DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2014/79

South-East Greenland Mineral Endowment Task (SEGMENT): 2014 Workshop Abstract Volume and Status Primo-2014

Bo Møller Stensgaard (ed.)

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

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Content

Introduction

The SEGMENT project (**S**outh-**E**ast **G**reenland **M**ineral **EN**dowment **T**ask) is financed jointly by GEUS and the Ministry of Industry and Mineral Resources, Government of Greenland (MIM; formerly the Bureau of Minerals and Petroleum). The objective of the SEGMENT project is to increase the data coverage and knowledge-base in order to facilitate and improve evaluation of the mineral endowment of the North-Atlantic Craton, the Ammassalik Mobile Belt, and the Palaeogene magmatic suite in South-East Greenland between 62°N and 67°N.

SEGMENT was initiated in 2009 with regional reconnaissance and stream sediment, till and fresh water sampling through 2009 and 2010. The analytical data for these samples represent the first modern comprehensive analytical data set from the region and were used for the planning of the investigations to be carried ut in the following years. In 2011 and 2012 the focus was centered in the Skjoldungen area of the North Atlantic Craton in South-East Greenland (62°N to 64°N). Analytical work continued through 2013 as preparation for field campaign further north in Proterozoic and Palaeogene terranes. The 2014 operation from a base in the Tasilaq region (Kuummiut) covered areas from the northernmost part of the North Atlantic Craton at 64°N and the Palaeoproterozoic Nagssugtoqidian Orogen (Ammassalik Mobile Belt), to the Palaeogene intrusions at Kap Gustav Holm and in the Kialineq district at 67°N.

The purpose of the 2014 workshop at GEUS in March 2014 was to summarise the ongoing work carried out as per primo-2014 on the basis of the in 2011 and 2012 fieldwork in the Skjoldungen region. The presentations from the workshop are available on the CD-ROM attached to this report.

The work in the Skjoldungen region includes detailed mapping and profiles, complimented with tectonometamorphic and petrological investigations. An extensive radiometric age determination program has allowed preparation of maps showing the regional distributions of radiometric ages and isotopic compositions. Extensive petrological investigations of the many different unites of intrusive complexes in the region have been and will be carried out. Tectonometamorphic models and lithostratigraphy of the mafic and supracrustal rock suites are also described and studied. The investigations include a follow-up on known mineralized sites in the region, a follow-up on stream sediment anomalies, as well as geophysical and remote sensing data.

The second objective of the workshop was a review the existing information and understanding of the geology of the Tasiilaq region as the basis for the planning of fieldwork to be carried out in the summer of 2014. A work program comparable to that in the Skjoldungen area was planned including a follow-up on the results from the Government of Greenland run Ujarassiorit program (public hunt-for-mineral program). In addition to the classic survey investigations outreach activities in the settlements were prepared and production local field-guides for towns and settlements of the regions were initiated.

SEGMENT is carried out in parallel with regional aeromagnetic surveys. The AEROMAG 2012 and 2013 projects cover all regions included in SEGMENT. These data have played an important role in the fieldwork, and extensive follow-up and geological cross-validation of anomaly patterns in the aeromagnetic data have been carried out.

Status on SEGMENT – 2013 to primo-2014

Year 2013 and the first quarter of 2014 were dedicated to continued work on and interpretation of data gathered during fieldwork in 2011 and 2012, as well as finalizing compilations of data from the Skjoldungen region, i.e., the areas between Timmiarmiut in the south (62˚N) and Umivik (64˚30'N) in the north. The enclosed list provides a status for the investigations.

It is divided into themes and includes reports, presentations, published research papers, Theses, etc.

All these and the results of investigations carried out and to be carried out in the Tasilaq region will provide a comprehensive digital geoscientific and exploration data base from South-East Greenland and for a basis for the revision of the 1:500 000 geological map sheets of the covered areas (GEUS map sheets 13 and 14). Revisions of map sheets for a updated revised digital release of the 1:500 000 scale geological map and a digital data compilations for the SEGMENT project area are continued processes initiated in 2011 and is still ongoing and will be finalized in 2014/2015.

Publications, thesis and presentations on the Skjoldungen region:
(including publication, thesis and presentation published after primo-2014)

Regional Geology, Structural Geology and Geochronology

- Kolb, J. 2014: Structure of the Palaeoproterozoic Nagssugtoqidian Orogen, South-East Greenland: model for the tectonic evolution. Precambrian Research in press, http://dx.doi.org/10.1016/j.precamres.2013.12.015
- Berger, A., Kokfelt, T.F. & Kolb, J. 2014: Exhumation rates in the Archean from pressure-time paths: Example from the Skjoldungen Orogen (SE Greenland). Precambrian Research, in press, http://dx.doi.org/10.1016/j.precamres.2014.04.011
- Kolb, J., Thrane, K. & Bagas, L. 2013: Field relationship of high-grade Neo- to Mesoarchaean rocks of South-East Greenland: Tectonometamorphic and magmatic evolution. Gondwana Research 23, 471-492, http://dx.doi.org/10.1016/j.gr.2012.02.018
- Bagas, L., Næraa, T., Kolb, J. & Reno, B.L., Fiorentini, M.L. 2013: Partial melting of the Archaean Thrym Complex of southeastern Greenland. Lithos 160-161, 164-182.
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- Næraa, T., Kokfelt, T.F., Bagas, L. & Thrane, K. 2014: The Neoarchaean Skjoldungen orogeny - a continent-continent collision orogeny? Goldschmidts 2014 Abstracts, p. 1777.

- Næraa, T.; Kokfelt, T.F. & Thrane, K. 2014: Zircon geochronology of the Skjoldungen region, SE Greenland. Abstract for the 31st Nordic Geological Winter Meeting in Lund, Sweden, January 8–10 2014, p. 92.
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- Stensgaard, B.M., Kolb, J., Nielsen, T.F.D. & Thrane, K. 2011: The Archaean craton and Palaeoproterozoic mobile belt in South-East Greenland: an overview of our current understanding. EGU General Assembly 2011, Vol. 13, EGU2011-14021, 1 pp.

- Wiewióra, J. 2014: Global carbon cycle of the Precambrian Earth. PhD Thesis, Natural History Museum of Copenhagen, University of Copenhagen, July, 2014. 138 pp. [Include: Chapter 2: Stable Isotopic Geochemistry of the Archaean Mantle recorded by the Singertât and the Tupertalik carbonatites. p. 51-76. Manuscript in preparation]
- Rennick, S. 2011: Structural control and stratigraphy of the mafic and ultramafic units between Graah Fjord and Bernstorff Isfjord, South-East Greenland. Thesis, Bachelor of Science in Geology (Honours), School of Earth and Environment University of Western Australia, October, 2011. Copy of thesis with an introduction by Jochen Kolb, Department of Petrology and Economic Geology, Geological Survey of Denmark and Greenland (GEUS). Danmarks og Grønlands Geologiske Undersøgelse Rapport 2012/67, 296 pp.

- Kolb, J., Dziggel, A., Bagas, L., Owen, J. & Fiorentini, M. 2013: Archaean granulite-gneiss terranes of western and eastern Greenland: tectonometamorphic evolution and nickel mineralization. Oral presentation at PhD workshop 2013, Oulu University.
- Kolb, J. 2012: Tectonometamorphic evolution in the North Atlantic Craton of South-East Greenland. Oral presentation at Greenland Day, Bureau of Minerals and Petroleum Government of Greenland, PDAC Toronto - March, 2012.
- Thrane, K., Kolb, J. & Stensgaard, B.M. 2011: Geology of the Archaean and Palaeoproterozoic parts of unexplored South-East Greenland. Oral presentation at Greenland Day, Bureau of Minerals and Petroleum Government of Greenland, PDAC Toronto - March 7, 2011.
- Kolb. J., Thrane, K. Bagas, L. & Stensgaard, B.M. 2012: Meso- to Neoarchaean evolution of mid- to lower crustal rocks from the North Atlantic Craton of South-East Greenland. Nordic Winter Meeting Abstract Volume, p. 75.
- Kolb, J. 2010: Southeast Greenland basement rocks. Oral presentation at structural geologist consortium meeting at GEUS, 2010.

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- Baden, K. 2013: Paleoproterozoic hydrothermal graphite-sulfide±gold mineralization from the Tasiilaq area, South-East Greenland. Thesis, Master in Geology-Geoscience, University of Copenhagen. June, 2013. 53 pp. + appendix 18 pp + digital appendix on USB memory stick.
- Lally, B. D. 2013: Geological mapping and tectonostratigraphy of mineralised mafic bands of the Timmiarmiut region of South-East Greenland. Thesis, Bachelor of Science in Geology (Honours), School of Earth and Environment, University of Western Australia. Copy of thesis with an introduction by Jochen Kolb, Department of Petrology and Economic Geology, Geological Survey of Denmark and Greenland (GEUS). Danmarks og Grønlands Geologiske Undersøgelse Rapport 2013/50, 43 pp.
- Owen, J. 2011: Characterisation of the nickel sulphide mineralisation between Graah Fjord and Bernstorff Isfjord, South-East Greenland. Thesis, Bachelor of Science in Geology (Honours), School of Earth and Environment University of Western Australia, October, 2011. Copy of thesis with an introduction by Jochen Kolb, Department of Petrology and Economic Geology, Geological Survey of Denmark and Greenland (GEUS). Danmarks og Grønlands Geologiske Undersøgelse Rapport 2012/66, 108 pp.

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- Kolb, J. 2010: Mineral resource assessments in SE Greenland. Oral presentation at Greenland Day, Bureau of Minerals and Petroleum Government of Greenland, Perth, 2010.
- Bartels A. 2014: The mid-Proterozoic Gardar Igneous Province, South Greenland – Geology and rare earth element potential. GEUS-Canada-Nunavut Geoscience workshop 2014, Nuuk, Greenland. 1 pp.

Metamorphic Petrology

- Kolb, J., Thrane, K. & Bagas, L. 2013: Field relationship of high-grade Neo- to Mesoarchaean rocks of South-East Greenland: Tectonometamorphic and magmatic evolution. Gondwana Research 23, 471-492, http://dx.doi.org/10.1016/j.gr.2012.02.018

Magmatic Petrology

- Klausen, Martin B; Nilsson, Mimmi K.M; Snyman, Dian; Bothma, Riaan; Kolb, Jochen; Tappe, Sebastian; Kokfelt, Thomas F; Nielsen, Troels F.D.; Denyszyn, Steven (2014). The >2 000 km-long 1.63 Ga Melville Bugt Dyke Swarm and its petrogenetic relationship to the ~1.8 Ga Ketilidian Orogen: Evidence from SE Greenland. Abstract for the 6th Annual Igneous and Metamorphic Study Group meeting at Rhodes University, January 20-22 2014.
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- Árting, T.B. 2013: A detailed study of a Fe-Ti oxide band in the Njords Glacier Intrusion, Skjoldungen Alkaline Province, SE Greenland. Thesis, Bachelor in Geology-Geoscience, University of Copenhagen, June, 2013. 30 pp.
- Greff, J. 2012: Petrogenesis of late-kinematic dykes and sheets within the 2.7 Ga Skjoldungen Alkaline Province, South East Greenland. Thesis, Bachelor of Science in Geology (Honours), Stellenbosch University, Department of Earth Sciences, 14 November 2012, 60 pp. + Appendix (29 pp.)
- Grobbelaar, M. 2012: Petrographical and geochemical variations across the layered ultramafic-mafic Vend-Om intrusion within the 2.7 Ga Skjoldungen Alkaline Province, southeast Greenland. Thesis, Bachelor of Science in Geology (Honours), Stellenbosch University, Department of Earth Sciences, November 2012, 40 pp.

- Bartels A., Klausen M. B., Nilsson M. K. M., Soderlund U.: Geochemistry and U-Pb geochronology of mid-Proterozoic dyke swarms within the North Atlantic Craton, South Greenland. North Atlantic Craton Conference 2014, St. Andrews, Scotland.

Ongoing studies on Skjoldungen region primo-2014:

The current ongoing studies, which will most likely also result in number of publications on the Skjoldungen region, are:

Regional and Structural Geology

- The geology of the Timmiarmiut area [contact person: J. Kolb, L. Bagas]
- The southern margin of the Thrym Complex and its transition into the Ketilidian Terrane [J. Kolb, L. Bagas, B.M. Stensgaard]
- Late tectonothermal history of South-East Greenland: structural observations integrated with geophysics and apatite fission track data [contact person P. Guernari, A. Berger]

Economic Geology

- Ni-Cu sulfide mineralization in the lower crust in the Thrym Complex, Skjoldungen Orogen, Greenland [contact persons: J. Kolb, B.M. Stensgaard, L. Bagas, M. Fiorentini, M.L., N. Thébaud]
- Molybdenum and tungsten mineralization in the Skjoldungen Orogen [contact person: D. Rosa, B.M. Stensgaard, T. Ulrich]
- The Skjoldungen Alkaline Province: genesis and mineralization potential – probably several contributions possible [contact person: T.F. Kokfelt, C. Tegner]

Geochronology & Isotopic mapping

- Isotopic map outlining different terranes of the Thrym Complex and possible major structural breaks [contact persons: K. Thrane & T. Næraa]
- Geochronology of ca. 2740-2690 Ma monzogranites and alkaline rocks [contact person: T.F. Kokfelt]
- Proterozoic mafic dykes and their ages [contact person: T.F. Kokfelt, M. Nilsson, M.B. Klausen]

Metamorphic Petrology

- The transition from TTG to orogenic magmatism and related metamorphic conditions: Examples from the Skjoldungen Orogen (SE-Greenland) [contact person: J. Kolb, A. Berger]

Magmatic Petrology

- Petrogenesis of mafic Palaeoproterozoic dykes and implications on mantle composition [contact person: T.F. Kokfelt, M.B. Klausen]
- The Skjoldungen Alkaline Province: genesis and mineralization potential [contact person: T.F. Kokfelt, M.B. Klausen, C. Tegner]

SEGMENT March, 2014 Workshop - Abstracts

The sedimentary succession at Kap Gustav Holm, SE Greenland

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The southernmost occurrence of sediments in East Greenland is situated at Kap Gustav Holm. It was discovered in 1930, and was briefly described as a sedimentary unit resting on gneissic basement and overlain by basaltic lava flows, heavily influenced by nearby plutons and the numerous intrusions of a dyke swarm (Wager, 1934; Fig. 1). It has only been visited a few times since (Myers 1978, 1993). It has thus been somewhat overlooked, particularly when compared to the much more closely studied sub-basaltic sedimentary succession in the Kangerlussuaq Basin (Dam et al. 1998; Larsen et al. 1999, 2001, 2006; Jolly & Whitham 2004; Larsen & Whitham 2005; Nøhr-Hansen 2012).

