 km/Ma will split in a slower exhumation rate in the middle crust (0.15 km/Ma) and fast exhumation rate (3.5 ± 2 km/Ma) under upper crustal conditions. These estimates have a relative error of ~20-50%.

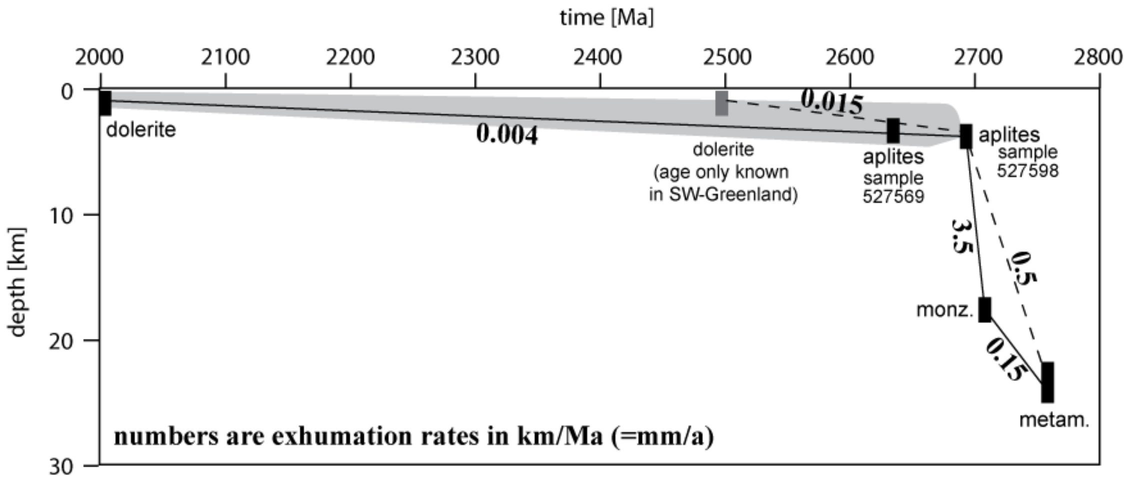

Figure 4. *Sketch illustrating the change in exhumation rate in the Ruinnæsset area.*

The miarolitic cavities in Archaean plutonic rocks are an indication of the intrusion of a magmatic rock at very low pressure. This suggests exhumation rates of the Archaean basement that are comparable to modern mountain belts. These plutons are syn- to posttectonic and give a minimum for the exhumation history of the Archaean mountain range. The conservative numbers are lower than exhumation rates of greenstone belts in South Africa (Diener et al. 2005: 2-5 km/Ma). Based on the intrusion of the Paleo-Proterzoic dolerite dykes the exhumation rates show a significant change after intrusion of the plutons and indicate the transition from mountain belts to a craton stage at around 2700 Ma.

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Polar bear studies in East Greenland

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The polar bear population which ranges year round along the entire coast of East Greenland (EG) is currently thought to constitute one coherent demographic entity with no or negligible exchange with the neighboring Barents Sea population.

The EG population of which the size is unknown is harvested in the Scoresby Sound (quota: 30 bears/year), Tasiilaq (25/yr) and SW Greenland (4/yr) areas. However, satellite telemetry studies in 1993-1998 and 2007-2010, and miscellaneous information obtained from polar bear hunters living in E and SW Greenland, indicate that the EG polar bear population is subdivided in two sub-populations (north and south of Kangerlussuaq at ca. 68° N, respectively). Determination of potential substructuring and differences in regional area occupancy of polar bears in E Greenland has implications for setting annual quotas and for planning of surveys to determine the population size.

During 28 July - 8 August 2011 the coastal areas between Tasiilaq (65° 37' N, 37° 38' W) and Prins Christians Sund (60° 03' N, 43° 10' W) were surveyed from helicopter during the SEG-2011 geological surveys in the area. The purpose was to detect “land-locked” polar bears for instrumentation with satellite transmitters in order to study movement patterns. During the surveys observations of seals and whales were systematically recorded. A total of 37.5 hours were used on 12 surveys dedicated to detect polar bears (ca. 6600 linear km flown) during which one polar bear was found. On 3 August a 15-17 year old male bear was immobilized in Timmiarmiut Fjord and a SPOT-5 satellite transmitter was fitted to the ear. The tag transmitted until 5 October 2011 during which time the bear used Timmiarmiut and neighboring Mogens Heinesen Fjord. During the surveys one narwhal, and one hooded, and several bearded and hundreds of ringed seals were observed.

In conclusion: (1) Only one polar bear was observed and subsequently tagged, (2) the bear showed local movement during the 63 days of tracking, (3) it cannot be precluded that polar bears were present in an up to ca. 50 km wide band of drifting open pack ice along the study area. However, this ice was unsuitable for immobilizing polar bears safely and was not surveyed, (4) during the polar bear study important information on distribution of other marine mammals was collected, (5) further attempts should be made to study polar bears in SE Greenland using satellite telemetry, and (6) the cooperation between GEUS and the bear studies functioned perfectly.

Post-Archaean tectonics in the Skjoldungen area

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Evidence of a Post-Archaean tectonic history in South East Greenland is poorly documented and only few papers addressed attention to late structures. For the entire region one mafic dyke could be dated 61 Ma (Storey et al., 2007). The few analyzed samples for apatite fission tracks highlight Late Paleozoic cooling events (Hansen and Brooks 2002) and the only published paper describing pseudotachylites analyzed along major faults shows an average Paleocene age (Karson et al. 1998). Despite SE Greenland is considered a volcanic rifted margin related to the North East Atlantic opening and the continental-ocean boundary is locate few tens kilometers offshore and described by the ODP Leg 152, any kind of interest was addressed in understanding the more recent tectonics of this area. For these reasons the main task of the Working Group is to characterize the late structural evolution of the Skjoldungen area in South East Greenland focusing on brittle deformation along major faults, late dyke intrusions and vertical uplift.

Analysis of Digital Elevation Model derived from satellite Aster data were used to extract major structural trends of the area together with ortho-photos analysis derived from aerial photos at 1:40000 scale.

During fieldwork in 2011 more than 800 oblique photos for 3D-photogeology were taken. Samples for fission track analysis were collected in order to define cooling and uplift history and almost 40 sample for apatite fission tracks and 2 for zircon fission tracks were sent to Geotrack lab for analyses. To better understand kinematics and ages of fault movements, structural analysis of brittle deformation along major faults was carried out together with sampling of pseudotachylites along fault zone. Almost 200 fault-slip measurements for kinematics and palaeo-stress reconstruction were collected together with 7 samples of pseudotachylites, recently sent to the lab for Ar-Ar dating.

Ages and kinematics of brittle deformation along the South East Greenland margin (Skjoldungen area)

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Structural analysis along major structures together with sampling of pseudotachylites along major fault zones was carried out in order to establish ages and kinematics of brittle deformation overprinting Archaean-Proterozoic gneisses and intrusions along the South East Greenland margin. Furthermore, samples for fission tracks from apatite and zircon where collected to investigate vertical movements and the exhumation history.

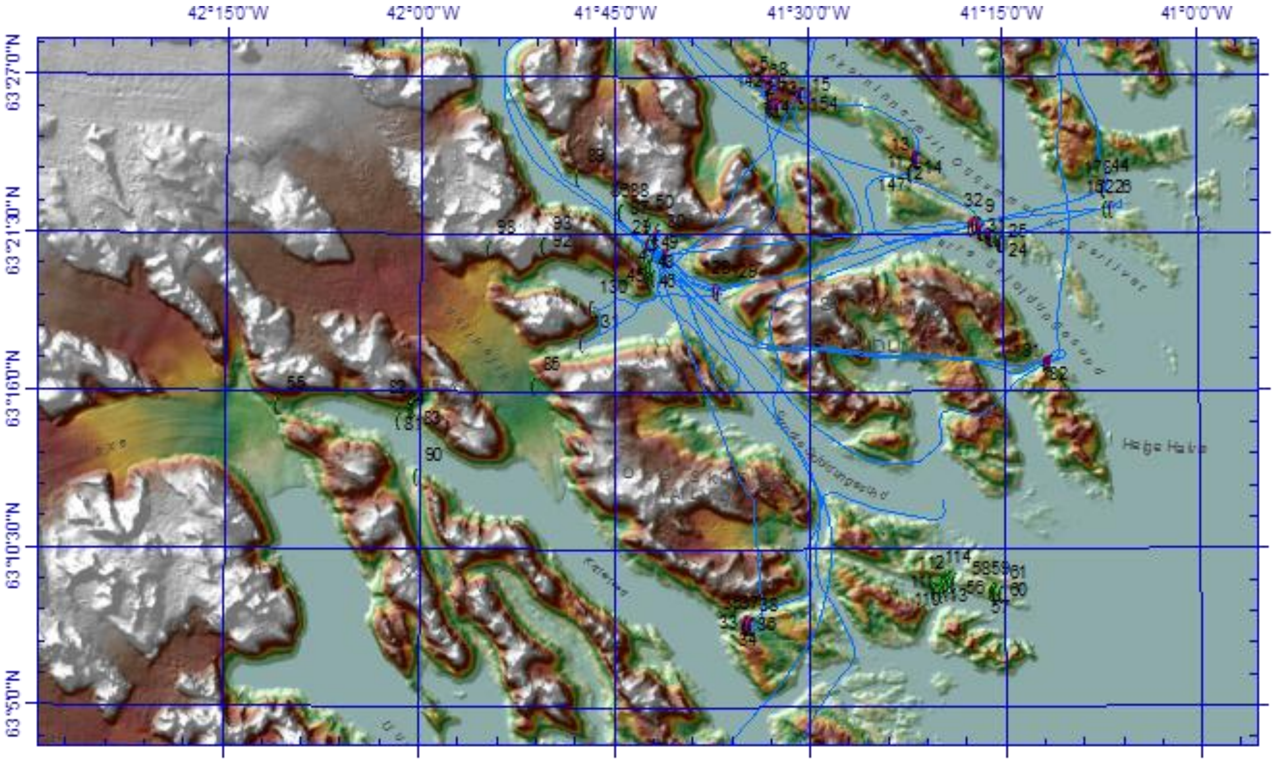

Figure 1. *Flight lines and waypoints after fieldwork in 2011 in the Skjoldungen area.*

ENE-WSW oriented trends, visible on the satellite images, were visited during fieldwork (Fig. 1). This trend is parallel and sometime corresponds to Proterozoic dykes well developed in the area.

Along Langenæse peninsula (Fig. 2) ENE-WSW oriented strike-slip deformation overprints a probable Proterozoic dyke. In order to define age and kinematics of the brittle deformation, pseudotachylite samples and structural data were collected along this structure (Fig. 3a-b). A preliminary paleo-stress reconstruction using fault-slip data performed in T-Tecto© (Zalohar, 2010), shows a SW-NE oriented maximum horizontal stress in a strike-slip tectonic setting (Fig. 3c) together with left-lateral movement along the ENE-WSW oriented structure.

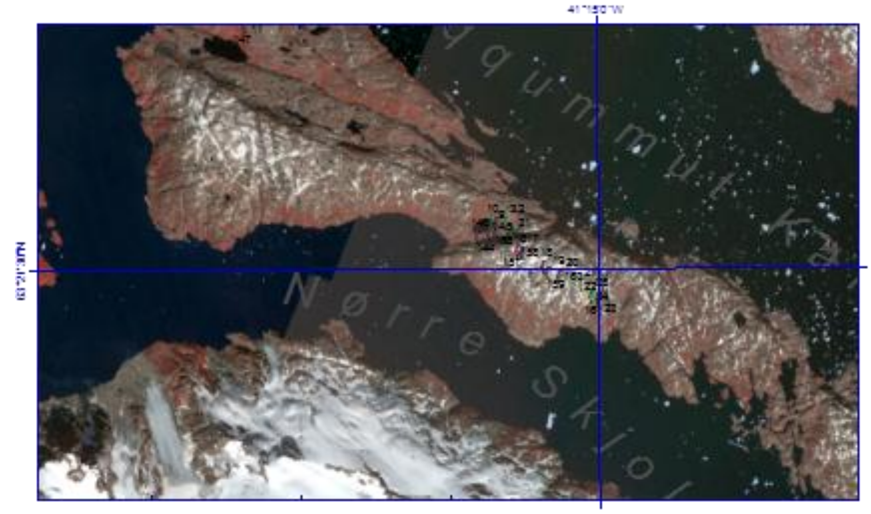

Figure 2 *Satellite image of Langenæse peninsula. Numbers correspond to GPS waypoints of visited sites for sampling and structural analysis.*

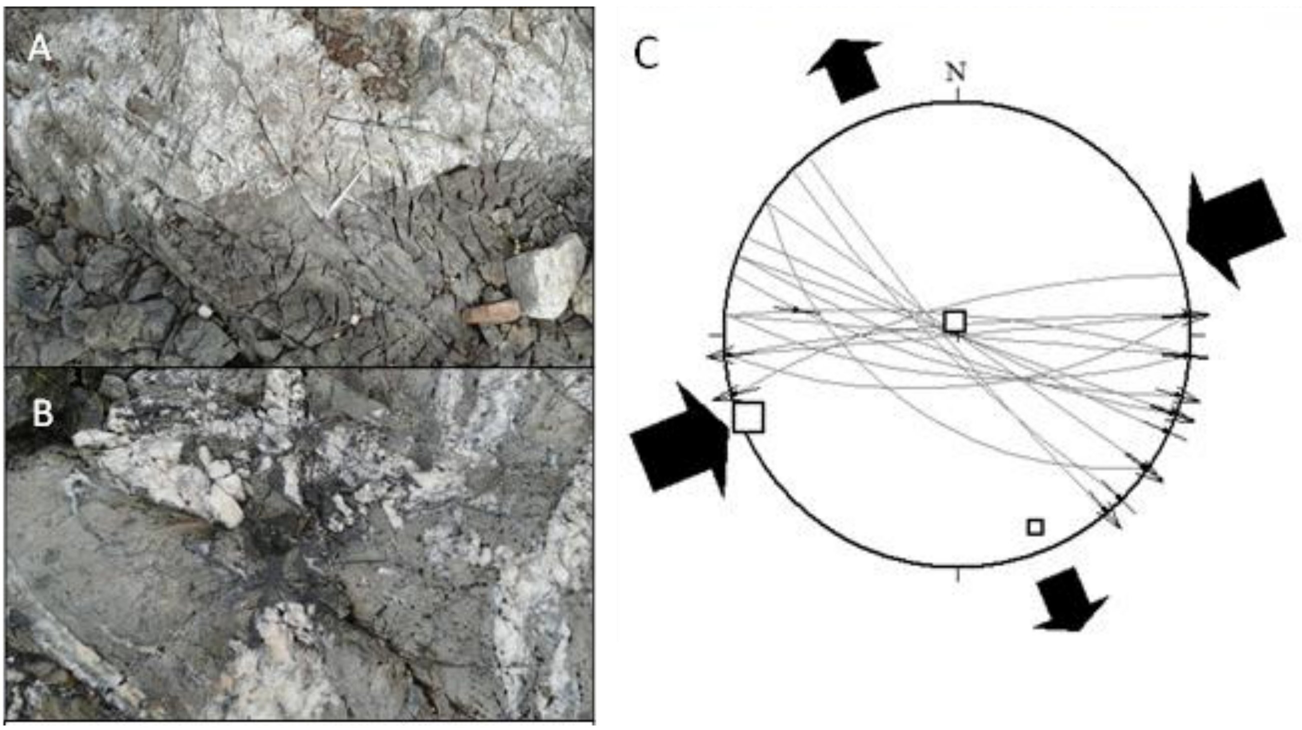

Figure3. *Site 144-146. A) brittle faults overprinting mafic dykes and basement rocks; B) Pseudotachylite; C) Paleo-stress reconstruction from fault-slip data.*