Wager (1934) recorded a c. 25-30 m thick succession of conglomerates, sandstones and metamorphosed shales. Fossils were found near the top in an apparently eye-catching bright-coloured bed initially thought to be a limestone, but which only contains a slight amount of carbonate. Ravn (1933, p. 9) considered it a volcanic tuff. The fossils include marine bivalves that with some uncertainty was considered to indicate a Late Cretaceous – Early Paleogene age. The conglomerates in the lower part of the succession could be equivalent to the fluvial conglomerates recorded in the sub-basaltic sedimentary succession in Kangerlussuaq, but the presence of pillow lava indicate a possible submarine depositional environment, hence the possibility for containing age diagnostic marine fossils.

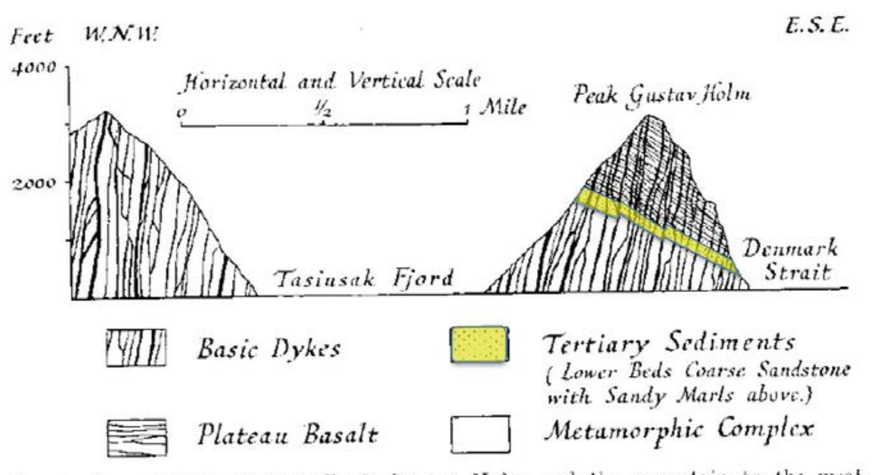

Fig. 4. Cross-section showing Peak Gustav Holm and the mountain to the west, both rising to the general level of the former peneplain, with Tasiusak Fjord cut along the former line of junction between the sediments and the Metamorphic Complex. The thickness of the sediments and the individual lava flows is exaggerated. (Reproduced by permission from the Geographical Journal).

Figure 1. *Cross-section showing Kap Gustav Holm . Thickness of the sediments and individual lava flows is exaggerated. From Wager 1934.*

A detailed study of a concordant Fe-Ti oxide band in the Njords Gletscher Gabbro, Skjoldungen Alkaline Province, SE Greenland

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Background

The gabbroic intrusion at Njord Gletscher in the Skjoldungen region of SE Greenland was visited by GEUS during the 2011 and 2012 field seasons. The intrusion is part of the ca. 2.7 Ga Skjoldungen Alkaline Province (Blichert-Toft et al. 1995; Kolb et al. 2013). The intrusion was initially registered as a diorite based on the preliminary mapping by Nielsen and Rosing (1990), who labelled the intrusion "Hermod Vig Diorite 2", however based on its composition, we propose the name "Njord Gletscher Gabbro" to be more appropriate. The intrusion is exposed in the western part of the southern slope of the Njord Gletscher valley in the central part of Skjoldungen island, where it outcrops over ca 1 km laterally by 500 m vertically (Fig. 1). The contact relation to the surrounding agmatitic gneiss basement is not clear, but the intrusion itself is partly broken up by later felsic intrusives. The intrusion is essentially a layered mafic intrusion of gabbroic rocks (gabbro and gabbronorite). Three parts of the intrusions were visited and sampled in various detail; in 2011 the lower part during a 1 day hike into the area, in 2012 the middle and upper parts during a 1 hour reco and a half day drop off, respectively. In the lower and middle part of the intrusion semi-massive magnetite rich bands of up to 30 cm thickness were localised and sampled. The highest density of oxide-rich bands occurs in the lower part of the intrusion, where at least three bands with an interspacing of 20-50 m were found within a layered gabbro sequence. No oxide bands were found in the uppermost part of the intrusion, although magnetite occurs as mineral throughout the entire intrusion. Concordant oxide-rich bands are also present in other SAP intrusions, such as the Vend Om Gabbro, and we seek here to investigate their significance by presenting mineral chemical data across a single oxide band from the middle section of the Njord Gletscher Gabbro.
Mineral chemistry data and texture

The onset of high Fe-Ti oxide concentrations in the lower part of the sampled section is accompanied by a network of cumulus phases, including tabular plagioclase, orthopyroxene and biotite. Due to the high concentration of these minerals in this lower part, we assume that a transition zone between the oxide band and the underlying layered gabbro actually starts a few cm below the sampled layer. Mineralogically, the change from the basal cumulate to the oxide band is characterized by a drop in the abundance of plagioclase and increase in ferromagnesian hornblende and orthopyroxene. Opaque inclusions in some plagioclase grains show that Fe-Ti oxides were present prior to plagioclase formation. At the lower boundary plagioclase changes over a few mm from An50 to An25. It is unlikely that plagioclase reached such evolved compositions from crystallising from the bulk liquid. Instead we consider two possible models: (1) Plagioclase formed from a trapped interstitial liquid, where hornblende reached the liquidus prior to plagioclase and giving way to Ab rich plagioclase; (2) zoned plagioclase with An0-50 was homogenized to form An25. Further up in the layer, plagioclase shows two distinct levels of An content, An25 and An50, which may be related to cumulus and intercumulus occurrences, respectively. Plagioclase composition stabilizes at An50 halfway up the oxide zone (Figure 2). In the top zone plagioclase is again present as cumulus phase, the aggregates of plagioclase and biotite have faint layering and lobate boundaries. Plagioclase grains are equant to sub-elongated. The gradual increase in plagioclase composition and texture and faint layering indicates that these grains are the result of flotation of plagioclase in the dense Fe-Ti oxide.

At approximately the same level as the maximum An contents is reached in the oxide zone, the affinity of V changes from magnetite (decreases from 0.75% to 0.1 %) to ilmenite (increases from 0.1% to 4 %). The observed ilmenite-magnetite ratio of ~1:3-1:4 can account for the mass balance of this change, indicating that in this particular horizon ilmenite probably crystallised before magnetite, and scavenged the available V out of the melt.

Table 1 *Zonal division of the studied section, height measured in cm from the base.*

Zone	Definition	Height (cm)
B1	Lower part of the basal cumulate with sub-horizontal prismatic/tabular plagioclase as the most abundant cumulate phase.	0-3
B2	Upper part of basal cumulate with orthopyroxene and hornblende as the most abundant cumulate phases. The lower boundary defined at the last occurring plagioclase aggregate.	3-5
Ox.	Fe-Ti oxide band with magnetite, ilmenite and spinel, with isolated silicate grains. The lower boundary defined at the last occurring silicate grain aggregate.	5-21
Top	Upper marginal cumulate with anhedral equant plagioclase as the most abundant cumulate phase. The lower boundary is set at first plagioclase aggregate.	21-26

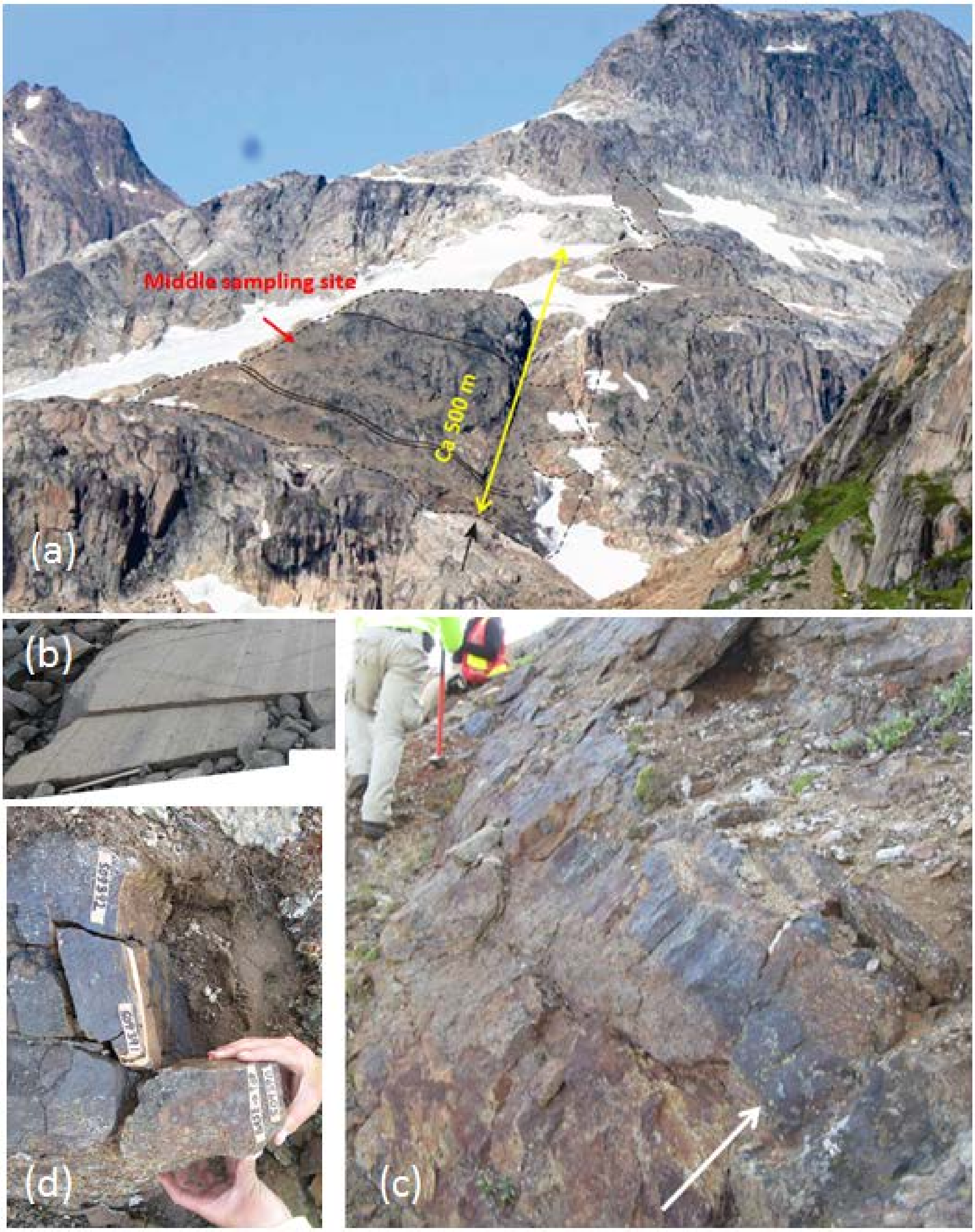

Figure 1 *(a) View towards south of the Njord Gletscher Gabbro with the sampling location indicated (red arrow). The outline of the intrusion (black dotted line) was not mapped out, but is largely based on an image analysis. Yellow arrow is 500 m for scale. (b) Example of outcropping layered gabbro in the middle part of the intrusion near the sampling site of the oxide band. (c) A 20-25 cm thick concordant oxide-rich layer stands out in the layered gabbro sequence. (d) Sampling of the layer for petrological thin sections and mineral chemistry analysis.*

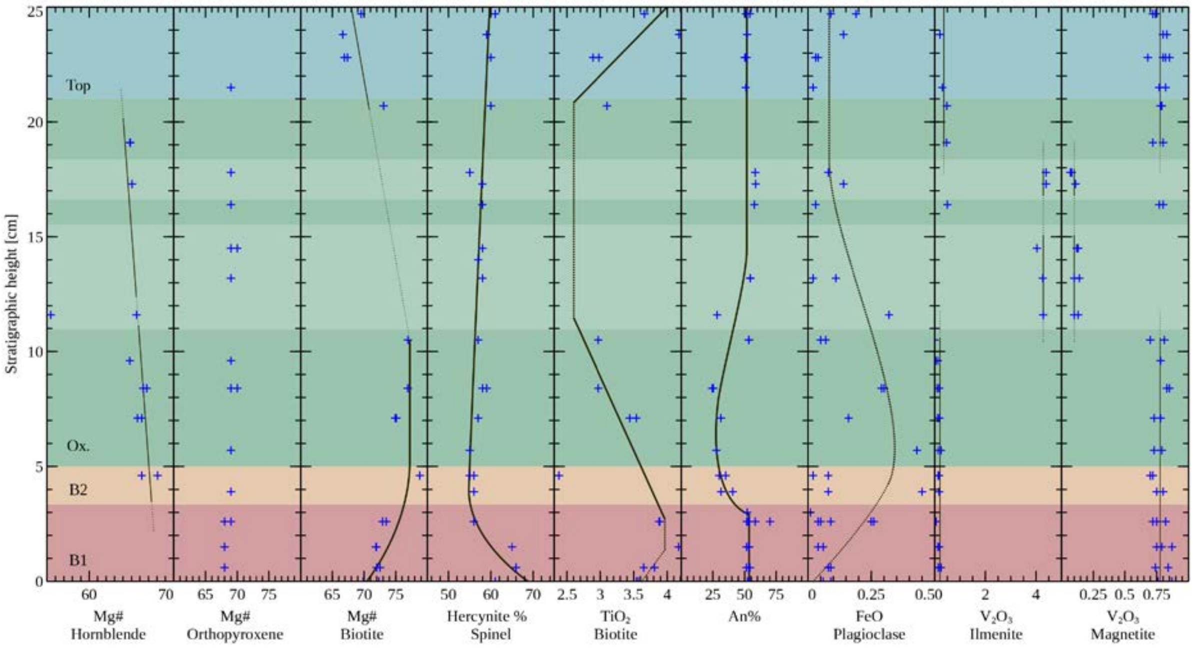

Figure 2 *Chemical variation across the oxide-rich band. Zone division is according to Table 1.*

Discussion

The Fe-Ti oxide band in the Njords Gletscher Gabbro shares a lot of the textural features with the Fe-Ti oxides of the nelsonites (Fe-Ti-P rich oxide ore) of the Permian Panzhihua Intrusion in southwest China as described by Pang et al. (2008), although in detail the phases differ. The Panzhihua ores consist of titanomagnetite, ilmenite and hercynitic spinel and the silicate phases olivine, clinopyroxene and plagioclase. Hercynitic spinel exsolution lamellae in magnetite and ilmenite are present, and hercynitic spinel exsolution along grain boundaries and at junctions. 120° triple junctions between oxide grains are also present in both intrusions. The resulting granoblastic textures are explained by sub-solidus re-equilibration of a primary Fe-Ti oxide during slow cooling. Presence of apatite, high K-concentration in hornblende, the presence of biotite, and moderate to low An contents in plagioclase show that the primary melt had a high concentrations of alkalis and phosphorous, which is considered critical for raising the binodal for liquid immiscibility and lowering the solidus respectively, therefore increasing the liquid immiscibility field.

The presence of hornblende and biotite in the Njord Gletscher Gabbro indicates that the melt was relatively water rich. High water contents in the magmas would promote an early fractionation of Fe-Ti oxides, thereby preventing the extreme Fe enrichment that characterizes a calc-alkaline differentiation trend. Implications of Charlier and Grove (2012) on tholeiitic compositions are that calc-alkaline magmas never reach the binodal since a Fe/Mg ratio of ~9 is necessary to reach immiscibility. Using their formula K¬D = (Fe2+/Mg)xl × (Fe2+/Mg)lq for orthopyroxene with an KD of 0.33, assuming all Fe in orthopyroxene is Fe(II) we arrive at stable melt ratio of 0.69-0.76 atomic ratio and 1.3 wt % ratio, not nearly enough to reach the melt immiscibility field.

Conclusions

The development of a Fe-Ti oxide rich band in the ca. 2.7 Ga Njords Gletscher Gabbro is probably best attributed to gravitational settling of dense oxide minerals from a single liquid. The hypothesis of silicate immiscibility along the liquid line of descent, causing melt segregation into a Fe-Ti rich silicate melt and a silica rich silicate melt is inconsistent with the reconstructed liquid Fe/Mg ratio of 1.3, and inferred high water contents in the melt. A granoblastic texture between ilmenite, magnetite and spinel, and exsolution lammellae in ilmenite and magnetite indicate some sub-solidus re-equilibration of the primary crystallized oxides. However, sub-solidus re-equilibration is apparently at odds with the partitioning of V into ilmenite (rather than magnetite) in the central part of the oxide layer, which rather would indicate a primary magmatic signature. The presence of resorption textures in cumulus plagioclase and orthopyroxene indicates that it was out of equilibrium at the time of intercumulus crystallization.

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The Gardar Igneous Province, South-East Greenland

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The mid-Proterozoic Gardar Igneous Province in South-West Greenland developed in a continental rift-related environment. Several alkaline intrusions and associated dyke swarms were emplaced in Archean and Ketilidian basement rocks during two main magmatic periods at 1300 – 1250 Ma and 1180 – 1140 Ma.

Based on field observations during the initial mapping period investigating the South-East coast of Greenland (1965-1970), J. A. Andrews and D. Bridgewater interpreted several dykes to represent a prolongation of the Gardar magmatic system. This suggestion was strengthened in 1996 with the discovery of the Paatusoq intrusion by A. Garde & B. Chadwick on the East coast of Greenland which was later dated to be 1144±1 Ma (Hamilton, M.A., unpublished data).

To further constrain a possible prolongation of the Gardar magmatism towards the North-East, Gardar mafic dyke swarms as well as mafic dykes from the Timmiarmiit area at the South-East coast of Greenland were investigated geochemically and geochronologically, using Fusion-ICP-MS and baddeleyite U-Pb TIMS, respectively.
In multi-element diagrams of incompatible elements, the oldest generation of dykes within the Gardar Igneous Province is characterized by enrichment of large ion lithophile and light rare earth elements and depletion of Th, U, Nb and Ta. Identical geochemical signatures can be found in samples of dykes from the Timmiarmiit area. Additionally, U-Pb baddeleyite analysis of three dykes within the Timmiarmiit area give ages between 1275±2 and 1270±2 Ma, similar to the known ages for the early Gardar intrusives.

The obtained data of this study provide strong evidence for a link of the investigated mafic dykes from the Timmiarmiit area to the early Gardar magmatic period. A geochemical comparison also strengthens the already hypothesized correlation of the early Gardar magmatism to mafic dyke swarms in central Labrador (Nain and Harp swarm) providing new evidences for a much more wide spread magmatism. These observations offer new insights into rift-related magmatic events, prior to the break-up of the Nuna supercontinent.

Characteristics of the UHP Metamorphic Complex In The Nagssugtoqidian Orogen Of West Greenland

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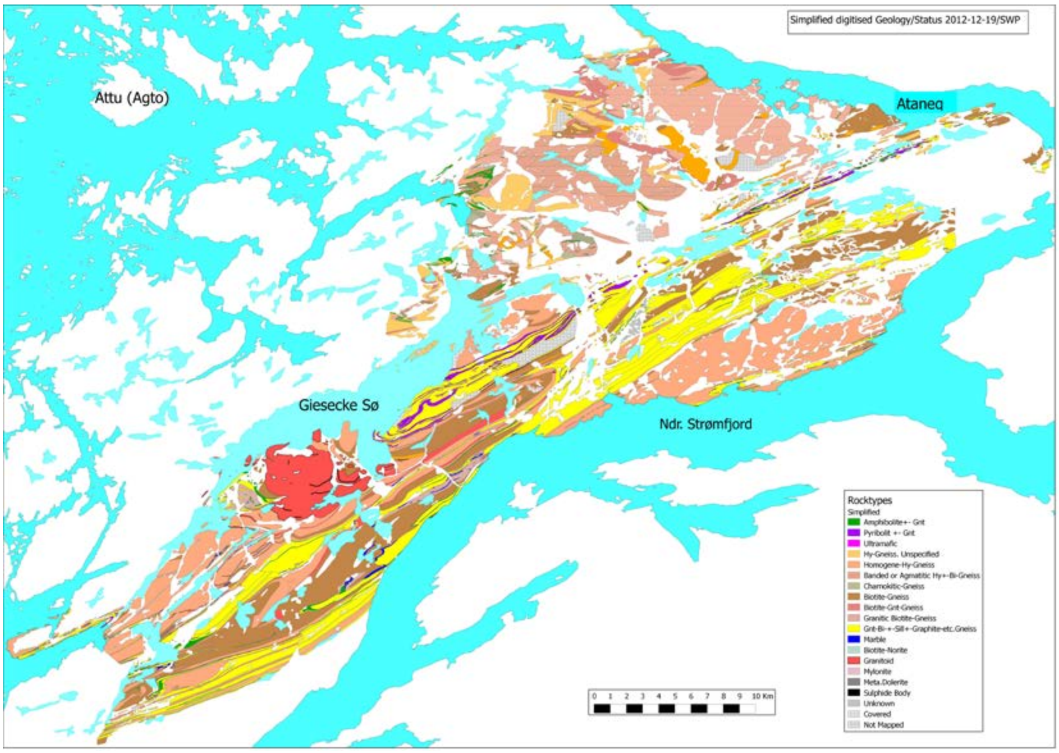
Four samples of metabasic and metasedimentary ocean floor rocks within the western segment of the Nagssugtoqidian Orogen preserve a record of UHP metamorphism. The samples were collected in an area south of Giesecke´s Sø in 1969 (by SWP) and in 2012 in a complex of mafic and pelitic supracrustals, see map.



The UHP episode is recorded by remnants of orthopyroxene exsolved from majoritic garnet, graphitized diamond, exsolution of rutile from garnet and pyroxenes, exsolution of magnetite from olivine, and complex exsolution textures in ortho- and clinopyroxenes (including omphacite). Associated with these mineralogical features is an unusual occurrence of quartz needles in Mn-rich fayalite. From textural characteristics, we infer that the quartz needles exsolved from the fayalite. To our knowledge, olivine with exsolved silica has not been reported. We note, however, that experimental studies have shown that β-spinel can incorporate excess silica. We therefore speculate these quartz needles may be silica that exsolved from Mn-rich ahrensite, the Fe analogue of ringwoodite, upon decompression and inversion to fayalite. If correct, this occurrence would be the first reported sample of naturally occurring olivine (fayalite) that inverted from ahrensite. Corroborating an early UHP history are reaction relationships that delineate a path through high-pressure and high temperature conditions during decompression. P-T conditions inferred for the UHP episode are ~ 7 GPa at ~975 oC. The unusually low T for this UHP system at ~1.8 Gya may reflect either very rapid subduction rates at that time, or unexpectedly cool mantle conditions. Preservation of the UHP assemblages probably is due, in large part, to the exceptionally low aH2O during decompression and cooling. These UHP rocks establish that the location of the subduction and suture zones that must have existed prior to and during the collision of continents was along what is now the northern edge of the Nordre Strømfjord shear zone. The field characteristics of these rocks are that they are garnet-rich, with multiple generations of garnet growth, are pyroxene-rich, and commonly olivine-bearing. They usually lack any significant amphibole or other hydrous phases, are Fe- and Mn-rich, and are associated with sillimanite-bearing metapelitic rocks. Because of the Fe- and Mn-rich nature of these rocks, they are usually very dark, and easily misinterpreted as amphibolites if not closely examined in the field.

Thermal history of outcrop samples from South-East Greenland based on apatite fission-track analysis

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Apatite fission-track analysis (AFTA) was applied to 47 outcrop samples from South-East Greenland, 61–66°N, as part of the Segment project in order to study the tectonic development of the continental margin. The AFTA data in each sample were used to define major cooling episodes (maximum palaeotemperature and onset of cooling), and this information was then synthesised to determine and quantify the major regional cooling episodes. Excellent yields of apatite were obtained from 36 of the 47 samples, while only three samples failed to yield any apatite suitable for analysis. The resulting data are of very high quality, and we consider the associated thermal history interpretations to be highly reliable. All but one of the samples gave apatite fission track age less than 400 Ma and most are less than 250 Ma (Figure 1), emphasising the importance of post-Palaeozoic events across the region. Inland samples generally give older ages while younger ages occur closer to the coast, with youngest ages in coastal samples in the north and south of the region.
Figure 2 shows constraints on the onset of cooling defined from AFTA in individual samples. In many samples the AFTA data require at least three discrete palaeothermal episodes, although a larger number of events have clearly affected many of the samples analysed for this study. Assuming that the AFTA data represent the effects of regionally synchronous cooling episodes, combining constraints from all samples results in definition of eight major regional cooling episodes, C1–C8, viz:

C1. Ordovician to Early Carboniferous: beginning between 460 and 360 Ma
C2. Early Triassic: beginning between 240 and 235 Ma
C3. Early Jurassic: beginning at ~175 Ma
C4. Early Cretaceous: beginning between 135 and 130 Ma
C5. Mid to Late Cretaceous beginning between 100 and 85 Ma
C6. Late Cretaceous - Early Cenozoic: beginning between 70 and 50 Ma
C7. Eocene-Oligocene: beginning between 40 and 30 Ma
C8. Late Miocene to Recent: beginning between 10 and 0 Ma

The timing of many of these cooling episodes correlates with events identified further north, around Kangerlussuaq in southern East Greenland (c. 68–70°N; Japsen et al. 2014), where the corresponding palaeotemperatures are interpreted as representing Palaeozoic and Mesozoic burial, with subsequent cooling due to exhumation. A similar interpretation seems likely for the events in southeast Greenland identified in this study. However, due to the lack of Phanerozoic sedimentary cover it remains uncertain if the cooling episodes in this region represent previous burial or simply the removal of basement rocks.

Japsen et al. (2014) interpreted cooling which began between 40 and 35 Ma in the Kangerlussuaq region as representing the onset of regional exhumation due to uplift following burial resulting from post-breakup subsidence which led to widespread peneplanation and formation of a regional erosion surface near sea level (the Upper Planation Surface, UPS; Bonow et al. 2014), now preserved at elevations up to 3 km or more above present-day sea level. Similarly, Japsen et al. (2014) interpreted cooling which began at ~10 Ma in the Kangerlussuaq region in terms of incision related to a late Miocene uplift phase that led to formation of a younger erosion surface (Lower Planation Surface, LPS; Bonow et al. 2014) below the uplifted UPS, while a Pliocene phase led to further incision of valleys and fjords below the uplifted LPS, leaving mountain peaks reaching 3.7 km above sea level.

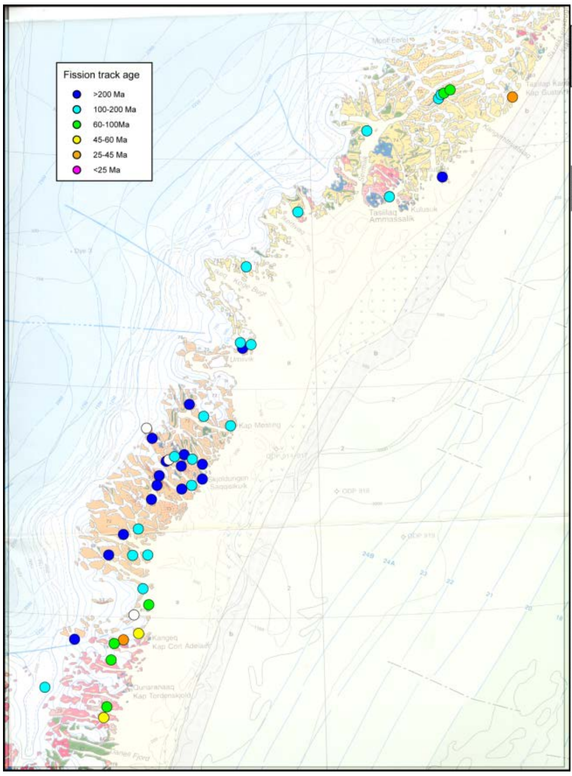

Figure 1 *Map of fission track ages.*

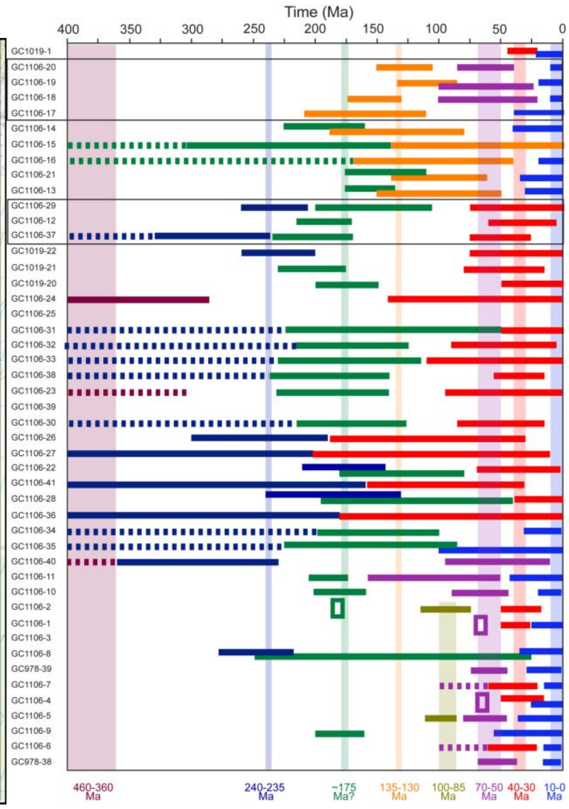

Figure 2 *Timing of major cooling episodes identified from AFTA in individual samples, illustrating synthesis to define major cooling episodes.*

The C7 episode is defined in this study pervasively across the southern half of the study area (Figure 3). Over most of that region palaeotemperatures characterising this episode are in the region of 50 to 80°C, but higher values are evident in the south. Palaeotemperatures around 60 to 70°C characterising the C8 episode (Figure 4) are recognised at locations in the north and south of the study area, but in the intermediate region evidence for this episode is absent and samples instead show consistent evidence of the C7 cooling episode, while in southern locations both the C7 and C8 episodes are recognised. C8 palaeotemperatures are generally <70°C at southern locations, while at northern locations values up to 90°C are identified. In the south, the higher C7 values explain why both episodes are recognised in this area. Further north, palaeotemperatures in the two episodes are more similar and the two events can only be resolved in one sample in the northern region, in which the C7 palaeotemperature is around 100°C. Note that the broad constraints on the timing in the C7 event in some samples from the Skjoldungen area (e.g. samples 26, 27; Fig. 2) may reflect the unresolved effects of earlier events.