Deciphering burial, uplift and exhumation history using geological data, landscape analysis and palaeothermal data. Experience from East and West Greenland

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The margins of East and West Greenland shares the characteristics of many elevated, passive continental margins around the world: Extensive, elevated plateaux of low relative relief at 2 km or more above sea level (a.s.l.) cut by deeply incised valleys, Mesozoic-Cenozoic rift systems parallel to the coast, and a transition from continental to oceanic crust further offshore. Other examples of such margins are found in SE Australia, Brazil and Norway. In previous and ongoing studies we have investigated the burial and exhumation history of elevated, passive continental margins in e.g. West and East Greenland and NE Brazil, both prior to and subsequent to breakup, by integrating geological data, landscape analysis and paleothermal data. Here we summarize some of our observations and interpretations from Greenland.

Breakup of the North-East Atlantic occurred at the Palaeocene–Eocene transition. The geological record in the Kangerlussuaq–Blosseville Kyst area (68–70°N) in SE Greenland shows that the area underwent short-lived uplift immediately prior to breakup followed by km-scale subsidence during the eruption of basalts, with no evidence for crustal upwarping at this time. The earliest basalts erupted partly in a marine environment, and there are marine incursions in the uppermost of the flood basalts. These observations imply that the landscape was without significant relief subsequent to the eruption of the Paleocene–Eocene basalts, and consequently, that the present-day relief is the result of post-rift uplift. This applies in particular to the highest summit in Greenland (Gunbjørn Fjeld, 3.7 km a.s.l.) which is located just north of Kangerlussuaq and which is made up of Palaeogene plateau lavas. Also in central West Greenland, Palaeogene volcanic sequences deposited during post-rift subsidence are exposed in high mountains, with Paleocene marine deposits within this section at elevations up to 1.2 km a.s.l. This clearly shows that the elevated topography of the West Greenland margin is not a remnant of the rifting process but developed later.

We have mapped the plateaux surfaces in SE Greenland between 68 and 71°N and in central West Greenland between 66 and 72°N, and we find that they are erosion surfaces that truncate both Palaeogene basalts and older rocks. Consequently, these low-relief erosion surfaces (or peneplains) are post-basalt in age, and we suggest that they formed by fluvial erosion towards the base level of the adjacent seas during the opening of the North Atlantic and the Labrador Sea, respectively. The present topography thus formed in two steps: first by erosion to form a base-level governed surface near sea level and second by uplift to form a high plateau and the deeply incised valleys. The present topography is mainly a result of these events, but especially the valleys have been reshaped by glaciers below the uplifted peneplain.

Many apatite fission-track studies have been published from East Greenland, and we present new results from apatite fission-track analysis (AFTA) of 100 samples focussed in the Kangerlussuaq area (68–69°N), but with a sporadic coverage along the coast from 62 to 70°N. Both published and new fission-track data reveal that regional, Cenozoic cooling of the margin started at the Eocene – Oligocene transition (c. 35 Ma). We interpret this reduction in palaeo-temperatures to represent a change from post-rift subsidence and burial to uplift and exhumation of the margin. Post-rift subsidence therefore lasted for about 20 Myr. Uplift and erosion at this time affected margins around the North Atlantic (including West Greenland), and because it also correlates in time with a major plate reorganisation in the region, we suggest that it was related to plate tectonic forces. Because the regional cooling starting at 35 Ma coincides in space with the post-basalt peneplain, we find that the peneplain along the margin was the end-result of this episode of uplift and erosion. The new AFT data from Kangerlussuaq also show that the peneplain was uplifted to its present elevation in the late Neogene (as was the case in West Greenland), and thus that the shaping of the present topography began several tens of millions of years after breakup.

South of Kap Gustav Holm (c. 66°N), the geological record onshore neither contains sediment nor lava that can provide us with constraints about when the exposed Precambrian basement rocks may have been near the surface of the earth in Phanerozoic time. The large-scale landscapes south of Kangerlussuaq have not been mapped, but Brooks (1985) reported the presence of isolated remnants of an uplifted plateau at about 1 km a.s.l. near Ammassalik.

The limited AFTA data that we have available, reveal a long history of Mesozoic–Cenozoic cooling of the Greenland margin south of 68°N. In particular, the data provide evidence that uplift and exhumation at the Eocene–Oligocene transition affected the margin as far south as the Skjoldungen area. However, AFTA data from two samples of the Ketilidian terrain south of 62°30'N show a cooling history that is remarkably different from that of samples further north. The planned work under the Segment project will provide valuable new data for understanding the development of SE Greenland's margin and thus also give us a better understanding of the nature and origin of such differences along the margin.

Acknowledgement
The results from the Kangerlussuaq area are part of the outcome of the Miss Green research project (Mountain Building and Ice Sheet Stability in Greenland). The project is funded as part of the International Polar Year program by KVUG (under the Danish Natural Science Research Council) and by GEUS.

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Mineralising systems in SE-Greenland: Methods of investigating mineralization processes and formation conditions

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During the last few years, mineralogists in Geocenter have been developing improved identification and quantification methods for modal analyses of rocks and detailed screening of mineral parageneses based on the in-house instrumentation available. Highly automatic diffractometers allow a complete insight into the structural state of minerals and enable fast and accurate quantification of mineral constituents. Integrated with other analytical methods, diffraction can be applied to quantify the proportions of minerals in rocks from different geological environments. Mineral quantification is based on the fact that relative intensities of individual contributions to a powder- diffraction pattern of a mixture are proportional to the quantities of the respective constituents. At the same time the diffraction patterns of diverse phases in the mixture do not affect each other apart from their mutual overlap, so powder diffraction is a straight-forward method for the quantitative phase analysis of mixtures. There are however practical complications, deriving from the structural and textural characteristics of the samples. In cases where differences in the properties of various constituents of a mineral mixture are insufficiently modelled, the results of quantitative analysis can be unreliable. The measurements are not specifically time consuming and with the appropriate treatment of the data, powder diffraction can give an accuracy of quantification close to 1%, applicable to most geological problems.

An area of special interest for such investigations is the Timmiarmiut Alkaline Province, where extensive K-feldspar-epidote-chlorite alteration in fault zones occurs. The crystal structure characterization of the mineral components derived from X-Ray diffraction can give an indication of the metamorphic grade, PT-conditions and the alteration processes in the region. Geochemical changes and mineral reactions can be quantified by the same method, based on previous experience of quantitative description of hydrothermal processes in greenschist facies alteration zones. Quantitative and structural mineral investigations will contribute to the understanding of the regional geological history of the post Archaean evolution in South-East Greenland.

Intrusions of the Archaean Skjoldungen Alkaline Province, South East Greenland: Observations from the 2011 field season and preliminary geochemical results

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Background

The Archaean Skjoldungen Alkaline Province (SAP), situated at ~63º30'N in South East Greenland (Fig. 1), consists of several smaller ultramafic-mafic (pyroxenitic-gabbroic-dioritics) and a few larger felsic (monzonitic-syenitic-granitic) intrusions. All intrusions are restricted within a ca 30 km-wide and NW-SE trending zone that is exposed for at least 80 km between the inland ice sheet and the North Atlantic Ocean. The basement hosting the Skjoldungen intrusions is dominated by granulite facies agmatitic gneisses interleaved with agmatized supracrustal rocks of presumed volcanogenic and terrigeneous derivation, and partly retrogressed to amphibolite facies. A single zircon ion-probe U-Pb age of 2696 ± 7 Ma (Nutman & Rosing, 1994) from a syenite makes this one of the oldest known alkaline provinces worldwide, and as such the SAP offers a rare opportunity to study alkaline magmatism in the early Earth system. Previous geochemical investigations by Blichert-Toft et al (1995) on SAP's ultramafic (cumulates) to felsic (differentiates and/or feldspar-accumulates) suite of intrusions suggests derivation from shoshonitic (i.e., high-K) parental melts, which are most commonly found along active margins. The narrow distribution of SAP intrusions and a 2664 ± 3 Ma carbonatite-nephelinite complex just outside and along its south-western margin, however, also opens up for the possibility that these intrusions were emplaced in either a continental, back-arc, or post-orogenic rift system. Either way, the parental melts' high Mg# and LILE/HFSE-ratios seems consistent with hydrous melting of a mantle wedge source that had been metasomatized by hydrous fluids from a subducting oceanic slab.

Detailed mapping of the Skjoldungen area has so far been lacking, and one aim of the renewed field work was to carry out more detailed work in selected key areas in order to develop a better understanding of the overall petrogenesis of the SAP as well as evaluate the economic potential of the area. Specific key questions to address include: (1) define and constrain the geographical extent of the SAP, (2) through a vigorous U/Pb (and Ar-Ar) dating program to pin down the temporal evolution within the SAP, (3) characterize the parental magma types for the SAP magmatism using geochemistry and isotope analytical work, (4) evaluate the geotectonic setting for the emplacement of the SAP, and (5) identify any economic potential within predominantly ultramafic and layered intrusions.

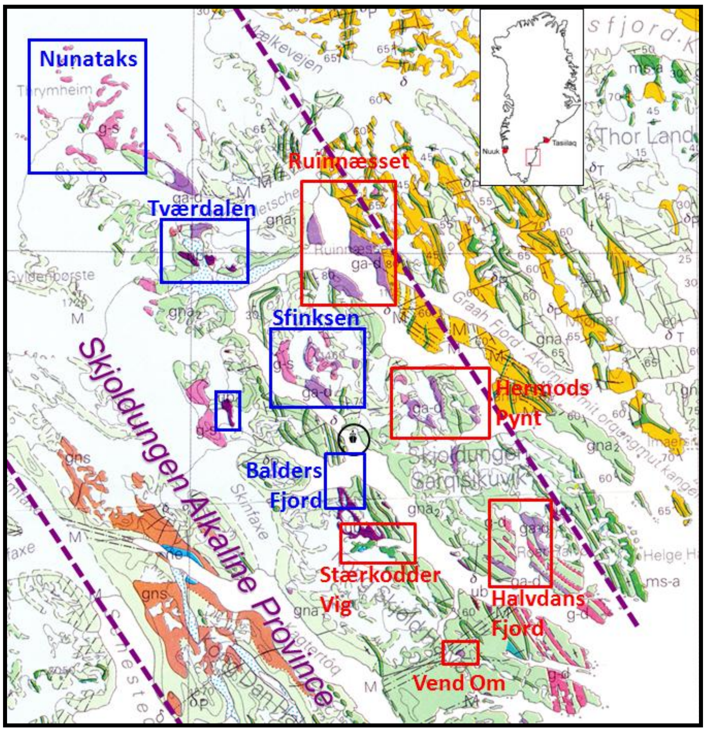

Figure 1. *Geological map of the central Skjoldungen area (Escher, 1990), showing the targeted areas by Team 3 during the 2011 field season. Red frames indicate field camp areas (typically of 2-5 days duration), blue frames indicate areas visited during helicopter reconnaissance (two half day trips) and drop-off (one day).*

Field observations and geochemistry data

The authors visited the SAP during four weeks in July-August 2011 and gathered in this period new field data from the mafic and felsic intrusions believed to make up the central part of the SAP (around Skjoldungen island). The areas visited include in chronological order, (1) Vend Om fjord, (2) Halvdans fjord, (3) Stærk Odder vig, (4) Balders fjord (boat reco), (5) Ruinnæsset, (6) Tværdalen, (7) inland Nunatak area (helicopter reco), (8) Hermods vig and (9) Sfinksen area (helicopter reco). Nearly 200 samples in total were collected in the field ranging in composition from mafic and ultramafic intrusive rocks (mela- leucogabbros and pyroxenites), to intermediate and felsic rock types (diorites, monzonites, syenites and granites), as well as, a number of dykes and sheets, including a number of Palaeoproterozoic dykes. A large selection of samples were processed and analysed for major and trace elements at the Central Analytical Facility (CAF) at the University of Stellenbosch, SA. The major element data are by XRF on fused glass discs whereas trace elements are determined by LA-ICPMS on same fused glass discs (Eggins, 2003).

Here we present new field observations and preliminary geochemical whole rock data for two selected areas: (1) the gabbroic 'Vend Om' intrusion and (2) the monzonitic-syenitic 'Ruinnæsset' intrusion. Field data and geochemical data from other of the areas visited will be available for discussion at the meeting.