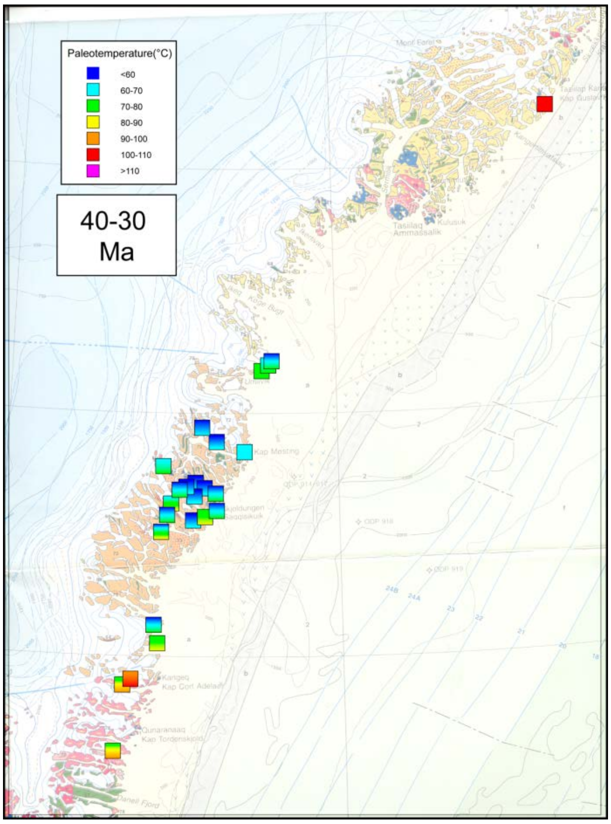

Figure 3 Map of palaeotemperatures from which individual samples cooled in the C7 event (40–30 Ma), determined from AFTA data in this study.

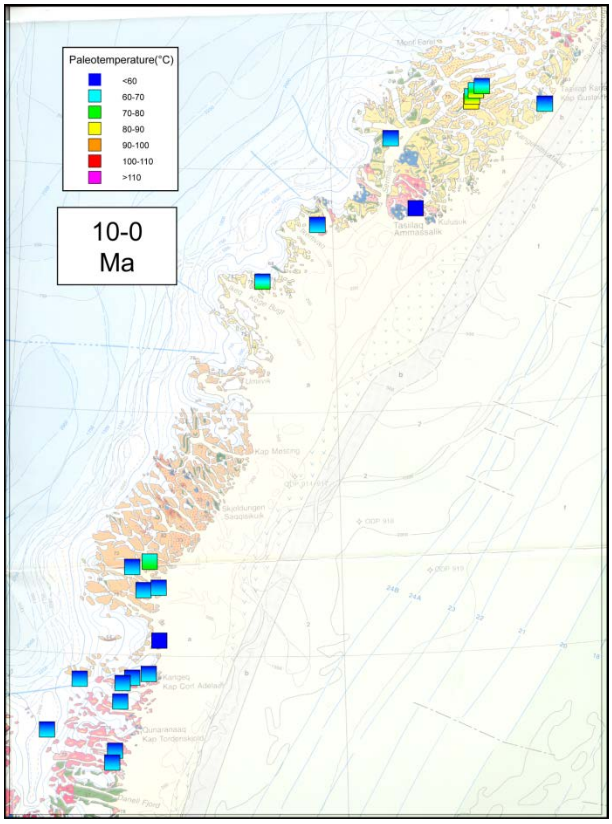

Figure 4 Map of palaeotemperatures from which individual samples cooled in the C8 event (10–0 Ma), determined from AFTA data in this study.

The close similarity in timing between the C7 and C8 events identified in this study and events identified by Japsen et al. (2014) in the Kangerlussuaq region to the north suggests a common origin for cooling episodes in both areas is likely. This reasoning suggests that C7 uplift at c. 35 Ma led to formation of a regional peneplain along the entire margin, 61–70°N, and that the C8 event that began at c. 10 Ma led to uplift and dissection of the peneplain and thus to formation of the present-day relief. A high-level plain is known in the Ammassalik area (Brooks 1985) whereas the terrain further south is heavily dissected. Only mapping of the large-scale landforms south of 68°N can reveal to what extent remnants of the UPS can be identified there. If so, the presence of an Oligo–Miocene peneplain there can be used as a constraint in the interpretation of the AFTA data.

Effects of the C6 event are restricted mainly to the extreme south of the study region and in a few samples in the north (Figure 5). In the south, this event is recognised in samples from coastal locations where most samples cooled from >100°C at this time, although lower values occur in samples just south of Tingmiarmiut Fjord where major fault systems follow the trend of that fjord and possibly also of the parallel Mogens Heinesens Fjord. Distinct offsets of C6 palaeotemperatures south of the Tingmiarmiut region indicate that these offsets may be structurally controlled. In the north, data in three samples are also attributed to this episode, but it is possible that these may define a later event. More data are required before firm conclusions can be reached.

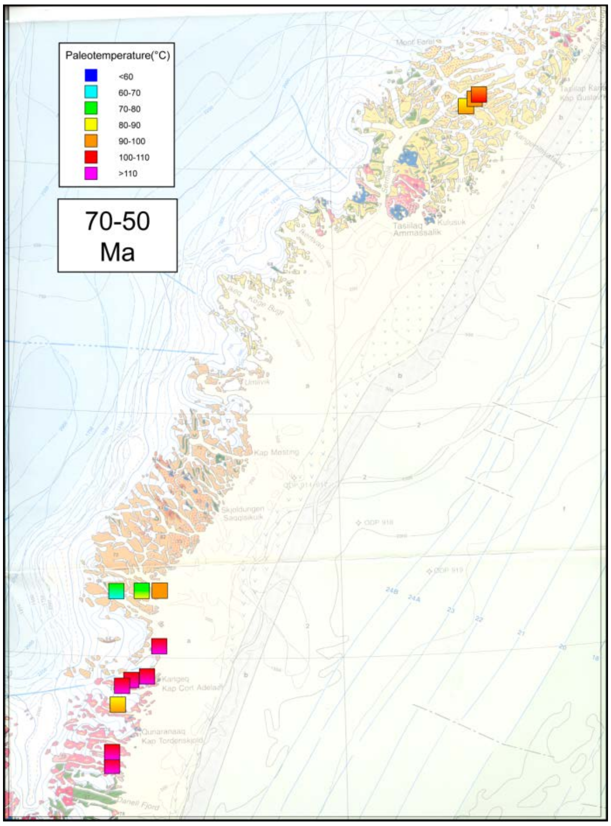

Figure 5 Map of palaeotemperatures from which individual samples cooled in the C6 event (70–50 Ma), determined from AFTA data in this study.

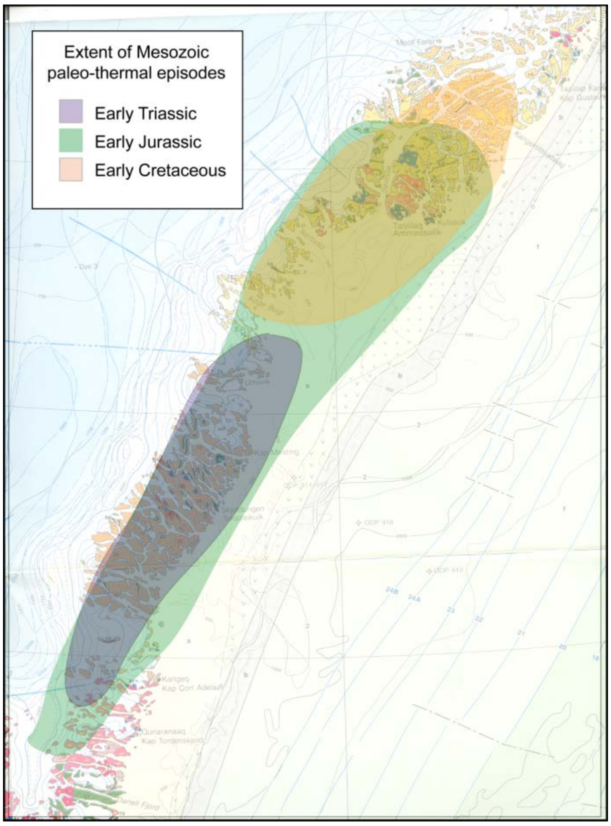

Figure 6 Extent of the dominant Mesozoic cooling episodes identified in this study. The clear demarcation between Early Triassic (C2) and Early Cretaceous (C4) cooling is particularly striking, and suggests a major tectonic offset in this region, while the Early Jurassic C4 event is identified across the whole region.

While the main focus here is on Cenozoic events, the importance of Mesozoic cooling episodes also shows major regional variation in the extent of individual episodes (Figure 6), which must reflect key structural control on cooling in major regional tectonic episodes. Further study linking the extent of individual cooling episodes to structural; domains has the potential to provide major insights into the pre-breakup history of the margin.

We emphasize that the available sample coverage is very much at the reconnaissance level at this stage. Thus, while this study has resulted in confident definition of a series of palaeothermal episodes over the last 400 Myr or more, several key issues remain uncertain in relation to the underlying mechanisms of heating and cooling which will require more detailed sampling in order to understand them in detail.

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Sulphide mineralization in the Tasiilaq Intrusion, Ammassalik Intrusive Complex, South-East Greenland

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The Tasiilaq Intrusion is part of the Ammassalik Intrusive Complex (AIC) situated around Tasiilaq in South-East Greenland. The contact aureole of the intrusion has been explored for komatiite-hosted Ni-Cu-PGE-Au sulphide mineralisation since the mid 1990's. The methods used were fieldwork, stream sediment and rock sampling, aeromagnetic data, and a short drilling programme. Previous fieldwork and studies of the Tasiilaq Intrusion have only shown irregular anomalies of < 1 % Ni and < 0.5 % Cu. Samples collected by Jochen Kolb in 2010 and Lars Lund Sørensen in 2011, however, show sulphide mineralization in the magmatic rocks of the intrusion for the first time. At the "Magmatic Nickel Potential in Greenland" workshop at GEUS in Nov. 2012, the tract of the AIC was estimated to have undiscovered nickel deposit potential. In this paper, we present petrographical and geochemical data on the sulphide-bearing samples from the Tasiilaq Intrusion collected in 2010 and 2011 and argue for orthomagmatic processes responsible for sulphide mineralisation.
The AIC consists of three ovoid intrusions aligned in a NW trend. It consists of syntectonic mafic to intermediate rocks that intruded at 1886 +/- 2 Ma into Archaean orthogneiss-amphibolite and Palaeoproterozoic Síportôq Supracrustal Association basement. The contact metamorphic halo is < 10 km wide and consists of garnet-bearing gneiss. The AIC is interpreted as arc-like intrusions related to convergence and collision of the northern Rae Craton and the southern North Atlantic Craton between ca. 1900 and 1680 Ma, namely the Nagssugtoqidian Orogen.

The focus is on the 10 x 30 km wide Tasiilaq Intrusion centre. The main series of igneous rocks consist of leuconorite (Pl+Otz+Opx), melagabbro (Opx+Pl+Qtz+Cpx+Ol) and anorthositic or dioritic (Pl+opx+Qtz) rocks. The leuconorite is dominant in terms of area in the intrusion and cross-cuts the melagabbro. Both are intruded by dykes and veins of anorthosite. The leuconorite is banded with more mafic material in which orthopyroxene of several stages and biotite are dominant. The modal composition of the mafic minerals varies from 10% to 40%. The anorthositic veins show a change in composition, with plagioclase-orthopyroxene where it is widest to quartz-biotite-feldspar where the veins are thin. The melagabbro also shows change in composition of plagioclase and orthopyroxene and large amphibole grains dominant in the plagioclase-rich dioritic bands of the melagabbro. In the contact between the more meso-olivine-gabbronoritic bands of the melagabbro and the dioritic are the ultramafic minerals fractured. In interpretation this gives the diorite a younger relative age to the melagabbro.

The main mineral phases in the garnet gneiss are plagioclase, alkali feldspar, quartz, garnet and biotite. Ortopyroxene occurs locally in garnet-poor gneiss. The outcrop north of the intrusion and the contact-metamorphosed halo are dominated by orthogneiss and amphibolite.The contact of the igneous and the surrounding rocks is in some places sharp, but mainly irregular. This is interpreted as the result of the emplacement of a high temperature melt into a wall rock at amphibolite facies. The igneous rocks of the Tasiilaq Intrusion crystallized in the middle crust at 6-8 kbar and 1000-1100°C. The temperature in the contact metamorphic aureole reached 800°C.

In the samples collected by Jochen Kolb have sulphides crystallized interstitial in the mafic and ultramafic rocks and contain 610 ppm Ni and 450 ppm Cu. Pyrrhotite and chalcopyrite have been recognised in thin section analyses and further studies of the petrology and the geochemistry of, in particular, the Tasiilaq Intrusion will clarify which type of Ni-Cu-PGE mineral system formed the sulphides in the Tasiilaq Intrusion. Comparison with the exploration targets in the contact aureole and regional geology investigations will enhance our understanding of potentially economic Ni-Cu-PGE-Au sulphide mineralisation in the Tasiilaq area.

The nickel mineral system of the Ammassalik Intrusive Complex, Nagssugtoqidian Orogen, South-East Greenland

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Regional geology

The 1885 Ma Ammassalik Intrusive Complex (AIC) is situated in the area around Tasiilaq in South-East Greenland. The complex stretches from the Kulusuk Island over the Tasiilaq peninsula and all the way west-northwest of Sermilik Fjord. The southeast trending AIC is placed north of the medium pressure Isertoq Terrane, which is part of the North Atlantic Craton and consist of orthogneiss, amphibolite, ultramafic and meta-sedimentary rocks. To the north of the AIC is the high pressure Kuummiut Terrane, which is part of the Rae Craton consisting predominantly of migmatitic orthogneiss and amphibolite along with dioritic, tonalitic, and ultramafic rocks (Kolb, 2014). At ca. 1885-1870 Ma the Rae Craton subducted under the North Atlantic Craton resulting in the Nagssugtoqidian Orogen. The subduction setting was oblique and the Kuummiut Terrane subducted in a west-southwest direction under the southeast trending AIC and Isertoq Terrane (Kolb, 2014).

Geology of AIC

The complex consists of three ca. 20 km long and 10-15 km wide, mafic to intermediate intrusive centres surrounded by contact metamorphic, predominantly banded garnet gneiss (Friend and Nutman, 1989; Kolb, 2014). The intrusive centres of the AIC are Johan Petersen Intrusive Centre, Ammassalik Intrusive Centre and Kulusuk Intrusive Centre (Lie, 1998). North and southeast trending conjugate sets of dykes of similar composition are found in between the intrusive centres (Friend and Nutman, 1989). These are coarse-grained, hypersthene bearing and occur with minor amounts of felsic, quarts and K-feldspar bearing layers (Wright et al., 1973). The intrusions consist of layered melagabbro and anorthositic rocks with lenses of mafic and ultrafic rocks (Wright et al., 1973; Kolb, 2014). The Tasiilaq intrusion contains additionally local felsic rocks along with up to 20 m wide layers of disseminated sulphides (Kolb, 2014). Three generations of pegmatitic dykes of anorthositic composition crosscut the intrusions (Wright et al., 1973). The magma forming the AIC was estimated to ca. 1100°C and 6-8 kbar with a retrograde overprint at 550°C and 2-3 kbar (Andersen et al., 1989). Diorite data suggests temperatures of 830-850°C and ca. 7.5 kbar (Nutman and Friend, 1989). The contact to the wall rocks is either sharp and tectonic, or characterised by mingling and veining (Wright et al., 1973). The banded garnet gneiss of the contact aureole was estimated to temperatures of 720-840°C and pressure of ca. 7.5 kbar at the contact. Temperatures of the rim was ca. 570-710°C (Andersen et al., 1989; Nutman and Friend, 1989).

Mineralisation

In 1998 340 m2 of semi-massive sulphide mineralised, partly serpentinised ultramafic rock was identified at the contact between the Ammassalik Intrusive Centre and the wall rock banded garnet gneiss. The rock had ca. 50% ore minerals and totally an average of 1% Ni associated with PGE, Au, Cu and Co (Lie, 1998). The lens shaped mineralisation is ca. 90 m long and variably 1-8 m wide and consist of semi-massive sulphides forming an interstitial network in the partly serpentinised rock. The ore minerals are pyrrhotite, Co-pentlandite, chalcopyrite and minor magnetite. Notably, the pentlandite contains 33% Ni. The gangue minerals were serpentinite, olivine, orthopyroxene, clinopyroxene and Zn-rich magnesiochromite. In a zone close to the contact with the banded garnet gneiss, the massive sulphides have been partially replaced by chalcopyrite and chalcosite (Lie, 1998). Lie (1998) notes that the petrography suggests a primary magmatic origin of the massive, predominantly Ni-rich sulphide ore and a later replacement of Cu-rich phases during serpentinisation. It was also noted that the Ni-mineralisation is not restricted to the massive sulphides, but has been indicated at several locations along lineation in the rock.

Fieldwork, July-August 2014

During the GEUS field season 2014 this study will mainly focus on the Ni-mineralisation in the intrusive centres of the AIC. Given that the intrusions have the parental magma it is likely that massive sulphide deposits similar to the one found in the Ammassalik Intrusive Centre can be found in the Johan Petersen- and Kulusuk Intrusive Centres. The fieldwork will thus be conducted in order to confirm/disprove this assumption and to estimate the mineral potential of the AIC with respect to nickel (and PGE, Au and Cu). Large scale detailed mapping will be done along with identification of magmatic rocks, structures and contact metamorphism. Furthermore it is the aim to identify and map the mineralisation(s) in even more detail. All the identified rock units will be sampled, and thin- and polished sections will be produced in order to perform petrographical and petrological studies (description, geochemistry, paragenesis, etc.). The chemistry of selected minerals will be examined with microprobe and/or LA-ICP-MS) in order to establish a model for sulphur immiscibility and general magma evolution. Stable sulphur isotopes will be examined in order to establish a model for the source of the magma and/or external sulphur, if that is the case. Lastly dating could be conducted if suitable minerals are found.

The project will result in the first author's master's thesis from University of Oulu along with a publication as an abstract, ROSA article or as part of a larger publication.

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Mafic dykes across Greenland’s North Atlantic Craton: An up-dated record of at least seven major magmatic events between 2.5 to 0.06 Ga

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Introduction

Since the review by Nielsen’s (1987) on the mafic dyke swarms across Greenland, considerable amounts of data have been collected in recent years as a result of GEUS’ commitments in SW and SE Greenland, warranting an update on the topic. In particular, more precise U-Pb baddeleyite ages, coupled with field observations, petrographical and geochemical studies now allow us to elaborate on the timing of major magmatic events that partially affected the Greenlandic part of the NAC over an extended time period from 2.5 to 0.06 Ga. Ernst & Bleeker (2010) also provide a recent overview of pre-2.5 Ga-old mafic dyke swarms and Large Igneous Provinces (LIPs) across the North American Craton (including Greenland), to which new data can readily be linked. Within a work group, involving Universities in Lund and Stellenbosch as well as GEUS, data was published on Palaeoproterozoic dykes from the western NAC coast of Greenland, whereas data from the eastern NAC coast of Greenland are in the process of getting published.

With this abstract we aim to review the status of the recent work done by the so-called SEGMENT Research Group with emphasis on showing which type of research projects are currently in progress on the different dyke swarms – and which has a fair potential to be instigated. The abstract is subdivided into (1) Palaeoproterozoic meta-dolerites, (2) syn-orogenic tabular intrusions, (3) Mesoproterozoic dyke swarms, and (4) Tertiary dykes.

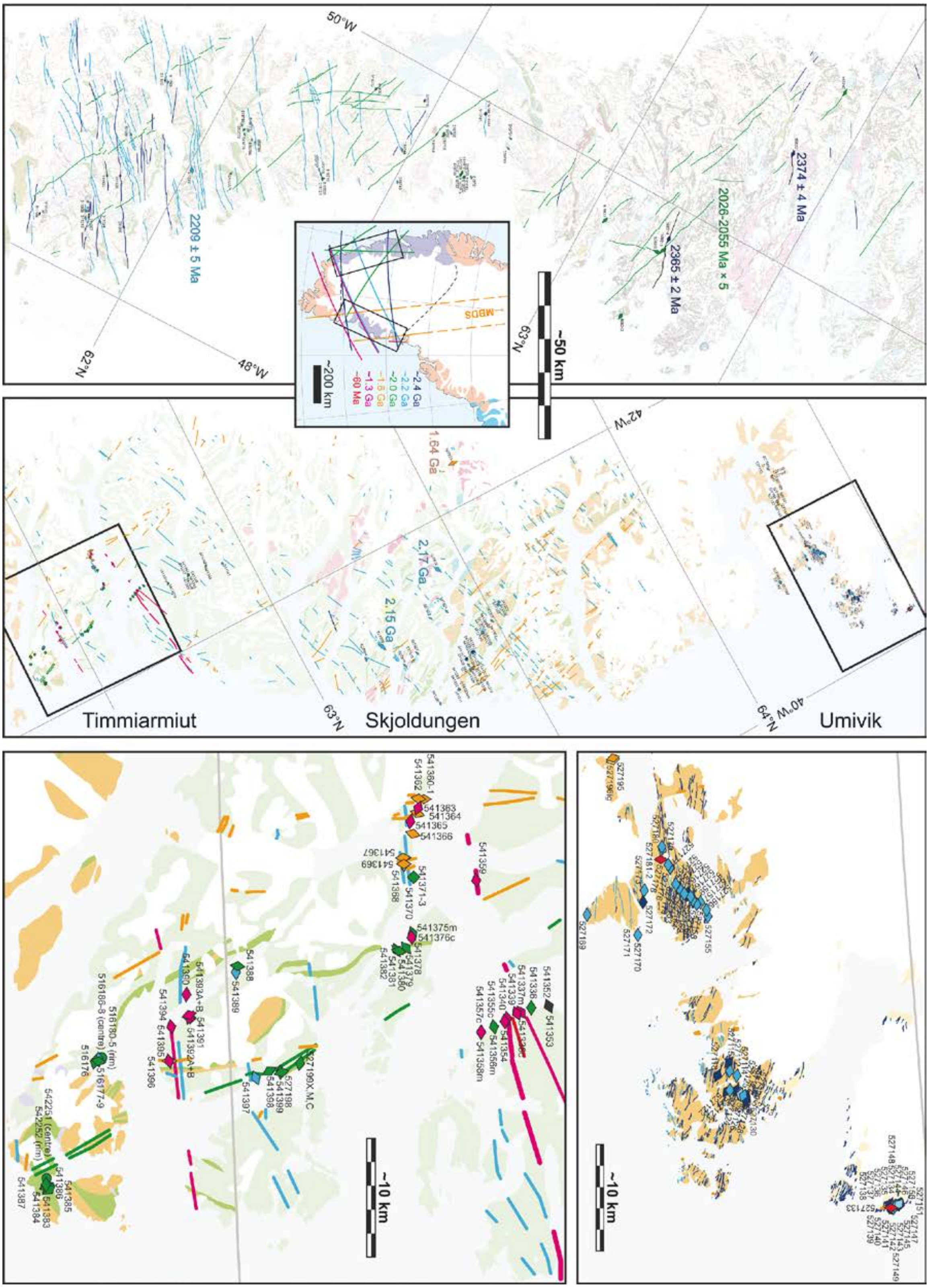

Figure 1 *Compilation of dyke and sample locality maps for the studied western and eastern NAC-coast of Greenland. Not every dyke have been properly mapped or classified into the proposed seven swarms. Ages on SW Greenland dykes are from Nilsson et al (2013), with minimum and maximum ages of 5 Kangamiut-MD3 dykes including uncertainties. Preliminary ages on SE Greenland dykes (M. Nilsson unpublished data) may be refined through further analyses.*

Palaeoproterozoic meta-dolerites (MDs)

A distinguishing feature of Paleoproterozoic dykes is arguably that they are relatively altered/metamorphosed compared to younger dykes; the main reason for applying the term 'meta-dolerites' for these dykes, or MD's, as first coined by Kalsbeek & Taylor (1985). Petrographically they have pyroxenes (± olivines) that often are variably uralitized (± serpentinized) and plagioclases that are saussuritized. However, as argued by Nilsson et al (2013), the degree of metamorphism is variable and a reference to swarms of specific ages (and names) is to be preferred to the MD1-3 classification. Individual MD swarms are compositionally indistinguishably from each other as variably evolved meta-dolerites, with MgO mainly ranging between 3-8 wt % (Nilsson et al 2013). In general the MD-swarms are characterized by enrichment in large ionic lithophile (LIL) elements over high field strength (HFS) elements, and by exhibiting moderate to strong negative Nb-anomalies, typical of mafic magmas derived from a metasomatized sub-continental lithospheric mantle (SCLM), or asthenospheric melts having undergone assimilation with continental crust.

From the geochronological and geochemical results on doleritic dykes across the western part of the preserved Archaean craton Nilsson et al (2010, 2013) were able to: (1) distinguish a more E-W trending 2.37 Ga swarm from a SW-NE trending 2.21 Ga swarm, which could extend beneath the Greenland inland ice sheet to the eastern NAC-coast of Greenland as indicated in the inserted map in Fig 1, (2) show that the 2.05-2.03 Ga Kangamiut-MD3 dyke swarm has a more variably radiating pattern than hitherto recognized, and (3) identify a, so far, isolated ~2.5 Ga dyke that tentatively correlates to the 2.51 Ga Mistassini LIP. Nilsson et al (2013) tentatively correlate the 2.37 Ga dykes to similar aged dykes on India's Dharwar Craton, which must have been near neighbours within the Superia supercontinent (their option #6 used in Fig 2). The 2.21 Ga dykes could be part of a giant radiating swarm related to the major Ungava LIP event (Ernst & Bleeker 2010), which ultimately belong to the breakup of the Superia supercontinent (Fig. 2).