Vend Om intrusion – a layered gabbro intrusion

The Vend Om intrusion consists of a c. 250×450 m large mafic layered mafic body (Fig. 2a) situated in the southeastern periphery of the SAP. The intrusion is made up of a 30-70 m wide marginal zone of coarse-grained and variably hornblende poikolithic melagabbro (Fig. 2b), surrounding a central part of a layered gabbroic sequence that shows repeated, gradational and steeply inclined magmatic layering (Fig. 2d-e). The layered sequence contains local horizons/bands of magnetite-rich rock that can be followed for over 100 m laterally and that locally reaches up to 1-2 m in thickness (Fig. 2f). Examples of crustal assimilation are observed at the marginal zone of the intrusion seen as hybridized rocks. Within the layered sequence xenoliths of leucogabbro is found forming drop stone structures and local depression of the layering (Fig. 2g). Locally towards the marginal zone, the intrusion is cross-cut by felsic pegmatites, and dating of these rocks will provide a minimum age of the Vend Om intrusion. The intrusion is generally fairly undisturbed by tectonic and metamorphic overprinting and therefore it is likely to represent a relatively late (single?) intrusive event within the SAP.

Gabbros of the layered sequence define a tholeiitic trend towards FeO-enrichment in the AFM diagram. Our working hypothesis is that this trend reflects accumulation of early crystallizing magnetite in the intrusion, consistent with the occurrence of more massive (cumulative) magnetite horizons. This included plagioclase accumulation, as indicated by progressive increases in Al_2O_3, Sr and Eu/Eu* with decreasing MgO and TiO_2 (Fig. 3).

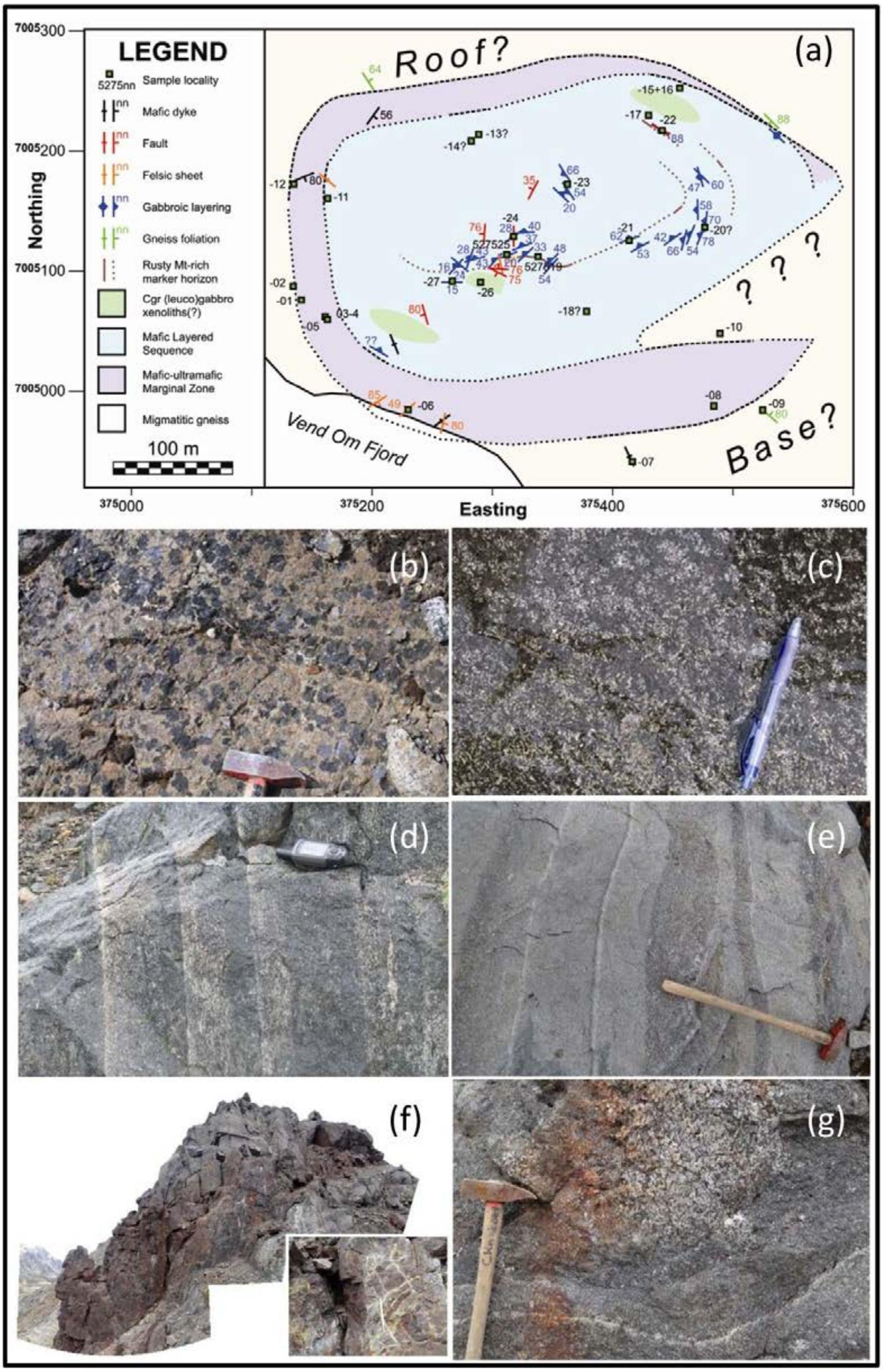

Figure 2. *The Vend Om intrusion. (a) New geological map of the intrusion showing sample locations and structural measurements of the magmatic layering. (b-e) Rock types as they occur from the margin towards the centre of the pluton. (b) Layered hornblende poikolithic (phyroblastic?) melagabbro. (c) Mottled gabbro texture. (d) Rhythmical modal layered gabbro, (e) Irregular (partly erosive?) and gradational layering in leucogabbro. (f) Massive horizon of almost pure magnetite within the layered gabbro sequence, 1-2 m thick, was traced for 100 m; insert: sporadic sulfide staining of rocks within* the magnetite-rich horizon. (g) Coarse grained leucogabbro found as a xenolith in the layered gabbro sequence forming drop stone structure.

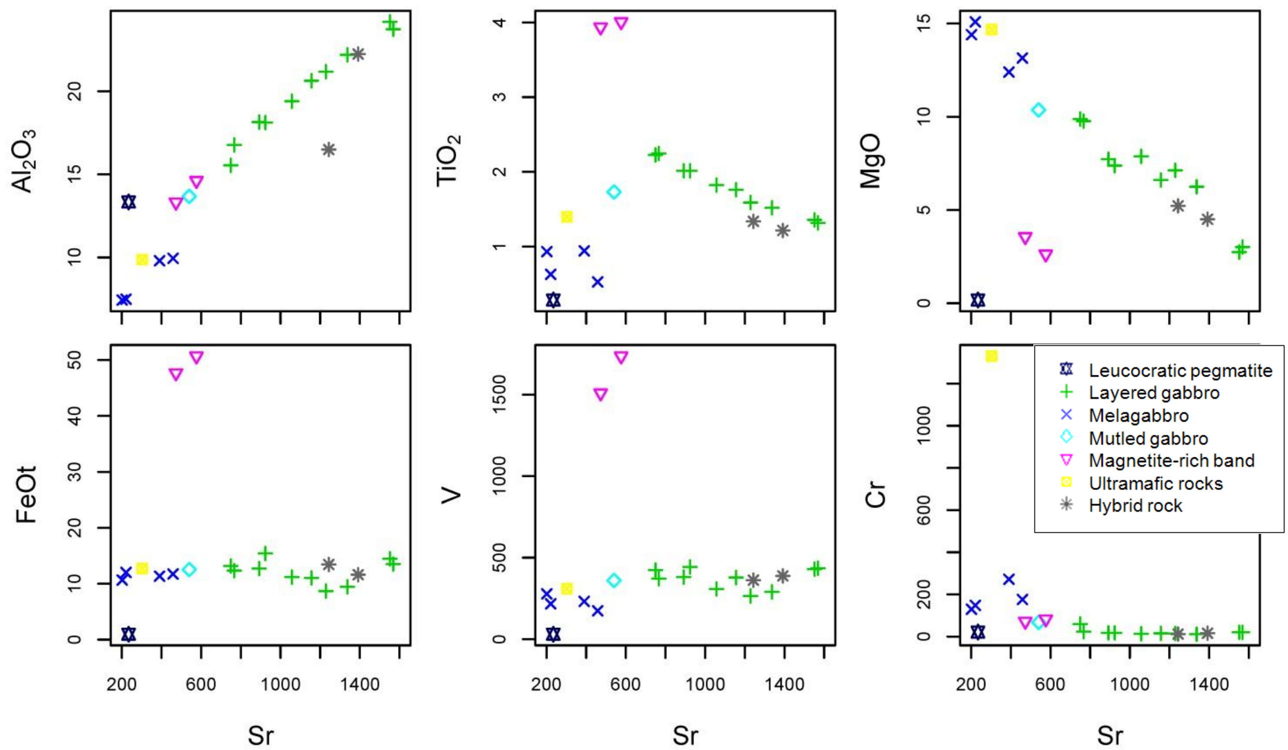

Figure 3. *Selected major (Al_2O_3, TiO_2, MgO, FeOt, all in wt% oxide) and minor elements (V and Cr, in ppm) plotted against ppm Sr for the Vend Om intrusion. Data indicate a control by cumulative processes, mainly through plagioclase accumulation. Note high contents of TiO_2 (~4 wt%) and V (≤ 2000 ppm) in the magnetite-rich rocks.*

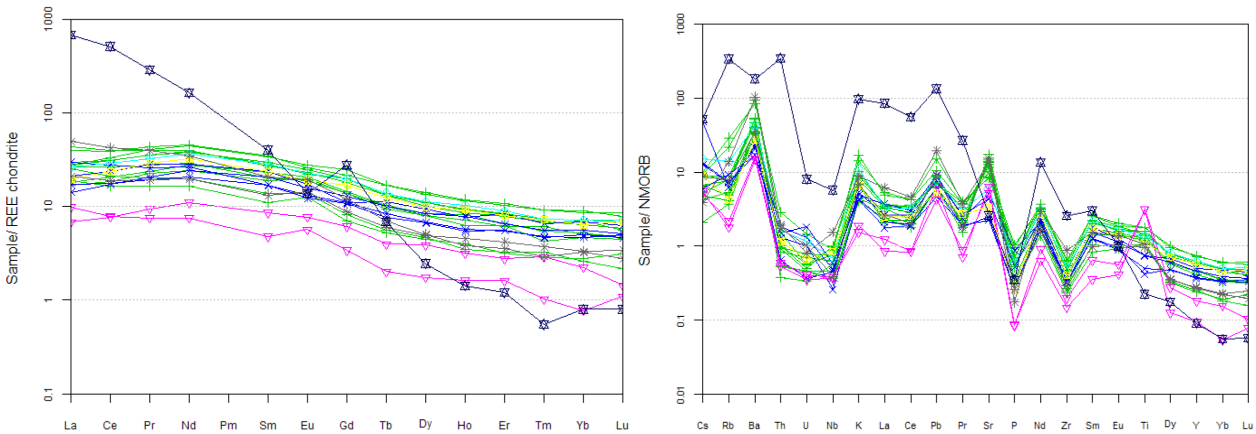

Figure 4. *Chondrite-normalised REE diagram (left) and extended primitive mantle normalised trace element diagram (right) for the Vend Om intrusion.*

All rocks of the Vend Om intrusion are only moderately enriched in the LREE's (<100 x chondrite) relative to the HREE (<10 x chondrite) (Fig. 4). In the extended trace element diagram the Vend Om rocks show enrichment in the LIL elements (Cs, Rb, Ba, K, Pb) and with pronounced positive anomalies for Sr relative to NMORB, consistent with a source region that was LILE-enriched by subduction zone processes and the above mentioned plagioclase accumulation. Future work will focus on establishing a fuller picture of the internal stratigraphy of the intrusion through more detailed mapping and sampling during the 2012 field season. Whole rock geochemical work will be complemented by micro-analytical and isotopic work, which will help to overall characterize the geological evolution of the intrusion, and help in evaluating any economic potential.

Ruinnæsset – a syenitic intrusion

The Ruinnæsset intrusion defines a c. 3×3 km large, well-preserved, rhomb-shaped intrusion (Fig. 5a) dominated by coarse grained syenites that shows variable modal layering (Fig. 5b). There is a systematic distribution of rock types within the intrusion, with the western part mainly being comprised of syenites and monzonites, whereas the eastern part also comprises more mafic lithologies, such as pyroxenites, gabbros and diorites, which occur as xenolithic domains or rafts in the syenite host (Fig. 5d). The main lithology is constituted by coarse grained syenite that commonly shows rhytmical layering as defined by c. 5-20 cm thick modally distinct layers rich in hornblende, pyroxene and Fe-Ti oxides. The intrusion is cut by multiple generations of late dykes, sheets and leucocratic pegmatites. Some of these late intrusions outcrop as irregular bodies that appear to intrude at a late magmatic phase into a semi-ductile (mush?) rock of syenite (Fig. 5e). Irregularly mafic bands rich in magnetite and apatite are observed to intrude the bulk lithologies (Fig. 5c), suggesting either these either represent late stage interstitial residual liquids that were squeezed out, or alternatively represent liquid immiscibility at a late stage of the magmatic evolution. A new zircon U/Pb age date of a ‘purple pegmatite’ sample gives 2632 ± 7 Ma (see Berger, Kokfelt and Ulrich, this volume). The main syenite body was zircon U/Pb dated to 2696 ± 7 Ma (Nutman & Rosing, 1994), suggesting an extended period of the overall magmatism in the area of at least 70 Ma.