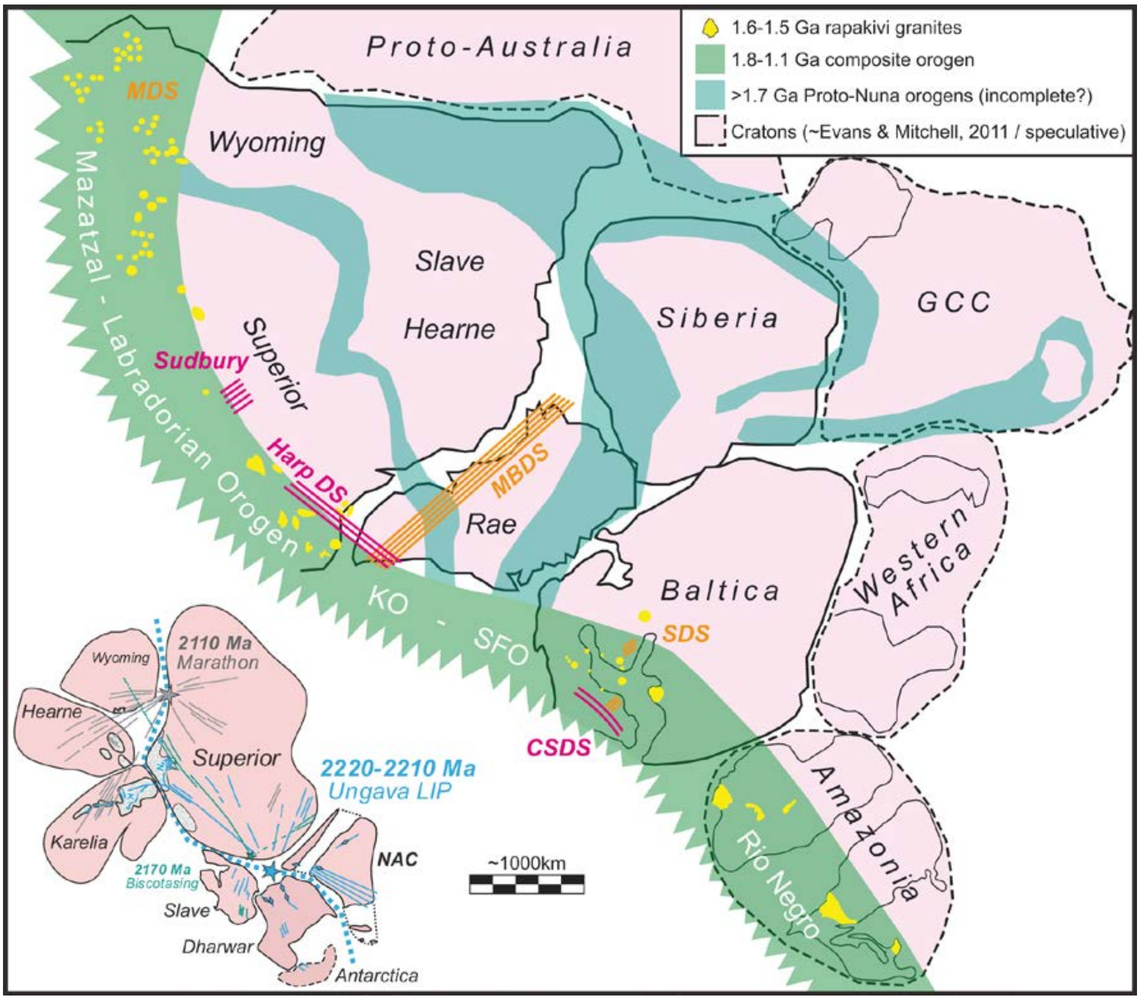

Figure 2 *Possible dyke swarm emplacements within two super-continental reconstructions (both in roughly the same scale). Lower left corner shows a partial Superia reconstruction, modified from Ernst & Bleeker (2010) and Nilsson et al (2013), where ~2.21 Ga dykes across the NAC are tentatively correlated to the coeval Ungava large igneous province (LIP). Together with the Marathon and Biscotasing, these LIPs were probably active during a major break-up event (tentatively indicated by a dashed blue line), which separated craton fragments that subsequently amalgamated into the Nuna supercontinent. The Nuna reconstruction is modified from Evans & Mitchell (2011) and conforms to current palaeomagnetic constraints. It suggests that the supercontinent was bound by a remarkably long-lived outboard margin, along which several 1.8-1.1 Ga orogenies (KO = Ketilidian Orogen; SFO = Svecofennian Orogen) formed and an unusually great abundance of rapakivi granites were emplaced, following the emplacement of giant mafic dyke swarms such as the Melville Bugt Dyke Swarm (MBDS) that cuts across Greenland, the Soumenniemi Dyke Swarm (SDS) across Scandinavia and the Mazatzal Dyke Swarm (MDS) within the Wyoming Craton Block. The emplacement of these roughly coeval dyke swarms was apparently not associated with any breakup. It is also uncertain how much break-up was accompanied by the 1.4-1.2 Ga emplacement of a vast array of dyke swarms, including the coeval Sudbury (Shellnutt & MacRae, 2012), Harp, early Gardar and Central Scandinavian (CSDS; Söderlund et al, 2006) dyke swarms or, as discussed in more detail by Bartels et al (this volume), were part of an extensive back-arc setting.*

Syn-orogenic tabular intrusions

The NAC of Greenland is bound to its northern and southern borders by two, roughly coeval orogenies; the Nagssugtoqidian (1.88-1.78 Ga; Kolb in press) and the Ketilidian (1.85-1.75 Ga; Garde et al 2002) orogenies, respectively. Given that the described Palaeoproterozoic meta-dolerites predate these orogenic events it is tentatively assumed that these orogenies may also have been the primary causes for their variable metamorphic overprint, even if this needs to be confirmed through metamorphic ages. A compressional tectonic regime is, furthermore, expected to inhibit the formation of giant mafic dyke swarms, which typically form during continental break-up, but also may form along back-arc spreading centres or even in post-orogenic rifts.

Possible 'syn-Nagssugtoqidian' dykes at Umivik

Along the east coast of Greenland, at Umivik, a dense swarm of roughly E-W trending mafic dykes straddle the boundary between the northern NAC and the Nagssugtoqidian deformational front. As also seen for the Kangamiut dyke swarm on the west coast, the Umivik dykes on the east coast become progressively more dextrally sheared when approaching the deformation front, hinting at a possible link between the two sets of swarms. In detail, the Umivik swarm is made up by a WNW-ESE trending and more 'amphibolitized' sub-swarm that is consistently cross cut by an E-W trending and less altered 'doleritic' sub-swarm, and Bothma & Klausen (2014) explained these field relationships in the following two ways:

(1) Correlating with swarms across the western NAC-coast of Greenland, the older 'amphibolites' could be 2.37 Ga (or older), whereas Umivik 'dolerites' most likely are extensions of the 2.21 Ga swarm, However, this requires an intermittent meta-morphic overprint (other than the Nagssugtoqidian Orogeny), which in that case is, hitherto, unrecognized.

(2) The Umivik swarm's sub-parallel trend and location ~250 km behind a likely oro-genic front at Tasiilaq, could tentatively be interpreted as a continental back-arc setting, wherein the 'amphibolites' first intruded, before being metamorphosed by the Nagssugtoqidian continent-continent collision, followed by the 'dolerites'. However, this suggests that the Umivik 'dolerites' are younger than any other currently known Palaeoproterozoic dykes.

The late-Ketilidian appinite suite

Mafic intrusions of tabular shape were emplaced during the latter stages of the Ketilidian Orogeny, extending across the southern border of the eastern NAC-coast of Greenland. These intrusions, however, are comparatively thinner than the other mafic dykes considered in this review and also have a different intrusive style, forming inclined sheets or even sills. They are also characterized by primary igneous amphibole (as opposed to their secondary mineralization within the Palaeoproterzoic dykes), pointing to high water contents in the magmas and thereby testifying to their late-orogenic setting. Their compositions range from ultramafic cumulates to felsic differentiates related to each other through a more Fe-depleted, calc-alkaline differentiation trend, that differs from all other dykes in this review (cf., Fig 3), where, e.g., a lack of Sr-depletion (Fig 4) is consistent with amphibole fractionation. Thus, these intrusions bear all the characteristics of the so-called appinite (e.g., Murphy 2013), or lamprophyre (Le Maitre 2002), suite.

Mesoproterozoic dyke swarms

Dykes from post-orogenic swarms are all relatively unaltered, compared to Proterozoic dykes. The following two Mesoproterozoic swarms cut across the eastern, but apparently not the western, NAC-coast of Greenland:

1.63 Ga Melville Bugt Dyke Swarm (MBDS)

A distinct swarm of NNW-SSE trending dykes cut across most of the eastern NAC-coast of Greenland. In the field these dykes stand out as being paler orange-weathered and variably feldspar megacrystic. Halls et al (2011) suggested a correlation with NE Greenland's Melville Bugt dyke swarm (MBDS) based on a coinciding structural trends across Greenland's ice sheet. Klausen et al (2014) further confirms the idea based on a perfect geochemical match between dyke core samples (note: samples of dyke margins are considered less diagnostic as they appear to be crustally contaminated (e.g. Kalsbeek & Taylor 1986)), as well as preliminary U-Pb TIMS dating (baddeleyite; M. Nilsson unpublished data). The extension of the MBDS to SEG would make it into a remarkable >2000 km-long trans-Greenlandic structure (cf., Fig 2).

Further geochemical matching between spessartites within the late-Ketilidian appininte/lamprohyre suite (cf., Fig 3) led Klausen et al (2014) to propose a common SCLM source for both swarms, even if the magmas for the MBDS were distinctly drier (as testified by a petrography that is consistent with crystallization of plg → ol → cpx) and these two events may have formed as much as 200 million years apart. A central source for the MBDS inside the Ketilidian Orogeny is supported by (1) a remarkable geochemical homogeneity along the >2000 km-long swarm (e.g., Kaslbeek & Taylor 1986), (2) an apparent northwards tapering out of the swarm in NE Greenland (Nielsen, 1990), and more indirectly by (3) similar relationships between roughly coeval and compositionally similar lamprohyre (e.g., Andersson et al 2007; Rutanen et al 2011) and diabase (e.g., Rämö 1991) intrusions within the Fennoscandian continuation of the Ketilidian Orogen.

Albeit still under investigation, a southern central magma source of the MBDS appears to have formed within a long-lived 'outboard Andean margin' of the Nuna supercontinent (e.g., Evans & Mitchell 2011; Pesonen et al 2012; Johansson 2014). It is tentatively suggested that the same SCLM that gave rise to hydrous appinites/lamprophyres following late stage (e.g., island arc) accretion along this margin and a possible slab break-up during ridge subduction also – for reasons yet unknown – generated large volumes of dry magmas at 1.63 Ma. These magmas could have accumulated within a deep-crustal magma reservoir (normative Ne-Di-Ol-Hy-Q-plots by Thompson 1982, suggests 30 km's depth), from which a cotectic assemblage of 2/3 plagioclase and 1/3 olivine fractionated. Lateral injections of a series of large-volume, and compositionally homogeneous dykes within the >2000 km-long MBDS suggest that this magma reservoir must have been correspondingly large and most likely able to generated slightly younger rapakivi granites through crustal anatexis of the magma chamber's roof zone. Any petrogenetic relationship between the MBDS' feldspar-megacryst bearing dykes and roughly coeval anorthosite-mangerite-charnockite complexes also needs to be investigated further.

1.27 Ga Early Gardar Dyke Swarm (EGDS)

The 1.27 Ga so-called 'early Gardar dykes' constitute WSW-ENE trending dykes that cut across the southern and south eastern part of the NAC. Although difficult to differentiate in the field from roughly parallel Palaeoproterozoic MDs these Gardar dykes were recognized early on in the Timmiarmiut area by Bridgewater et al (1973), from cross cutting relationships. The preliminary ~1.27 Ga age of these dykes are now verified through unpublished ages by Mimmi Nilsson, and the chemistry of the dykes are included in further petrogenetic studies by Bartels et al 2014 (this abstract volume). Bartels et al (2014) propose a correlation between the Gardar Province proper and coeval Harp dykes in Newfoundland and also compare these to the roughly coeval Sudbury and Central Scandinavian dyke swarms (Fig 2). It is worth mentioning that these Gardar dykes also exhibit geochemical 'fingerprints' that are consistent with SCLM source and/or having assimilated continental crust, like the sub-parallel but much older Palaeoproterozoic dykes (cf., match in Fig 3).

Tertiary Dykes

Coast-parallel tholeiitic Tertiary dykes are found around much of Greenland, including the western NAC-coast of Greenland, where Larsen et al. (2009) identified a number of coast-parallel Tertiary tholeiites amongst Mesozoic-Palaeogene lamprophyres, kimberlites and related intrusions. Denser swarms, as part of a landward edge of a relatively narrow continent-ocean transition along East Greenland (e.g., Klausen & Larsen, 2002), are exposed within 500 km of the proto-Icelandic hot spot centre near Kangerlussuaq (67°N). Farther south, Tertiary dykes are much rarely exposed on land, but three samples from two N-S trending dykes across the seaward parts of the Umivik area – initially regarded in the field as part of the MBDS – are suspected to be Tertiary, because of their (1) consistently younger cross cutting relationships, (2) seaward location, close to the Tertiary break-up of the North Atlantic, (3) distinct OIB-signatures (positive Nb-anomaly), which are very unlike any other of the mafic dykes reviewed in this abstract and resemble basalts derived from the proto-Icelandic hot spot, and (4) coinciding aeromagnetic anomalies that appear to track the dykes across an offshore and crustally extended margin that formed during the break-up of the Atlantic (B.M. Stensgaard, pers. comm.).

It is thought-provoking how all older continental mafic dykes across the NAC are characterized by higher LILE/HFSE and more variably Nb-anomalies, suggestive of a SCLM source and/or crustal assimilation. This makes one speculate on whether Precambrian LIPs and their associated giant mafic dyke swarms never formed as directly from any enriched mantle plume as otherwise postulated by e.g., Ernst & Bleeker (2010), or at least not without a much greater influence from the continental lithosphere, as many Phanerozoic LIPs seem to have done during the last break-up of the Pangaea-Gondwana supercontinent.

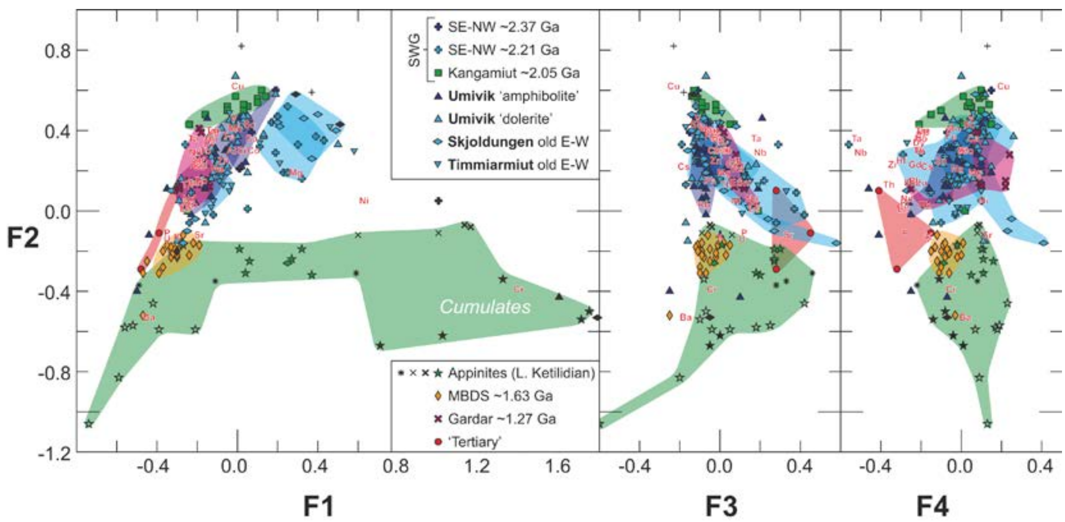

Figure 3 *Results from a correspondence analysis on 202 samples and 43 elements (Esbensen, 1994), showing most variation due to differentiation and accumulation along the F1-axis, but also a major separation along the F2-axis between more LREE & LILE-rich appinites-MBDS and other mafic dykes swarms that are otherwise more difficult to differentiate between. Kangamiut dykes stand out as the most HREE and HFSE-enriched of these. Ba, Cu & Sr appear to be particularly good discriminants as shown in Fig.4.*

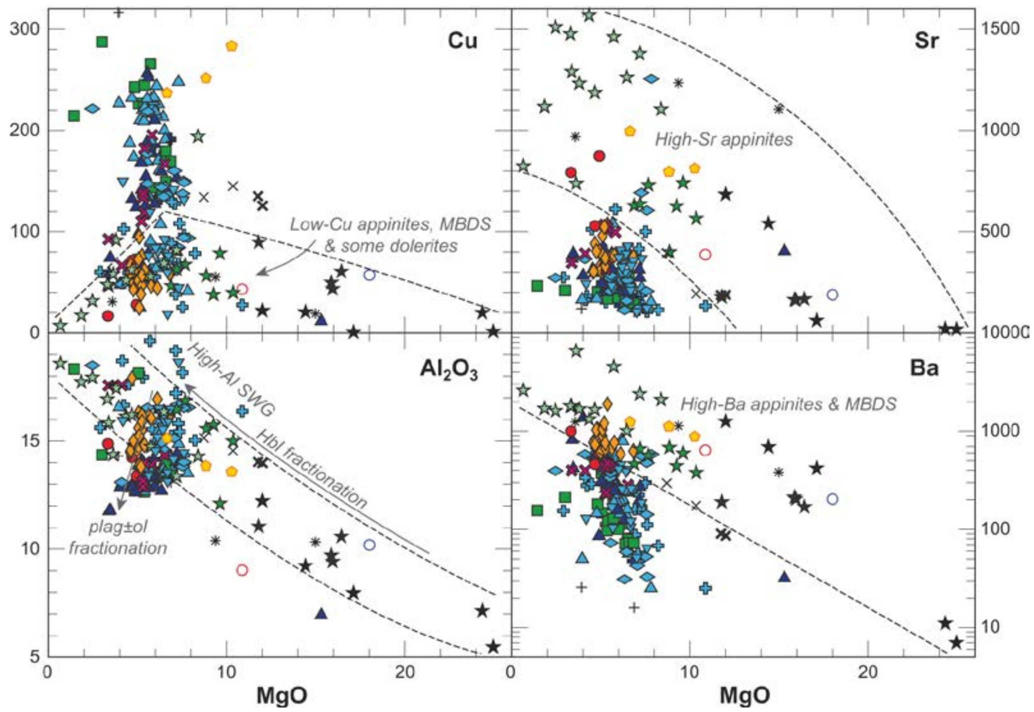

Figure 4 *Three of the most distinct elemental differences between samples, as deduced from Fig. 3, plotted against MgO as a differentiation index. As noted by Nilsson et al (2013), there is a separation, not only between low-Cu appinites and the MBDS, but also amongst some of the presumed Palaeoproterozoic dykes, where the Kangamiut dykes appear to be particularly Cu-rich. The MBDS is in most cases similar to the appinite suite's spessartites, except for having distinctly lower Sr – like most other dykes. This is probably because hornblende fractionation differentiated (or accumulated within) the appinite suite magmas, whereas plagioclase is a dominant fractionating phase amongst the other swarms' drier basaltic magmas. This plagioclase fractionation is also evidenced by decreasing Al_2O_3 with decreasing MgO. The appinite suite and the MBDS are both characterized by exceptionally high Ba.*

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The Nagssugtoqidian Orogen of South-East Greenland: Facts, new interpretation and research needs

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The Nagssugtoqidian Orogen in South-East Greenland was formerly known as the Nagssugtoqidian, Ammassalik or Angmagssalik Mobile Belt and is cited as such in the older literature. Recent investigations confirmed the correlation with the Nagssugtoqidian Orogen in western Greenland and its evolution as a collisional orogen instead of a mobile belt. The actual extent of the orogen, correlations in detail and the distribution of Palaeoproterozoic rocks are a matter of confusion, because different interpretations and maps exist.

Palaeoproterozoic rocks

Palaeoproterozoic mafic dykes of different ages are ubiquitous in South-East Greenland. There are dykes of different ages with similar strike, which makes a simple mapping by dyke orientation impossible (Klausen & Nilsson, this paper).

Síportôq Supracrustal Association is the umbrella term for all Palaeoproterozoic supracrustal rocks in the Tasiilaq area. The southernmost occurrence is at Kitak, whereas the rocks extent to Juragletscheren in the north. In particular in the Kap Tycho Brahe area, however, the Síportôq Supracrustal Association is tectonically imbricated with similar Archaean rocks, which is not distinguished on currently available maps, and the Archaean rocks are grouped with the Palaeoproterozoic rocks into one map unit (which is very confusing in the field). A clear distinction in the field is, however, always possible by detailed structural and petrographic observations. Archaean rocks contain an older foliation, show retrograde mineral reactions, are dominated by amphibolite and always separated by a mylonite from the Síportôq Supracrustal Association.

A detailed review of the Síportôq Supracrustal Association suggests a subdivision into three units based on differences in the stratigraphy (Kolb, 2014): the ca. 2200-2100 Ma Helheim and Kuummiut units that include marble, meta-pelite and psammite and amphibolite, where the Kuummiut unit is characterised by less marble and amphibolite and more metamorphosed siliciclastic rocks; and the <1910 Ma Kap Tycho Brahe unit including bimodal meta-volcanic and meta-sedimentary rocks.

Palaeoproterozoic intrusions north of Tasiilaq include a diorite complex east of Sermilik of unknown age (Thrane, this paper). The rocks are largely undeformed and form a layering of gabbro-diorite-anorthosite. To the south of this complex, the dunite-“amphibolite” Ivnartivaq Complex intruded at 1955 ± 28 Ma into Archaean orthogneiss (hornblende Ar-Ar; Brooks and Stenstrop, 1989). A tonalite intrusion east of Sermilik has a Pb-Pb zircon intrusion age of 1901 ± 9 Ma (Nutman et al, 2008).

The ca. 1885 Ma Ammassalik Intrusive Complex (AIC) forms three centres with a northwest trend around the Tasiilaq settlement. The intrusions are complex mafic intrusions of variable composition and magmatic fabrics, which are not studied or mapped in detail.
The youngest Palaeoproterozoic intrusions are the ca. 1680 Ma granite-granodiorite-diorite-gabbro intrusions north of Tasiilaq and at Isertoq. The different rocks show mixing and mingling structures, indicating contemporaneous intrusion.

Metamorphism and Deformation

In general, the rocks show mineral assemblages of amphibolite- to granulite-facies grades. The timing of metamorphism and deformation is however different in different parts of the wider Tasiilaq area, which resulted in the subdivision into different terranes (Kolb, 2014). From north to south:

1. Schweizerland Terrane: Archaean rocks in the hanging wall of the Niflheim Thrust have undergone Neoarchaean granulite facies metamorphism and amphibolite facies retrogression still in the Neoarchaean (Nutman et al., 2008). No significant Palaeoproterozoic overprint is evident from petrology and geochronology, except for mafic dykes and faults. This is important, because the rocks north of the Niflheim Thrust are often shown as “reworked Archaean” or as “reworked in the early Proterozoic”, which has no basis in the recent literature and data.
2. Kuummiut Terrane: Archaean orthogneiss, Archaean greenstone belt equivalents and Palaeoproterozoic mafic dykes have relic eclogite facies reaction textures. The rocks have been strongly retrogressed in the granulite facies and amphibolite facies. The entire recognisable metamorphic history is Palaeoproterozoic. The high-pressure assemblages make this terrane the lower plate of the Nagssugtoqidian Orogen. An interesting target could be the Blokken Gneiss area, which is relatively little affected by deformation but includes mafic dykes with relic eclogite facies reaction textures. The Archaean rocks are always structurally overlain by the Kuummiut and Helheim units. Interestingly, there are both extensional and reverse shear zones of similar age, which could be responsible for exhumation of the high-pressure terrane.
3. AIC: The rocks of the AIC intruded Archaean orthogneiss, Archaean greenstone belt equivalents and rocks of the Palaeoproterozoic Kap Tycho Brahe unit. The mafic intrusions have migmatitic contact metamorphic aureoles and peak pressures are estimated at 8 kbar, which characterises this terrane as a low-medium pressure – high temperature terrane. The AIC is dominated by pure shear and transcurrent deformation. The north of the AIC is bound by a prominent, steep shear zone, which also marks a drastic change in magnetic signal, to the Kuummiut Terrane. The AIC and terranes to the south, thus, most likely represent the upper plate as opposed to interpretations by Nutman et al. (2008). The shear zone north of the AIC is interpreted as the suture between the different continents that collided during the orogeny.
4. Isertoq terrane: The AIC is part of this terrane, which is additionally characterised by Archaean orthogneiss, Archaean greenstone belt equivalents and rocks of the Pal-

aeoproterozoic Kap Tycho Brahe unit. Palaeoproterozoic peak metamorphism here is in the amphibolite facies and locally retrogression from granulite facies can be observed in the Archaean rocks. Structurally, Archaean and Palaeoproterozoic rocks are intensely tectonically imbricated. The Palaeoproterozoic overprint becomes less pronounced in the south and the southern orogenic front is not well-defined but is probably situated in the Køge Bugt – Umivik area.

The most recent large-scale geological interpretation is that the Isertoq Terrane and the AIC belong to the North Atlantic Craton, which forms the upper plate during the Nagssugtoqidian orogeny. The Kuummiut and Schweizerland terranes belong to another Archaean block, which could be the Rae Craton extending from Canada in the west. The Kuummiut Terrane represents the lower plate that was obliquely subducted to the WSW. The stress field subsequently changed during collision between the cratons to N-S.

Economic Geology

There are different mineralisation types known from the area, including the exploration target represented by the Ni-sulphide mineralisation in the contact aureole of the AIC (21st North). There has been furthermore evaluation of graphite mineralisation, and several samples collected by local prospectors (Ujarassiurit program) yielded high values of gold, which however could not be ground confirmed up to today.

Nickel sulphide mineralisation is known from the Tasiilaq area since the mid 1990's and explored for a couple of years. It is now under the license of 21st North (Ammassalik Prospect), who explores the contact aureole of the AIC for komatiite-hosted Ni-Cu-PGE-Au mineralisation. In 2010 and again 2011, GEUS teams sampled sulphide-bearing igneous rocks from the AIC. The sulphides comprise pentlandite and are interstitial to pyroxene and olivine, suggesting liquid immiscibility during the igneous evolution of the AIC, which sheds new light on the potential for Ni-sulphide mineralisation in the complex (Grøtner, this paper; Johannesen, this paper).

The ca. 1955 Ma Ivnartivaq Complex is a ~300 x 800 m sized ultramafic complex dominated by serpentinite and dunite. An amphibolite body in the complex contains a ~230 m2 magnetite layer, which is not studied in detail (Brooks and Stenstrop, 1989).

Graphite is widespread in the rocks of the Síportôq Supracrustal Association, and two areas have been investigated to a greater detail for a potential economic use, namely Kangikajik and Augpalugtoq. In the Helheimfjord north of Augpalugtoq, amphibolite and garnet-biotite gneiss contain graphite in assemblage with hydrothermal pyrrhotite and chalcopyrite, indicating an epigenetic hydrothermal origin of the graphite (Baden et al. 2014). The evaluation of the graphite occurrences indicates interesting quality returns but only small estimated resources, but also outlines potential directions of future research (Kalvig and Bohse, 1992; Rosing-Schow, this paper).

A sample from close to Sermiligaq sent to the Ujarassiorit mineral hunt returned high Pb and Zn. Joint GEUS-BMP(MIM) field reconnaissance in 2010 identified narrow quartz veins at the orthogneiss-amphibolite contact. The veins are milky white and contain < 10 cm long amphibole, calcite, pyrite, chalcopyrite, magnetite and galena. They form a complex network but appear to be controlled by a N-trending oblique dextral-reverse (E-side up) fault that runs parallel to the Sermiligaq fjord.

Besides the igneous Ni-PGE and the hydrothermal graphite and Pb-Zn mineral systems, no mineral occurrences are reported. The felsic and mafic meta-volcanic rocks of the Kap Tycho Brahe unit suggest bimodal volcanism in a potential arc setting proximal to the arc-related AIC. Such a setting would be favourable for VMS-type of massive sulphide Cu-Au systems. The Helheim unit contains thick marble units of similar age as the Karrat Group in western Greenland, which hosts the Black Angel Pb-Zn deposit. These marbles could thus be a favourable unit for Broken Hill-type Pb-Zn mineral systems. A better understanding of the geology of these units is, however, required.

Major questions and research needs

The nature and geological evolution in the Archaean remains unresolved. Current geotectonic models suggest collision between two Archaean terranes during the Palaeoproterozoic orogeny. Whether these terranes belonged to one larger Archaean continent or whether they represent two different continents remains an important question to be resolved. Does the system of ca. 2200-2050 Ma mafic dykes and subsequent WSW-vergent subduction until ca. 1870 Ma collision and following orogenic collapse represent a complete Palaeoproterozoic Wilson-cycle? Detailed isotope studies on zircon from Archaean orthogneiss may aid in the interpretation of the pre-2200 Ma evolution. Additional information may be obtained from investigations of the different sets of Palaeoproterozoic mafic dyke systems.

The Síportôq Supracrustal Association was further subdivided into 3 units (Kolb, 2014). A detailed tectonostratigraphy of Palaeoproterozoic rocks is, however, lacking. This is needed in order to (1) interpret the Palaeoproterozoic evolution and geological setting in, e.g., a passive or active continental margin; (2) correlate the units with Palaeoproterozoic rocks from western Greenland and Scandinavia or Canada; and (3) identify possible mineral systems.

The AIC is generally accepted as an arc-related igneous complex. This, however, has never been substantiated by geochemical or isotopic data.

The tectonometamorphic evolution of the Nagssugtoqidian Orogen is now relatively well-constrained on a relative timing basis. There are, however, several deformation stages that are difficult to explain without information about their absolute timing. What is the nature and timing of the early SE-vergent deformation in the Isortoq Terrane? How is the complex evolution of different metamorphic units, i.e. eclogite facies orthogneiss and mafic dykes and amphibolite facies Síportôq Supracrustal Association, in the Kuummiut terrane? What is the nature and timing of the late Niflheim Thrust, one of the youngest structural features in the orogen? Is there a significant Palaeoproterozoic overprint of Archaean rocks of the Schweizerland Terrane north of the Niflheim Thrust, as suggested by several maps and publications but not confirmed by zircon U-Pb dates?

Tertiary igneous complexes are known from the north of the study area, but are not well-investigated. Their extent and mineral potential remain unknown, which is an important target when compared with the potential of mineral deposits hosted in Tertiary igneous rocks of East Greenland.