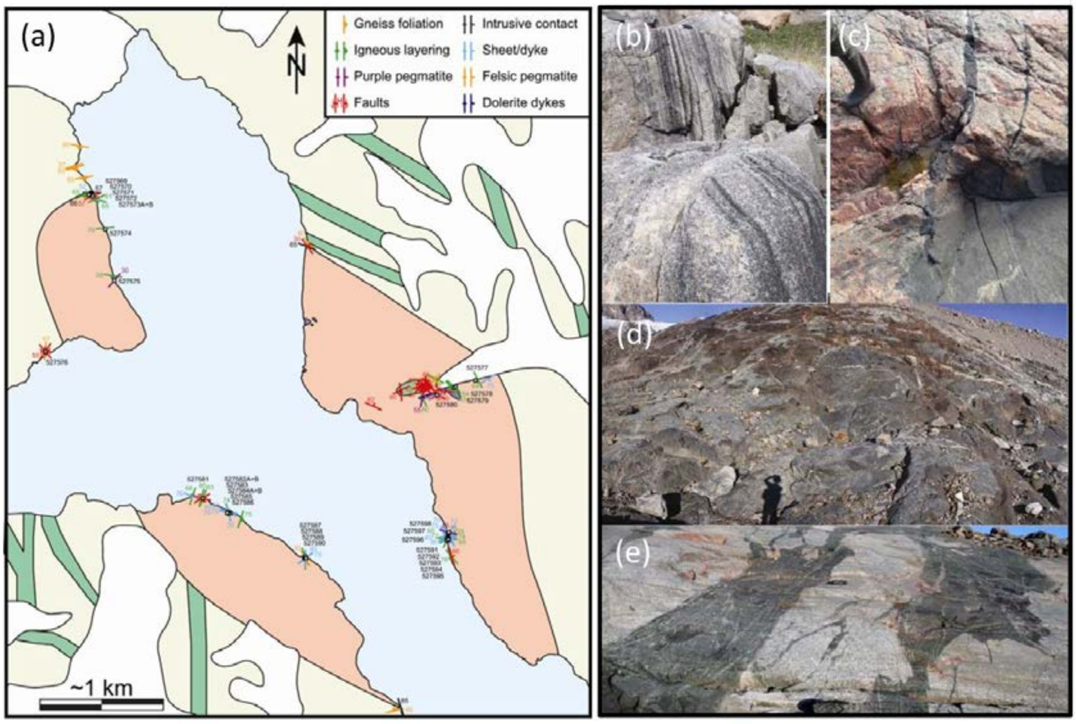

Figure 5. *(a) Geological map (sketch) of the syenitic Ruinnæsset intrusion. Sample localities and structural measurements taken during the 2011 field season are shown. The occurrence of more mafic and ultramafic rocks seems to be confined to a margin-parallel band along the eastern part of the intrusion. (b) Nearly vertical layering in coarse grained syenite, cut by a felsic pegmatite vein. (c) Late magnetite-apatite-rich mafic bands intruding into a host of syenite, possibly reflecting either extraction of interstitial residual melt or liquid immiscibility. (d) Xenoliths of metamorphosed and partly brecciated melanocratic rocks (melagabbroic to pyroxenitic rocks intruded by syenite) occur within a zone some hundreds of meters from the exposed eastern margin of the intrusion. (e) Intrusion of feldspar porphyritic monzonite into syenite; the irregularly lobate boundaries reflect the intrusion into a semi-ductile host rock.*

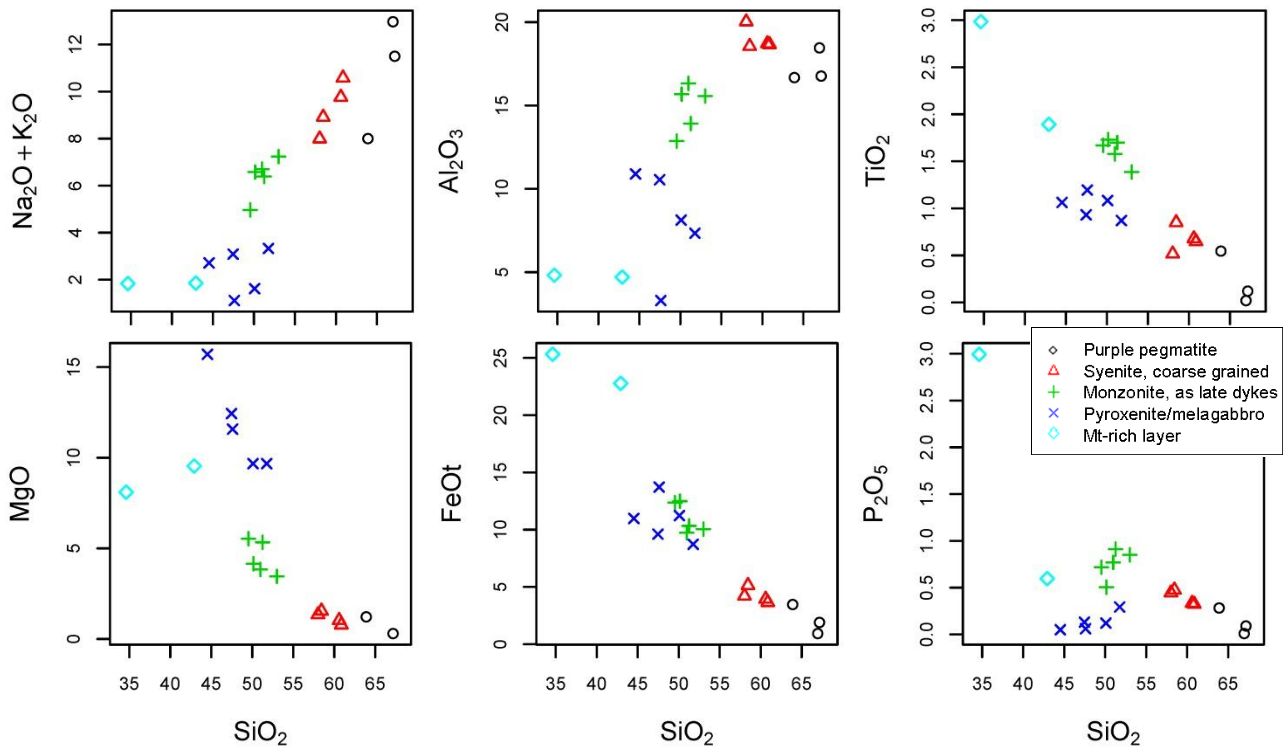

Figure 6. *Selected major elements for the Ruinnæsset intrusion; Al_2O_3, TiO_2, MgO, FeOt, and P_2O_5 plotted against SiO_2 (all in wt% oxide). The Ruinnæsset rocks define a wide, continuous compositional range over a wide spread in SiO_2 that indicate fractional crystallization as the main responsible process. Note the high FeOt (± P_2O_5) in the magnetite(±apatite)-rich layer samples.*

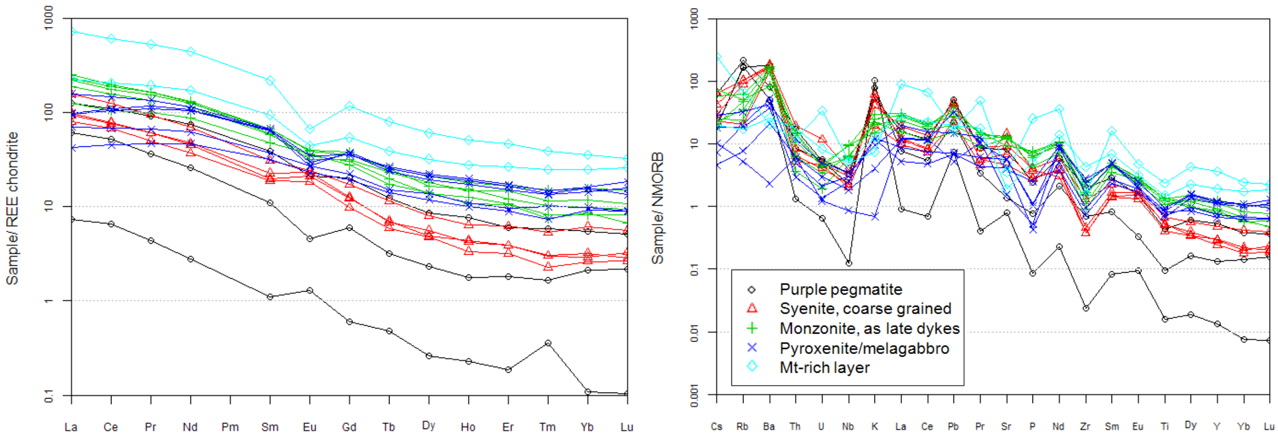

Figure 7. *Chondrite-normalised REE diagram (left) and extended primitive mantle normalised trace element diagram (right) for the Ruinnæsset intrusion.*

Overall, the Ruinnæsset rocks define an alkaline evolutionary trend (suite) towards enrichment in K_2O+Na_2O with increasing SiO_2 that likely reflects crystal fractionation processes exerting a main control on the chemical differentiation. The silicate rock samples show moderate to strong LREE enrichments (typically ~100-200 x chondrite) relative to the HREE (~10 x chondrite). The magnetite-rich samples are high in FeOt and generally enriched in REE's and P_2O_5, presumably reflecting variable modal abundance of apatite in these mafic layers.

Future work in the Ruinnæsset intrusion will encompass a detailed mapping and sampling campaign, followed by petrological studies based on whole rock and mineral chemistry data, and isotope data, as basis for constraining petrogenetic models and to explore its economic potentials.

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Mineral systems in the North Atlantic Craton of South-East Greenland

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The North Atlantic Craton (NAC) of South-East Greenland (SEG) represents a characteristic high-grade Archaean craton, consisting of migmatitic orthogneiss, narrow bands of mafic granulite, paragneiss and ultramafic rocks. The protoliths to the orthogneisses took place episodically by ca. 2865 to 2730 Ma probably into a basement of mafic granulite, paragneiss and ultramafic rocks. Alkaline rocks and carbonatites of the Skjoldungen Alkaline Province (SAP) intruded in two pulses at ca. 2720-2700 Ma and 2680-2650 Ma.

The area is structurally complex with evidence of at least seven deformation events including reclined and mushroom-like fold interference patterns. An early foliation formed during the > 2790 Ma Timmiarmiut Orogeny (D_T). The ca. 2790 - 2700 Ma Skjoldungen Orogeny (D_S) folds this early foliation, develops a penetrative foliation, and refolds this foliation progressively in a NE-SW oriented palaeostress field that rotated into NNW-SSE orientation in the last stages of the orogeny. The Skjoldungen Orogeny is characterized by syn-deformational anatexis during ca. 2790-2750 Ma at approximately 800°C and 5-8 kbar, with retrogression in the amphibolite facies at ca. 2730-2700 Ma. N-S extension during the Singertat Stage (D_R) formed discrete shear zones at greenschist facies grades and is coeval with pegmatite, ijolite, and carbonatite emplacement at ca. 2680 - 2650 Ma.

In the following, we identify different mineral systems for the NAC in SEG in order to evaluate the potential for mineralisation that could be of economic interest in the future. High-grade Archaean terranes are in general not well-endowed: “These terranes as a whole are about the least mineralised settings imaginable, avoided by explorationists” (Laznicka 2006). A few examples include orogenic gold deposits in the Limpopo Belt (Kolb et al. 2000; van Reenen et al. 1994), gold-copper intrusion related deposits in Western Australia (Allibone et al. 1998), IOCG deposits in the Amazon craton (Requia et al. 2003) and orthomagmatic Ni, PGE, Cr occurrences as, e.g., the Fiskenæsset Complex in southern West Greenland (Page et al. 1980; Ghisler 1970; Ghisler 1971).

The regional stream sediment data set records maximum values for gold of 35 ppb, and 3.1 ppt in water samples. Although reshaped, modified and pristine gold grains (up to 10 grains) have been found in moraine material, gold is considered to be not well-endowed in the study area. The areas to the south of Timmiarmiit Kangertivat and on Thor Land represent the strongest anomalies. Thor Land on the other hand is a strongly glaciated area. Quartz veins of the orogenic gold type have been observed on an island in Timmiarmiit Kangertivat. The quartz veins are narrow, form approximately 10 m wide zones that can be followed over several 100 meters along strike. The veins show a hydrothermal alteration halo of pyrrhotite-chalcopyrite-quartz-biotite-garnet, but are deformed and retrogressed to carbonate-chlorite-muscovite assemblages. One quartz vein sample returned 6 ppb gold, the alteration zone is below detection limit (< 2 ppb Au). Several prerequisites for the orogenic gold mineral system are not matched in the study area: (1) the regional metamorphic grade is in the granulite facies and, therefore, much higher than the typical greenschist facies PT window for orogenic gold; (2) no major long-lived structures have been identified to be spatially associated with the quartz veins and the gold anomalies; (3) no palaeo-craton margins have yet been identified; and (4) the geodynamic setting is probably not characterized by accretion of terranes. The most promising area for orogenic gold mineral systems will be the southern contact to the Ketilidian Mobile Belt, where accretionary tectonics at a craton margin could be associated with gold mineralising systems similar to those in the Limpopo Belt.

Both the younger intrusions of the SAP and the mafic-ultramafic rock assemblage of the basements host orthomagmatic mineralisations. Laterally extensive mafic-ultramafic bands, hosting Ni-Cu sulphide mineralisation can be found in the region between Graah Fjord and Bernstorff Isfjord. The sulphide mineralisation is also enriched in PGEs in the hundreds of ppb range. The ultramafic rocks are dominantly peridotites with a smaller volume of pegmatitic pyroxenites (Owen 2011). The ultramafic rocks can be subdivided into two generations based on their trace-element geochemistry (Owen 2011): (1) one generation sourced from a deep relatively undepleted mantle source; and (2) the other sourced from a shallow depleted mantle source. The shallow sourced ultramafic rocks host the majority of the mineralisation and probably interacted with a volatile, incompatible element, S, Cu and Ni bearing mineralising fluid in the mantle before emplacement in the deeper crust. Thus, this mineralisation does not represent a typical orthomagmatic Ni sulphide system (Owen 2011).

The mafic intrusions of the SAP host, locally, cm-scale magnetite bands and disseminated sulphides that are attributed to orthomagmatic mineral systems. Magnetite ± apatite bands have been found in the Vend Om and Ruinnæsset intrusions. Stream sediment data also indicate anomalies in the related elements (Fe, P, Ti, etc.) associated with these intrusions and also the Sphinxen Complex. The extend of the mineralisation observed in the field is relatively restricted; however, orthomagmatic mineralising processes have been active, which could have formed oxide and/or sulphide mineralisation elsewhere.

Orthomagmatic processes are also responsible for the formation of rare metal mineralisations (Nb, Ta, Zr, REE+Y, Th, U, Be, Hf) in alkaline rocks. Concentrations of these elements in stream sediment, water and rock samples are anomalous but not very high. Especially the rocks of the Singertât Complex and the Timmiarmiut Alkaline Province (TAP) are slightly enriched. The source of the melts that formed the rocks of the Singertât Complex is situated in a metasomatised mantle setting above a subduction zone (Blichert-Toft et al. 1995), which is considered one possible source of the rare metal enrichment in ore deposits. The alkaline rocks in the study area form, however, dykes, sills and plugs, which are too small for mineralising orthomagmatic processes, which require differentiation processes in larger magma chambers. Thus underlying magma chambers or hydrothermal processes would be required to enrich the rare metals to an ore grade. However, both have, to date, not been identified in the study area. The Ruinnæsset Complex is indeed a larger magmatic system, but despite of this, the concentration of rare metals remains relatively low, probably because the start magma had too low levels in the first place.

Magmatic hydrothermal mineral systems were not directly observed in the field. However, the intrusions of the SAP have the potential for having developed such systems. The layered mafic intrusions described above could be associated with IOCG mineral systems. Regional alteration systems that would account for IOCG mineralisation are, however, not observed and also not detected by remote sensing and Aster data. Water and stream sediment geochemical data indicate a Sn-In anomaly to the southeast of the Singertât Complex, spatially associated with syenitic-monzonitic rocks. The locus of the anomaly could not be recognized in the field, and hydrothermal alteration is not recognized by Aster remote sensing data. The lack of regional-scale hydrothermal alteration systems indicates that (magmatic) hydrothermal mineral systems have not been active at a larger scale that would have formed ore accumulations.

Anatectic paragneiss occurs in a small belt of several hundred metres strike extent on Helge Halvø. The paragneiss contains disseminated pyrrhotite, chalcopyrite and arsenopyrite with up to 0.2 wt.% As and Au in the hundreds ppb range. Based on metamorphic recrystallisation textures and the lack of hydrothermal quartz veins and alteration zones, this mineralisation is interpreted to represent a syn-sedimentary sulphide accumulation that was subsequently metamorphosed. Taken the low grades and the small lateral extent, this sulphide mineralisation is not considered to be of future economic interest.

Several mineral systems are identified in the NAC of SEG. The mafic and alkaline (ca. 2720-2700 Ma and 2680-2650 Ma) SAP intrusions are the most promising for future research on ore formation. The emplacement of these intrusions is associated with orthomagmatic processes and possibly also magmatic hydrothermal systems. Ore deposits related to these mineral systems could have formed in the study area, but only small, economically uninteresting occurrences have been found until today. Furthermore, Ni mineralisation is hosted in the ultramafic rocks of the basement, which probably formed by processes in the mantle rather than typical orthomagmatic systems.

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Tectonometamorphic evolution in the North Atlantic Craton of South-East Greenland

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The North Atlantic Craton (NAC) of South-East Greenland (SEG) represents a characteristic high-grade Archaean terrane, consisting of migmatitic orthogneiss, narrow bands of mafic granulite, paragneiss and ultramafic rocks. Alkaline rocks and carbonatites of the Skjoldungen Alkaline Province (SAP) intruded in two pulses at ca. 2720-2700 Ma and 2680-2650 Ma.

The earliest deformation fabric recognized is a foliation preserved in mafic and ultramafic rocks and the early- to syn-tectonic orthogneiss. The fabric is best preserved in the Timmiarmiut area and, therefore, named Timmiarmiut Orogeny (D_T). The S_T foliation in this area is a broadly NW-SE trending regional foliation, whereas it is only preserved at outcrop-scale in the other areas. Locally, a down-dip mineral stretching lineation (L_T) is observed in the S_T foliation planes.

The S_T foliation is folded into regional-scale upright to reclined isoclinal folds during the Skjoldungen Orogeny (D_S). The S_T foliation and the later penetrative axial planar (S_{S1}) foliation are usually parallel due to the isoclinal nature of the F_{S1} folds and can only locally be distinguished in the hinge zones. The F_{S1} fold axes plunge gently S in the Timmiarmiut area, whereas NW plunges are recorded in the SAP. The parallel arrangement of S_T and S_{S1} foliations in the orthogneiss that forms layers between the bands of basement rocks suggests that the oldest orthogneiss was emplaced in the basement rocks and its age marks that minimum age for the deformation prior to the Skjoldungen Orogeny at ca. 2790 Ma. The age of charnockite emplacement at 2785 ± 9 Ma (Nutman and Rosing, unpubl. data) indicates granulite facies conditions at that time.

The axial planar S_{S1} foliation is the regional, penetrative, locally mylonitic, NW-SE trending fabric in the SAP. The S_{S1} foliation dips mainly moderately to steeply to the SW. The L_{S1} mineral stretching lineation plunges (1) to the west in the western part, (2) south in the central area, and (3) southeast in the east such as on Helge Halvø. Together with abundant S-C, S-C' and mica-fish fabrics, this indicates reverse to oblique-reverse movement to the NE. Some of the (2720-2700 Ma) SAP rocks have a magmatic foliation parallel to S_{S1}. In the Timmiarmiut area, the S_{S1} foliation is near vertical, trending NE-SW. The penetrative S_{S1} foliation is folded into regional-scale open to close folds (F_{S2}), forming "mushroom" shaped fold interference patterns. Higher-order F_{S2} folds are close to isoclinal, gently to moderately inclined, and the fold axes plunge at shallow to moderate angles to the W.

Three types of D_{S2} shear zones are developed at a smaller scale: (1) several tens of meter wide reverse D_{S2} shear zones that sheared off fold limbs preferably at the contact between orthogneiss and mafic granulite south of Bernstorff Isfjord; (2) discrete cm-m wide, northeast-southwest trending, near-vertical, sinistral D_{S2} shear zones; and (3) < 20 cm wide, east-west trending, near-vertical, dextral D_{S2} shear zones. The near-vertical shear zones form a conjugate set together with syn-tectonic pegmatite dikes, and trend NNE and NW. These shear zones and pegmatites are common features that are particularly found associated with intrusions of the SAP and can be followed over several 100s of meters to kilometers. The acute angle in a northerly orientation and N-S trending extension veins suggest north-south compression and east-west extension during D_{S2}. The Skjoldungen Orogeny is characterized by syn-deformational anatexis during ca. 2790-2750 Ma at approximately 800°C and 5-8 kbar, with retrogression in the amphibolite facies at ca. 2730-2700 Ma. The latter stage in the evolution of the region was synchronous with the emplacement of the alkaline intrusive rocks forming the SAP in a subduction setting. Our U-Pb zircon age data shows a continuous evolution from ca. 2755 Ma to 2700 Ma with emplacement of intrusions and metamorphic recrystallisation, suggesting a protracted convergent setting during the Skjoldungen Orogeny that lasted ca. 50 m.y., which is correlated with the exhumation of the high-grade rocks.

A conjugate set of up to 1 m wide, near-vertical, sinistral NW- and dextral NE-trending shear zones are present in the Singertât Complex. The shear zones formed under retrograde greenschist-facies conditions and cross-cut all rock types. These zones can be followed over several 100s of meters. The orientation of these shear zones is indicative of N-S extension and E-W compression during deformation, which is here assigned to the Singertat Stage. Relaxation of the Skjoldungen Orogeny stress field at ca. 2680-2650 Ma lead to orogen-normal extension and emplacement of late granites. This extensional stage correlates to the Singertat Stage, where the carbonatite-bearing ijolite was emplaced, arguing for a post-orogenic extensional setting. Incidentally, this ca. 2680-2650 Ma age marks the youngest Neoarchaean event in the evolution of the NAC in Greenland.

This evolution can be compared to similar tectonometamorphic stages in the Tasiusarsuaq Terrane of western Greenland and the Lewisian Complex in Scotland, suggesting widespread deformation during 2800-2700 Ma. This would imply a large Archaean terrane that would span at least 500-600 km east-west and at least 200 km in north-south extent, which is not unusual for Archaean cratons preserved in Canada, southern Africa, South America, and Australia.

Field observations and geochemical characteristics of the supracrustal rocks at Helges Halvø and Langenæs.

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Helges Halvø contains one of the main exposures of supracrustal rocks in the Skjoldungen region and the supracrustal rocks observed on Lange næs compose the same rock types. Here describe our field observations from 2012 from these two areas (Fig. 1) and explore the geochemistry of ultramafic, mafic and felsic gneisses.

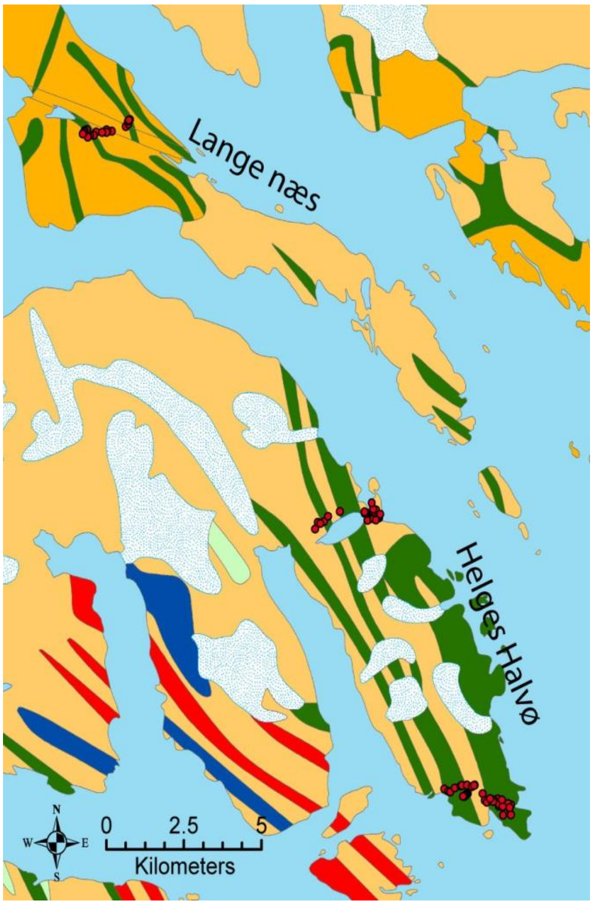

Figure 1. *Map of Helges Halvø and Lange næs. Visited stations are shown.*

In the supracrustal units, mafic gneiss and migmatite form the main rock types and generally consist of equal portions of pyroxene and plagioclase with some outcrops containing minor amounts hornblende. A well developed foliation is observed in most of the mafic rocks and isoclinale folds are observed in some outcrops. Leucocratic pyroxene bearing veins, often set in an undeformed network, constitute various amounts of the mafic gneisses (Fig. 2A). Rare lenses of coarse grained igneous textured rocks containing pyroxene and plagioclase are observed as 2-5 m wide enclaves within the mafic gneiss, and along the contact between the mafic and felsic gneisses. Ultramafic rocks are fine grained often with mineral filled extensional fractures; they outcrop as small lenses up to 5 m wide and appear to concentrate into distinct zones following the main foliation within the mafic gneisses. Garnet bearing mafic gneisses and garnet bearing quartzite are associated with rusty weathered horizons that are parallel to the main foliation.The horizons are typically between 10-30 m wide, occurring repeatedly and transverse the field area and are commonly associated with centimetre scale quartz veins and region scale faults, folds and fracture systems. The larger units of mafic and ultramafic gneisses outcrop in 100-400 m wide units that are possibly continuous for several km as indicated on the map (Fig. 1).

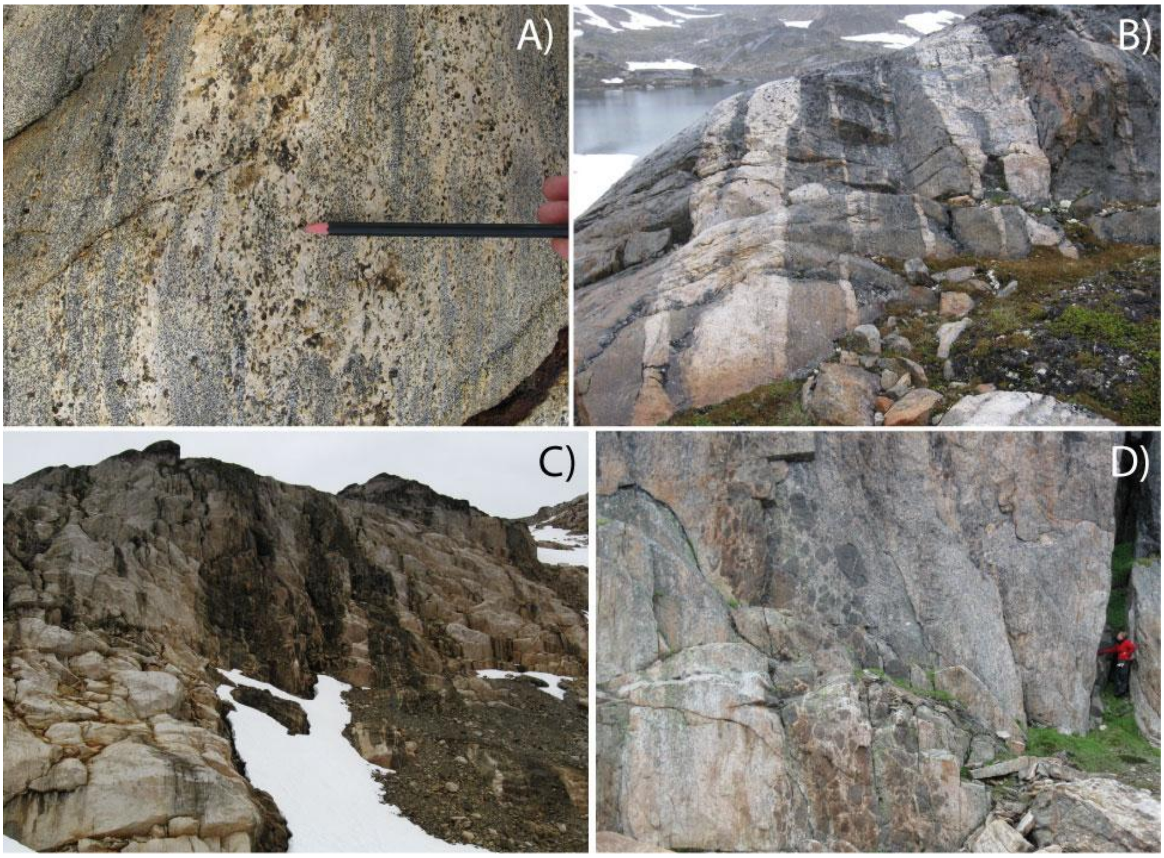

Figure 2. *Field images from Helges Halvø and Langenæs.* ***A)*** *Px bearing veins in mafic gneiss.* ***B)*** *Mafic gneiss intruded by felsic sheets.* ***C)*** *Mafic enclaves in slightly deformed granitoid.* ***D)*** *Agmatitic textures in slightly deformed granitoid.*

The mafic gneisses are often intruded by felsic rocks that range from cm to meter wide veins or sheets that in some places transgresses into major intrusive bodies several of hundreds meters wide (Fig. 2B, C). Felsic gneisses and granitoids mainly consist of plagioclase, quartz, hornblende, pyroxene, ±K-feldspar and are present in two generations throughout the studied area. These include early foliated and strongly deformed gneiss and a late weakly or undeformed granitoid commonly structurally discordant to the surrounding gneiss. The undeformed granitoid appears in some locations to be petrographically continuous with the leucocratic px bearing veins in the mafic gneisses. In areas dominated by felsic gneisses, mafic enclaves are common (Fig. 2C) and the characteristic agmatitic textures can be observed as transitions from the mafic to the felsic units or as distinct zones within the felsic units (Fig. 2D).

Based on field appearance and geochemistry (mainly REE pattern) we have made a preliminary classification of the main rock types as follows.

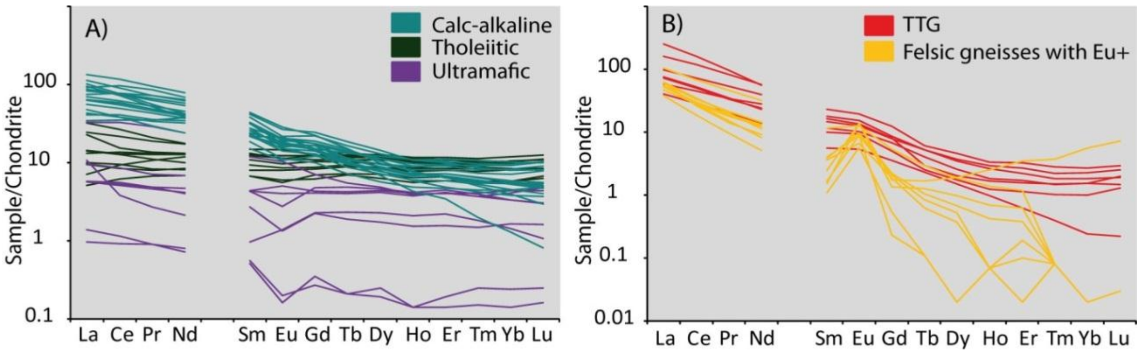

Figure 3. *REE patterns of the different groups. A) Mafic and ultramafic gneisses; B) TTG gneisses and felsic gneisses. Concentrations are normalized to chondrite (Boynton 1984).*

Mafic gneisses are classified as calc-alkaline and tholeiitic (Fig. 3A) with a sub-group displaying pronounced negative Eu anomalies (not shown). The calc-alkaline rocks have a smooth REE pattern (chondrite normalised), with enriched LREE and a flat HREE pattern (Fig. 3A). The tholeiitic rocks have flat REE patterns some with slightly depleted or enriched LREE elements, generally the REE are 6-12 times enriched compared to chondrite. For most major elements the calc-alkaline and tholeiitic rocks plot together. However, K_2O and Rb contends are distinctly higher in calc-alkaline rocks. Two garnet bearing rocks have been analysed and these fall within the calc-alkaline suite for most elements and have similar REE patters, however both samples show depletion in CaO and Na_2O and one of the samples are enriched in Fe_2O_3. Ultramafic units form quite a heterogeneous group with MgO values ranging from 20-45 wt.% they often form coherent trends for major element plots and generally have the lowest concentration of REE element, which however also shows large variance in patterns (Fig. 3A). In one profile sampled across ca. 200 m thick unit of mainly mafic and ultramafic gneisses that is strongly deformed and sheared, the north western section is tholeiitic and the south eastern section is calc-alkaline, whether this reflect an original compositional variation or that the calc-alkaline unit has been subjected to a higher degree of late stage overprinting e.g. by melt infiltrations are at present uncertain.

Felsic orthogneisses divides into two groups one that classify as tonalite-trondhjemite-granodiorite (TTG) and one that is characterised by strong positive Eu anomalies and by having very low and fractionated HREE contents (Fig. 3B). The felsic otthogneisses with positive Eu anomalies have the highest SiO_2 contends and show increased K_2O/Na_2O ratios when compared with the TTGs. Geographically TTG gneisses are mainly from the outer tip of the Helges Halvø whereas felsic gneisses with positive Eu anomalies are from Lange næs and the north western area of Helges Halvø (Fig. 1), however this might reflect a sample bias as we have not yet been able to distinguish the two types based on their texture.

Our preferred interpretation based on our field observation and geochemistry is that the mafic gneisses on Helges Halvø and Lange næs form the original basement, this mafic crust likely contained both calc-alkaline and tholeiitic rocks and probably represent a mafic protocrust. The mafic protocrust were initially intruded by felsic rocks that are now represented by the strongly deformed variety and this event likely reflect the initial differentiation event stabilising felsic crust. This differentiated crust section experienced a later remelting event during which the exposed basement was migmatised and intruded by the second phase of felsic rocks, the now relatively undeformed granitoids. Whether there is a relation between two geochemical groups of felsic gneisses (the group with TTG chemistry and the group displaying positive Eu anomalies and low HREE concentrations) with the two intrusive events have at present not been resolved, however it seems that both the deformed and undeformed varieties display both types of geochemical characteristics. This problem probably needs to be solved by isotope geochemistry and geochronology. The rusty-weathered zones are interpreted as garnet bearing versions of the mafic gneisses and/or garnet bearing silicified gneiss. This interpretation is based on the similar geochemistry of mafic and garnet bearing gneisses and the association with the regional faults and quartz veining, thus our interpretation is that garnet bearing zones have a hydrothermal or mesothermal origin.

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Characterisation of nickel sulphide mineralisation between Graah Fjord and Bernstorff Isfjord, South-East Greenland

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Laterally extensive mafic bands, hosting Ni-Cu sulphide mineralisation can be found throughout the orthogneiss which dominates the relatively unexplored region between Graah Fjord and Bernstorff Isfjord in South-East Greenland. The mafic bands are dominantly gabbroic in composition but they do show large variation, ranging from gabbros to pyroxene hornblende norites. The mafic bands display some similarities with the mafic complex of the Ivrea-Verbano Zone (IVZ) in Italy which is thought to represent lower crustal material. Amphibole-bearing ultramafic bodies can be found locally within the mafic bands. The ultramafic rocks are dominantly peridotites with a smaller volume of pegmatitic pyroxenites. It seems most likely that the mafic bands of this study represent lower crustal material intruded by mantle-sourced ultramafic magmas.

The ultramafic rocks can be subdivided into two generations based on their trace-element geochemistry. One generation was most likely sourced from a deep, relatively undepleted mantle source, while the other was sourced from a depleted shallow mantle source. The shallow sourced ultramafic rocks host the majority of the mineralisation and display evidence for having interacted with a volatile, incompatible element, S, Cu and Ni bearing fluid. This fluid is interpreted as a key factor in the formation of the mineralisation.

All of the rocks comprising the mafic bands show enrichment of incompatible elements with Nb depleted relative to K and La. This is interpreted as evidence that all of the lithotypes in the mafic bands have interacted with a second, incompatible element bearing, Nb depleted fluid.

The mineralisation in the study area most likely does not represent a typical orthomagmatic Ni sulphide system, which are usually controlled by processes at the site of emplacement including interaction with crustal material. Rather, this mineralisation is controlled by mantle fluid processes.

Observations of Mesoarchean melt formation and migration in Langenæs and Helge Halvø, South-East Greenland

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The Skjoldungen region of South-East Greenland exposes a well-preserved section of Mesoarchean mid- to lower-continental crust that provides a unique window into crustal evolution and differentiation processes during the Archean. Langenæs and Helge Halvø, within Skjoldungen, preserve a sequence of mafic granulite rocks exhibiting clear textural evidence for having been subjected to in-situ partial melting, and subsequent generation of TTG melt. These rocks exhibit an aerially extensive network of former melt-bearing veins that preserve evidence of TTG melt generation in the lower crust and transport from mm-scale leucosomes within the mafic granulite to m-scale dikes that are structurally discordant to the mafic granulites and appear to be feeding larger-scale mid-crustal TTG bodies.

Mafic granulites in Helge Halvø and Langenæs are predominantly Px-Pl bearing and exhibit evidence of having been partially melted. The degree of migmitization increases along the traverse from Camp 1 on the Atlantic Coast of Helge Halvø to Camp 3 further inland on Langenæs, with only minor leucocratic layering observed at Camp 1 and extensive in-situ leucocratic layering indicative of a former widespread melt-flow network feeding multi-meter-scale tonalite dikes observed at Camp 3. The gradation in degree of former partial melt observed between Camps 1 and 3 requires either the exposure of differing levels of crust or compositional differences in the mafic granulites.

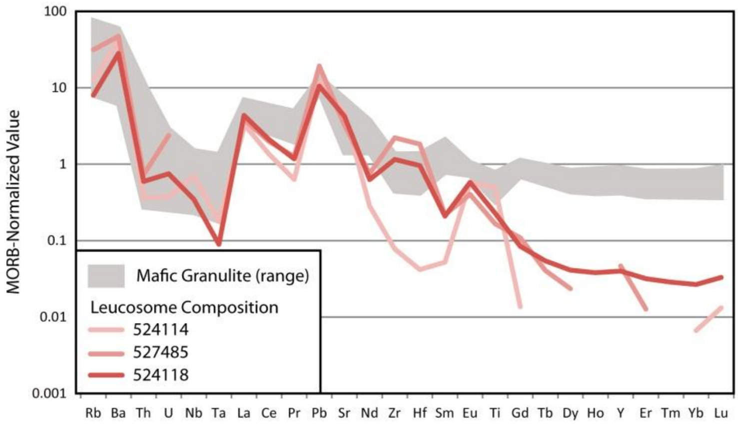

Figure 1. *N-MORB-normalized (Arevalo and McDonough 2010) trace element pattern of mafic granulites and leucosomes derived from partial melting of mafic granulites in Langenæs. Elements are arranged in order of decreasing MORB-melt compatibility.*

The highest degree of former partial melting is observed in the mafic granulites on Langenæs. Leucocratic layers within the mafic granulites on Langenæs are characterized by cm-scale peritectic Opx, and form a large-scale network of former melt-bearing veins, in which smaller mm-scale foliation-parallel leucosomes are petrographically continuous with larger cm-scale structurally-discordant former melt-bearing channels which are texturally consistent with having fed large TTG sheets. The cm–m scale TTG layers exhibit enrichment in the most incompatible elements, HREE depletion, and are characterized by strong Pb enrichment, a subchondritic Nb/Ta ratio and higher Mg-number (~50). Trace element systematics are broadly consistent with these TTGs falling in the medium-(to high-) pressure sodic TTG groups of Moyen [2], suggesting partial melting of the mafic granulites occurred at pressures around ~1.5 GPa. Some of the larger-scale TTG dikes in exposures of structurally higher crustal levels exhibit similar geochemical characteristics, suggesting that partial melting of Px-Pl mafic granulites is one source of TTGs in South-East Greenland.

Kimberlite emplacement patterns in Canada and West Greenland: Expectations for the East

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A glance at the geological map of the North Atlantic region suggests that South-East Greenland should be a prime exploration target for kimberlite diamond deposits. The approximately 100 x 300 km large area predominantly consists of Mesoarchean and Neoarchean basement rocks (Kolb et al., 2012) and, thus, satisfies Janse's Rule, in which it was recognized that kimberlite diamond deposits are confined to Archean continental blocks (Janse, 1984). However, kimberlites and related rocks have not yet been discovered in South-East Greenland, and first indicator mineral surveys have yielded rather discouraging results. In my presentation I will evaluate the likely reasons for a possible dearth of kimberlitic rocks in South-East Greenland. On a more positive note, I will speculate about the possibility of a new kimberlite province in South-East Greenland.

The following approach seems appropriate: First, I will give a brief summary of our current understanding of diamond formation and kimberlite magma generation in the Earth's mantle. This will be followed by a detailed analysis of kimberlite emplacement patterns in Canada and West Greenland, as well as in northern Europe, which is relevant for our understanding of the lithospheric control on this deep magmatic activity (Kjarsgaard, 2007). The observed kimberlite emplacement patterns will be viewed together with modern plate reconstructions, which provide the basis for my optimistic expectations for a new kimberlite discovery in South-East Greenland.

Although an early assessment of the diamond potential of South-East Greenland should be primarily based on classic exploration tools such as indicator mineral studies, modern concepts of craton formation must also be taken into account. For example, recent studies on mantle-derived xenoliths from West Greenland have provided strong evidence for the coupling of Archean crust and mantle throughout much of the history of the North Atlantic craton (Wittig et al., 2010; Tappe et al., 2011). In other words, Janse's Rule truly applies in West Greenland, where we now know with confidence that Archean crust is indeed underlain by Archean mantle. Importantly, the latter has the highest likelihood of being diamond-bearing (Gurney et al., 2010), because it had the possibility of experiencing the highest number of potential diamond forming metasomatic events. For South-East Greenland, on the other hand, it seems almost impossible that a thick diamond-bearing Archean mantle root has survived the tectonic stresses and thermal perturbations associated with repeated continental break-up along this rifted margin. In South-East Greenland, sampling of diamondiferous mantle by kimberlite eruptions would depend more than in any other Archean continental block on the timing of the deep magmatism in relation to break-up related erosion of the cratonic root.

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Reconnaissance of the economic potential of the Timmiarmiut region - Field observations and results from the 2011 SEG field season.

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Field reconnaissance in the Timmiarmiut area was carried out to follow up the spectral indications interpreted from the ASTER multispectral satellite imagery, identified as gossans, limonitic/hematitic alteration, vegetation anomalies and other types of hydrothermal alteration. The interpretation of the thermal infrared (TIR) data outlined minor mafic-ultramafic lithologies, some of them could be tentatively interpreted as carbonate rocks. Gossans and limonitic/hematitic alteration are related to major volcanic-sedimentary supracrustal sequence with graphite and Fe-sulphides- in places as massive sulphide bodies with minor chalcopyrite and arsenopyrite. The conspicuous vegetation and TIR anomaly in Narssaq is related to an igneous body of gabbroic composition with abundant carbonate veining. The postulated carbonatite potential of the area remains unclear – minor bodies of marble as part of the migmatite as well as discordant portions of pervasive carbonatisation of the agmatitic migmatite occur in the Timmiarmiut area.

ASTER multispectral satellite imagery – mapping the lithological features in South East Greenland

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The Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) aboard NASA's Terra satellite measures thermal infrared (TIR) emission from the earths surface. Based on the TIR spectral properties of rocks several mineral indices including the Quartz index (QI) Carbonate index (CI) and mafic index (MI) for detecting mineralogical or chemical composition of quartzose, carbonate and silicate rocks with ASTER-TIR data are available. The 90 m spatial resolution of the ASTER-TIR data was used to detect the major lithological categories in selected parts of the Skjoldungen - Timmiarmiut area.

The geochemistry of mafic and ultramafic basement rocks in the Skjoldungen area SE Greenland

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Introduction

The Skjoldungen alkaline province (SAP) comprises a variety of alkaline intrusions that range from ultramafic/gabbroic to evolved syenitic and nepheline-bearing rocks that intruded into older basement rocks. The focus of this study, however, is the geochemical signature of the basement rocks, in particular the mafic and ultramafic rocks (see also Berger et al., this issue for a discussion of the felsic rocks). The basement rocks are composed of agmatic and grey gneisses with variable migmatitic textures. The agmatic gneiss contains several types of mafic and ultramafic inclusions that show older internal structures. The protolith of these gneisses intruded supracrustal sequences that are characterized by mafic granulites/amphibolites, ultramafic units and possibly metasedimentary garnet-sillimanite-bearing gneisses with migmatitic textures in places (e.g., Kolb et al in review). The basement rocks underwent several stages of deformation and metamorphism and have likely reached conditions of partial melting in places as indicated by petrological (migmatitic textures, reworked/inherited zircons (e.g., Kolb et al in review)) and geochemical (large spread in element concentration, see Berger et al., this issue) constraints.

The aim of this study was to characterize (based on geochemistry only so far) the mafic and ultramafic rocks that occur in the supracrustal sequences and as inclusions in the agmatic gneiss.

The database

The whole-rock geochemical database for the Skjoldungen area was compiled by B. Møller Steensgaard and comprises data from the first expeditions in the 80's as well as more recent data from the 2009 and 2011 GEUS expeditions.

Mafic and ultramafic rocks were roughly singled out based on the SiO_2 content (<60wt%) of the analysis. Furthermore, only analyses that carried a rock description/classification were used. The latter constraint decreased the number of potentially mafic and ultramafic rocks to be used from the database and requires following up on verification of locations based on coordinates. Therefore, the present results are preliminary and it is expected that more data will be added.

Due to the lack of trace element data for several of the older geochemical analyses they are not represented in all of the plots.

Results

The complex geological history of multiple deformation and metamorphic events potentially alters the trace element content of the rocks. Consequently, the data were screened on alteration features based on the criteria in Polat and Hofmann (2003). Using various element correlations (e.g., REE, Ti, Nb) with Zr we were able to single out samples that were affected by post-magmatic element changes. They are not included in the further discussion of the samples. Furthermore, trace element spider diagrams (normalized to N-MORB) were used to distinguish different groups of samples and also to detect altered samples.

Up to date, 6 main groups of rocks were distinguished (Fig. 1), whereas group 3 and 4 show similar trace element patterns, but group 4 rocks are dominated by high Mg-samples. Equally, group 5 samples are divided in two subgroups, 5a and 5b, where the latter group is showing a weaker Ti depletion.

The general feature of the trace element patterns in all the groups is a moderate to strong Nb depletion. In Group 2 samples the Nb concentration is even below detection limit (0.2 ppm). Group 6 has the smallest Nb depletion compared to Th. Moreover, Ti and Zr show negative anomalies to different degrees. Zr is always depleted, whereas the Ti anomaly is not always present. These anomalies could indicate that rutile was a residue phase during melting.

An additional feature of the trace element patterns is the La to Nd slope, which distinguishes group 1 and 4 from the other groups. Overall group 5 shows the most fractionated pattern between LREE and HREE, whereas the other groups have generally flat HREE patterns. HFSE correlations were used to delineate possible sources and and tectonic settings. This is however, very pliminary and will be extended in the ongoing study of the mafic and ultramafic rocks from the Skjoldungen area.

Based on the Zr and Y plot (Fig. 2) it can be seen that the data trends from the tholeiitic field across the transitional to the calc-alkaline field. Obviously the high Mg rocks have low Zr and plot to the tholeiitic and transitional fields.

Figure 3 shows the trace element ratio between Nb-Yb-Th and indicates that a large portion of the data has comparable ratios to Cenozoic oceanic island basalts (see also Polat et al., 2011). Nevertheless, group 6 samples fall on a MORB-OIB trend related to mantle wedge melting. In contrast the more vertical trend indicates crustal contamination (Polat et al., 2011).

The Ba-La-Nb ratio plot in Figure 4 indicates that all data plot in the field for Archean arc-like rocks (see also Jenner et al 2009).

Condie (2005) used HFSE ratios to distinguish basalt from different tectonic settings. We use the Nb-Th-Zr plot to show our data (Fig. 5). It can be seen that all group 4, and a large portion of group 5 samples, plot in the arc field and an enriched component. Group 3 and 6 as well as some of the group 5 samples fall on a mixing trend between primitive mantle and depleted mantle in the oceanic plateau basalt field.

Further interpretation of the data will follow during a later, more advance stage of the study.

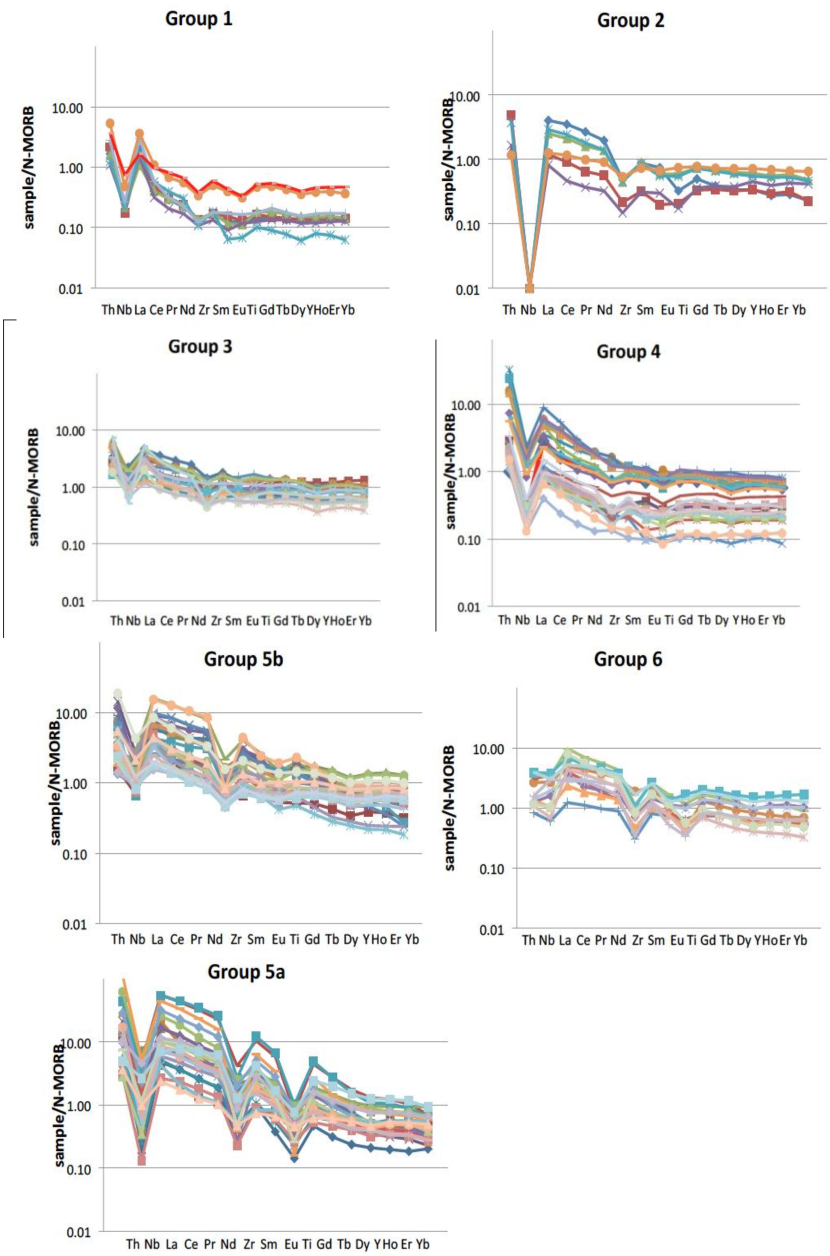

Figure 1. *N-MORB normalized trace element patterns for mafic and ultramafic rocks from the Skjoldungen area. (N-MORB values from Sun and McDonough, 1989).*

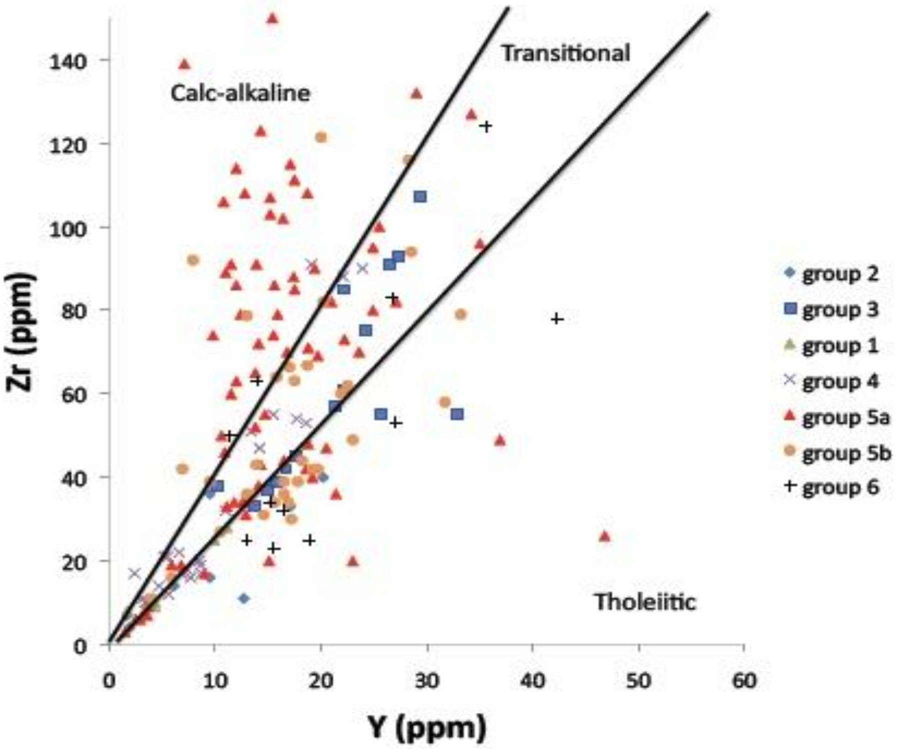

Figure 2. *Y-Zr classification diagram (adopted from Ross and Bedard, 2009)*

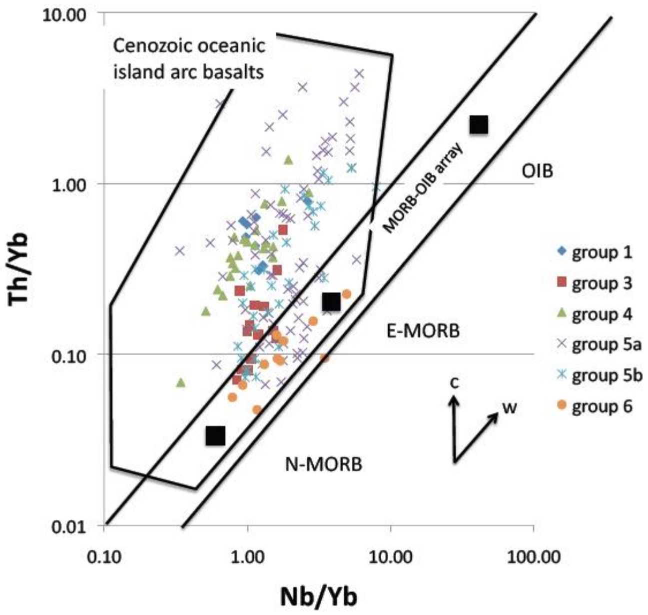

Figure 3. *Petrogenetic variation diagram showing a trend of crustal contamination (vertical, c) and mantle wedge melting (w) along the MORB-OIB array. The field of Cenozoic oceanic island arc basalt is defined from 700 analyses from the GEOROC database (see also Polat et al., 2011)*

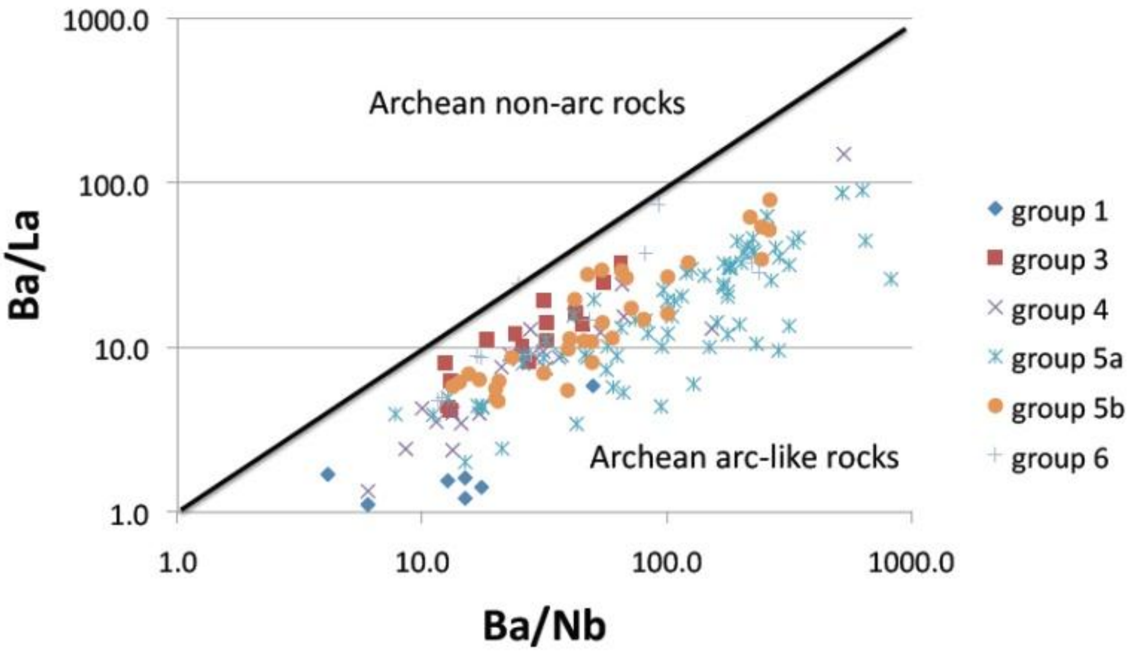

Figure 4. *Ba/Nb-Ba/La covariation diagram showing that all data plot in the field for Archean arc-like rocks.*

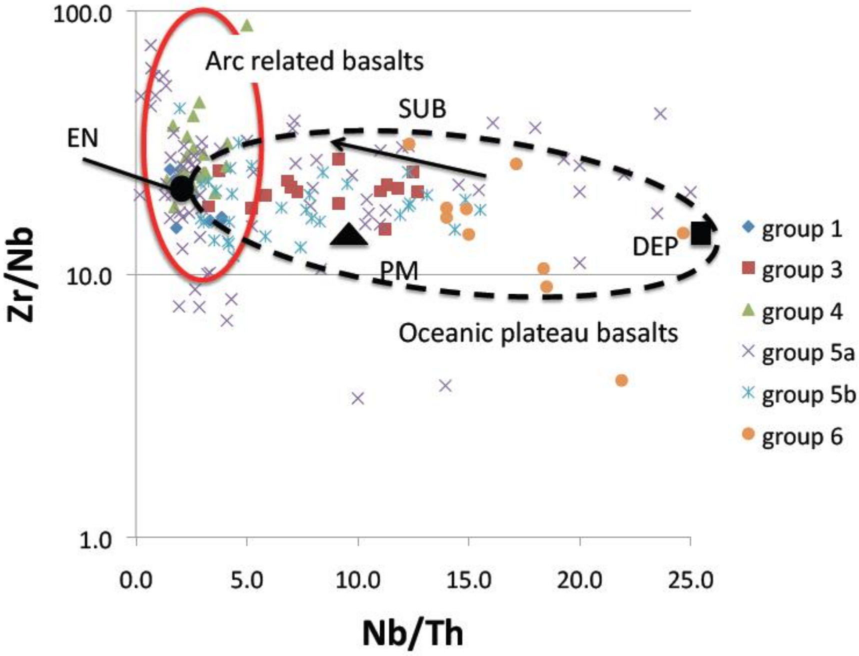

Figure 5. *HFSE ratio diagram showing mantle component fields and tectonic settings for basalts. EN: enriched component, PM: primitive mantle, DEP: deep, depleted mantle, SUB: arrow shows effect for subduction (see also Condie 2005)*

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Archaean subduction in Greenland shown by diamonds from kimberlite (West Greenland) and the oldest carbonatite in the world (South-East Greenland)

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Introduction

The $\delta^{13}C$ in carbonatites, kimberlites and diamonds in a mantle is normally in the range -3‰ to -8‰ while biologically derived carbon is more depleted in $\delta^{13}C$ as a result of photosynthesis during which organisms preferentially take up ^{12}C. Current research has been directed towards investigation the source of carbon in Archaean rocks from South-East Greenland and diamonds from West Greenland to test if carbon originates from early Archaean seafloor sediments which were subducted into the mantle.

Sample preparation and analyses

1. We collected nine carbonatite samples from Singertat nephelinitic-carbonatitic complex and one from a carbonate-quartz vein in supracrustal rocks in Langenæs peninsula (Table 1). Rocks including carbonates were located on either sides of Singertat delta and to the north and south from Kassortoq fjord (Fig. 1). We extracted some of the samples from carbonatite matrix, other from syenitic pegmatites in ijolite and carbonatitc breccia.
2. We mechanically disaggregated and crushed rocks.
3. We hand picked calcite under a stereomicroscope.
4. We weighted 8 mg of sample and packed them into small tin capsules and folded them.
5. In total we prepared four 8 mg samples for each location.
6. We loaded samples into auto sampler on a Picarro Cavity Ring-Down Spectrometer, and analyzed for the carbon isotopic composition.

Table 1. *Sample characteristics*

Sample number	**Rock type**	**Location**
528504	carbonatite	west part of Singertat delta
528508	carbonate-quartz vein in supracrustal rocks	Langenæs peninsula
528510	carbonatite	west part of Singertat delta
528512	syenitic pegmatites in ijolite	south coast of Kagssortoq Fjord
528513	syenitic pegmatites in ijolite	south coast of Kagssortoq Fjord
528515	syenitic pegmatites in ijolite	east shore of the little bay east of Singertat delta
528516A	carbonatite	east shore of the little bay east of Singertat delta
528516B	carbonatite	east shore of the little bay east of Singertat delta
528517	carbonatitc breccia	east shore of the little bay east of Singertat delta
528519	carbonatite	east of Singertat delta

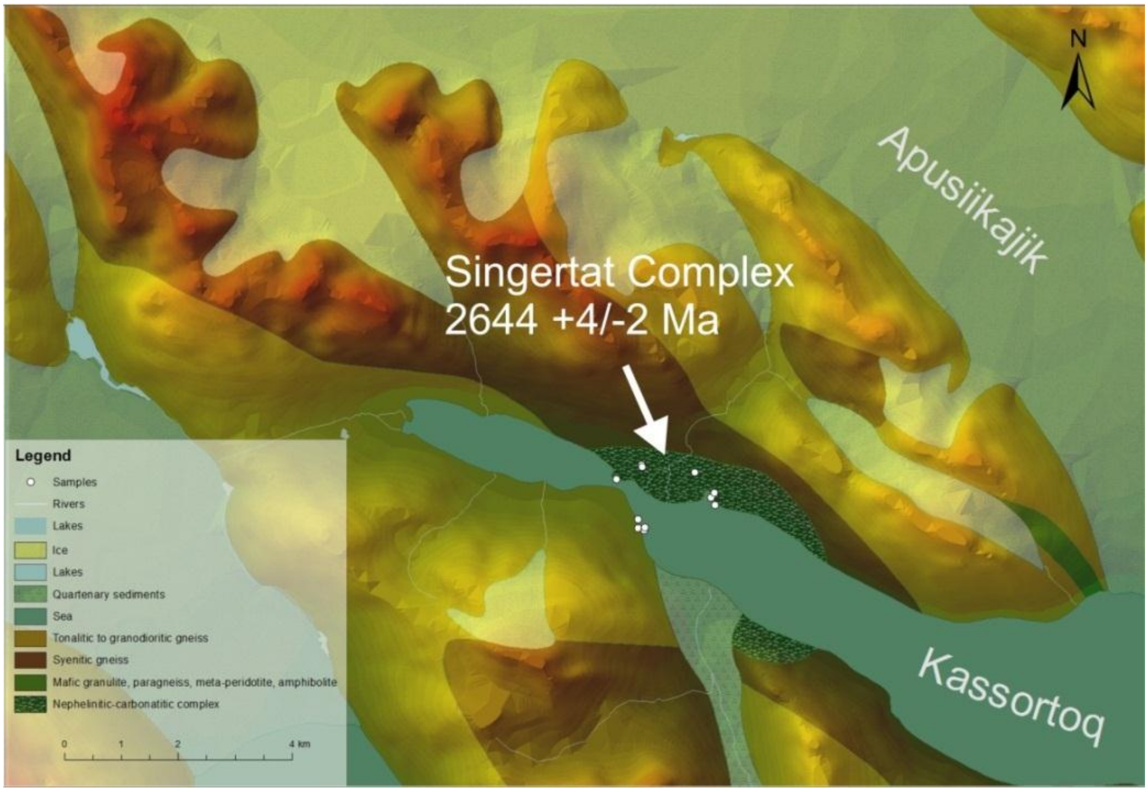

Figure 1. *Nephelinitic-carbonatitic Singertat complex, Skjoldungen, South-East Greenland.*

Cavity Ring-Down Spectrometer

We used Picarro CM-CRDS (Fig. 2) which is a combination of a traditional IRMS combustion module (CM) to transform the carbon sample into CO2 that is subsequently measured by the Picarro cavity ring down spectrometer (CRDS). The method is less expensive than IRMS, easy to operate, requires no ultra high vacuum and achieves precision of 0.1‰.

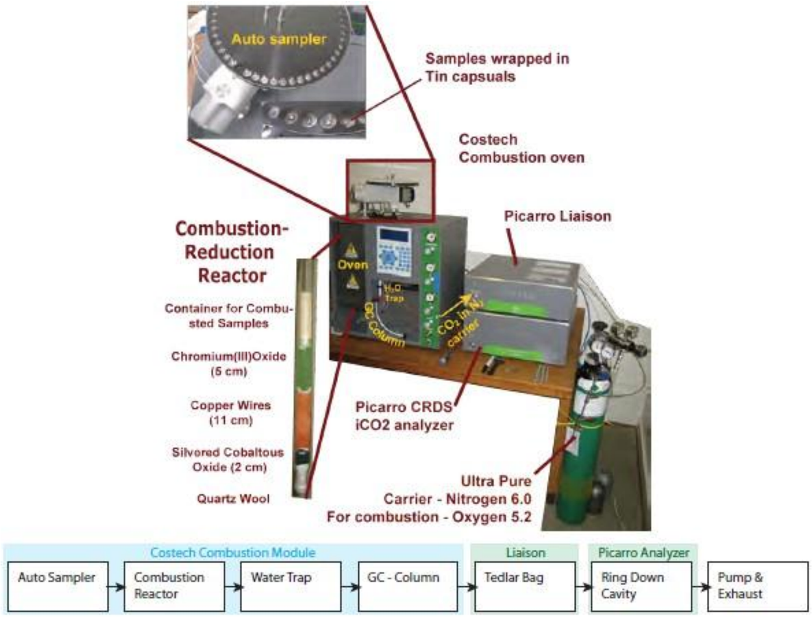

Figure 2. *Top: Picture of the setup. Insets show closeup of the combustion/oxidation reactor and autosampler. Bottom: Flow chart showing the processing of the sample (after Balslev-Clausen, 2011)*

Hypothesis

Regarding to the age of samples (carbonatites from Singartat in SE Greenland are 2664 +4/-2 milion years old) (Blichert-Toft et al., 1995) we hypothesize that subduction could have taken place before 2.664 Ga and subducted material could have contributed isotopically light carbon which would provide evidence for correspondence between the mantle and Earth's surface environments (Fig. 3). Carbon sources will be also analyzed in diamonds from West Greenland. We will use a Secondary Ion Mass Spectrometer at the Natural History Museum of Sweden in Stockholm for carbon isotopes analyses in diamonds.

Future research

Another aspect of the project is to establish the age of lithosphere stabilization under the Greenland Archaean craton. This will be addressed by studying sulfide and silicate inclusions in diamonds and other mantle xenoliths found in kimberlite and lamprophyre intrusions emplaced into the early Archaean complex. Isotope and trace element geochemistry will be used to determine the ages of kimberlite inclusions and their sources.

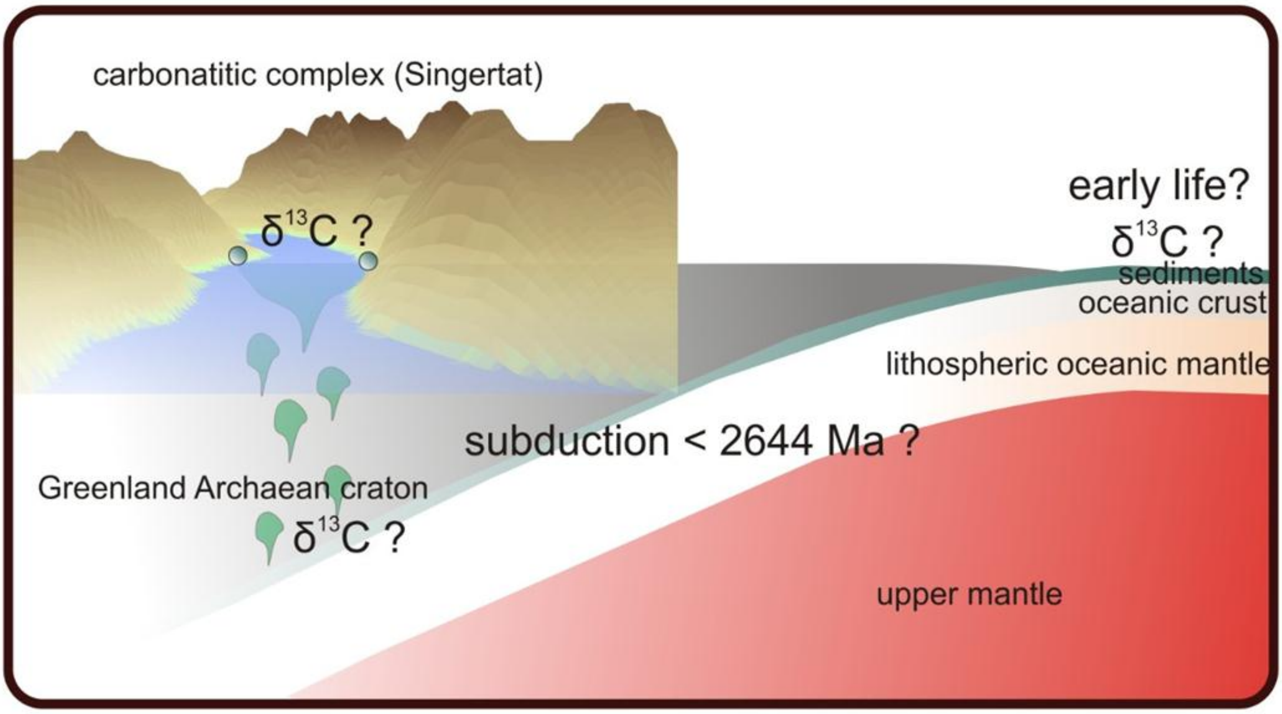

Figure 3. *Hypothesized origin of carbon in Singertat complex.*

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