Earthquake swarms in Greenland

Tine B. Larsen, Peter H. Voss & Trine Dahl-Jensen

Geological Survey of Denmark and Greenland (GEUS)

Earthquake swarms occur primarily near active volcanoes and in areas with frequent tectonic activity. However, intraplate earthquake swarms are not an unknown phenomenon. They are located near zones of weakness, e.g. in regions with geological contrasts, where dynamic processes are active. An earthquake swarm is defined as a period of increased seismicity, in the form of a cluster of earthquakes of similar magnitude, occurring in the same general area, during a limited time period. There is no obvious main shock among the earthquakes in a swarm.

Earthquake swarms occur in Greenland, which is a tectonically stable, intraplate environment. The first earthquake swarms in Greenland were detected more than 30 years ago in Northern and North-Eastern Greenland. However, detection of these low-magnitude events is challenging due to the enormous distances and the relatively sparse network of seismographs. The seismograph coverage of Greenland has vastly improved since the international GLISN-project was initiated in 2008. Greenland is currently coved by an open network of 19 BB seismographs, most of them transmitting data in real-time. Additionally, earthquake activity in Greenland is monitored by seismographs in Canada, Iceland, on Jan Mayen, and on Svalbard. The time-series of data from the GLISN network is still short, with the latest station been added in NW Greenland in 2013. However, the network has already proven useful in detecting several earthquake swarms. In this study we will focus on two swarms: one occurring near/on the East Greenland coast in 2008, and another swarm occurring in the Disko-area near the west coast of Greenland in 2010. Both swarms consist of earthquakes with local magnitudes between 1.9 and 3.2. The areas, where the swarms are located, are regularly active with small earthquakes. The earthquake swarms are analyzed in the context of the general seismicity and the possible relationship to the local geological conditions.

Petrology of the 2.7 Ga Vend Om Intrusion, Skjoldungen Alkaline Province, SE Greenland

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The Vend Om Intrusion is part of the Skjoldungen Alkaline Province that forms a belt of Archaean (2720-2665 Ma) intrusions in southeast Greenland ranging from pyroxenite and hornblendite over hornblende-rich norite and monzonite, to granite, syenite and carbonatite (Blichert-Toft et al., 1995: J. Pet. 36, 515-561). These intrusions represent a shoshonitic liquid line of descent and were emplaced into the lower crust of an arc setting (Thomsen, 1998, unpubl. PhD thesis, University of Copenhagen).

The Vend Om Intrusion is a small 300x400m oval-shaped (map-view) hornblende-norite plug- like layered intrusion first described by Blichert-Toft et al. (1995). To examine magma chamber processes and subsolidus modifications we present petrography and whole-rock geochemistry data of 93 samples, including a SW-NE transect though the intrusion. The contact to the country- rock orthogneisses is steep/near-vertical and is often intruded by granite sheets up to 3 m wide extending up to 30 m into the intrusion. The outermost up to 40 m thick zone denotes a steeply dipping marginal series of coarse grained hornblende-mela-gabbronorite. The inner layered series consists mainly of magnetite-bearing hornblende-norites that show prominent cm- to m-scale modal layering including up to 2 m thick layers and irregular bodies with up to 80% magnetite (with hercynite). In the same part locally wraps around blocks of leucogabbro. Overall, the modal layering appears to define a concentric structure that is steeply inward-dipping, but with a sense of stratigraphic up towards southwest.

Questions to be addressed include the origin of layering, hornblende, magnetite-rich bodies, granite sheets, and leuconorite blocks, as well as the architecture of the intrusion.

Petrology and zircon isotope and trace element data from the main garnet bearing sequence on Helge Halvø

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The rocks on Helge Halvø represent one of the main belts of supracrustal rocks in the Skjoldungen region. We present detailed field observation geochemistry, zircon U/Pb and trace element data from garnets and zircon from a spectacular geological sequence found on the north-eastern shore of the peninsula.

The main rock units are:
1) mylonitic gneisses (Fig. 1A, B and C);
2) garnet-sillimanite (gt-sill) gneisses (1D, E and F);
3) undeformed leucocratic veins (often garnet bearing) that intrude the mylonites and the gt-sill gneisses and
4) enclaves of mafic of ultramafic composition that occur throughout the mylonite, some of these contain internal isoclinal folds (Fig. 1C), some are boudinaged and some are folded within the mylonite.

The mylonites constitute the main part of the sequence and the gt-sill gneisses occur as scattered patches that vary in size with the large patches ranging up to around 20*60 m (Fig. 1D, E, F). The gt-sill gneisses consist mainly of garnet, often of quite large size with diameters up to ca. 1-2 cm (Fig. 1F). Sillimanite is situated as matrix in between the garnets. The garnet bearing leucocratic veins are present in pressure shadow regions around competent units (Fig. 1C) and the gt-sill gneiss patches are infiltrated by the leucocratic veins either as a network of cm thick veins or in pressure shadow regions e.g. in boudinaged units (Fig. 1D).

Zircon grains have been extracted from the leucocratic veins within the gt-sill gneisses; these zircons have low HREE contents, suggesting growth in equilibrium with garnet, and have U/Pb age of 2701 ± 14 Ma. Garnets from the

These observations suggest that the mylonitic gneisses and the garnet sillimanite gneisses represent a metamorphosed and deformed basement that was infiltrated by leucocratic melts at ca 2701 ± 14 Ma.

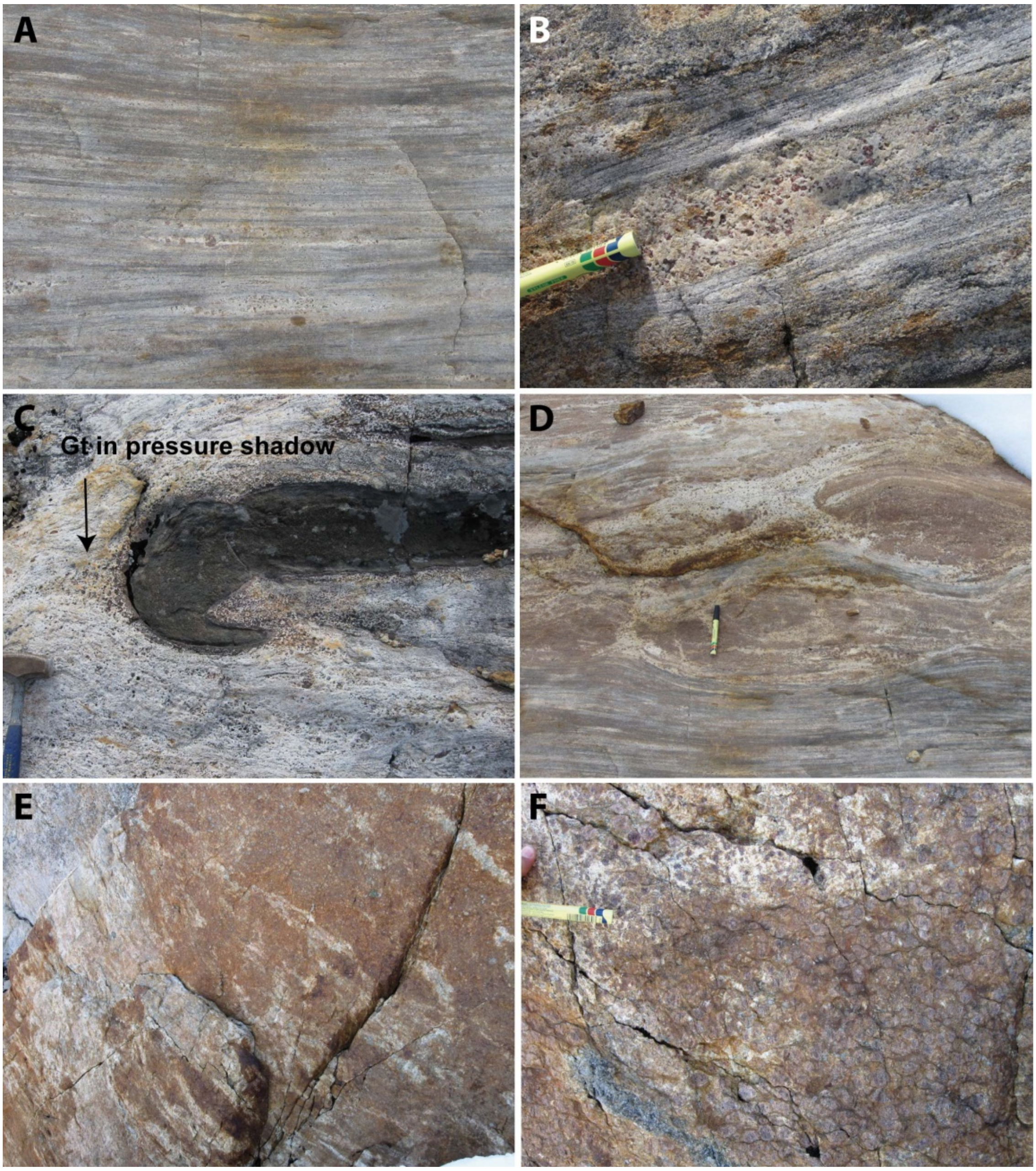

Figure 1 *Rock textures from the north-eastern shore of Helge Halvø. The entire sequence is situated in a strongly sheared isoclinale folded zone and mylonites are observed in all felsic incompetent units, more competent units of mainly garnet-sillimanite are boudinaged and in-fluxed by leucocratic melts. A) Mylonite with foliation parallel garnet bearing leucosome. B) Garnet bearing leucosome in mylonite. C) Mafic enclave in mylonite with garnet bearing leuco-some consentrated in pressure shadow region. D) Boudinaged gt-sill gneiss infiltrated by gt bearing leucocratic melts. E) A patches of gt-sill gneiss with gt bearing leucosome. F) Gt-sill gneiss with gt bearing leucocratic melts in pressure shadow region.*

Metamorphic evolution of mafic dykes in the Nagssugtoqidian Orogen, South East Greenland

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The Nagssugtoqidian Orogen is a deeply eroded, southeast-northwest trending, 200 km wide, Paleoproterozoic collision orogen in the Ammassalik region of South-East Greenland (Fig. 1, Nutman et al. 2008). It consists of a variety of Archaean and Paleoproterozoic rocks that were affected by deformation and high-grade metamorphism, with the core being dominated by TTG gneisses and sheets of Paleoproterozoic supracrustal rocks. The orogen is bounded by two Archaean high-grade gneiss terranes, including the Rae craton to the north and the North Atlantic craton to the south (Bridgwater and Myers 1979; Myers 1984). Prior to Paleoproterozoic deformation, swarms of discordant mafic dykes containing relics of high-pressure mineral assemblages intruded the Archaean country rocks (Chadwick et al. 1989; Nutman et al. 2008).

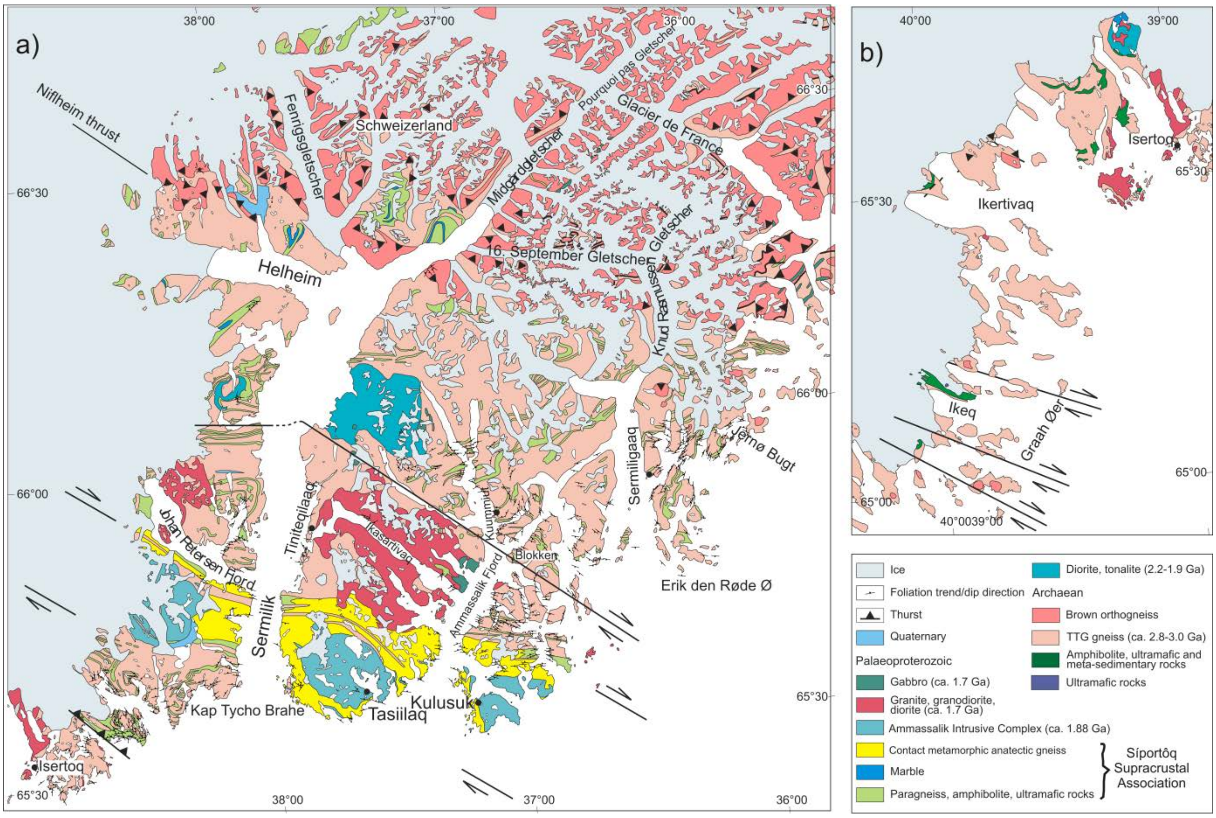

Figure 1 *Geological Map of the a) northern and b) southern Nagssugtoqidian Orogen.*

This study investigates the metamorphic evolution of the mafic dykes in order to provide new insights into the geodynamic processes and subduction depths of this Paleoproterozoic orogen.

The mafic dykes show a variable petrography with mineral parageneses typical of amphibolite to granulite facies conditions. Most useful for investigation of the PT-evolution of the mafic dykes are samples that were interpreted as retrogressed eclogites. They mostly consist of garnet, clinopyroxene, hornblende and plagioclase, with the four minerals being distributed over two subdomains that were formed during the exhumation of the eclogites.
The first subdomain consists of clinopyroxene, hornblende and plagioclase (Fig. 2).

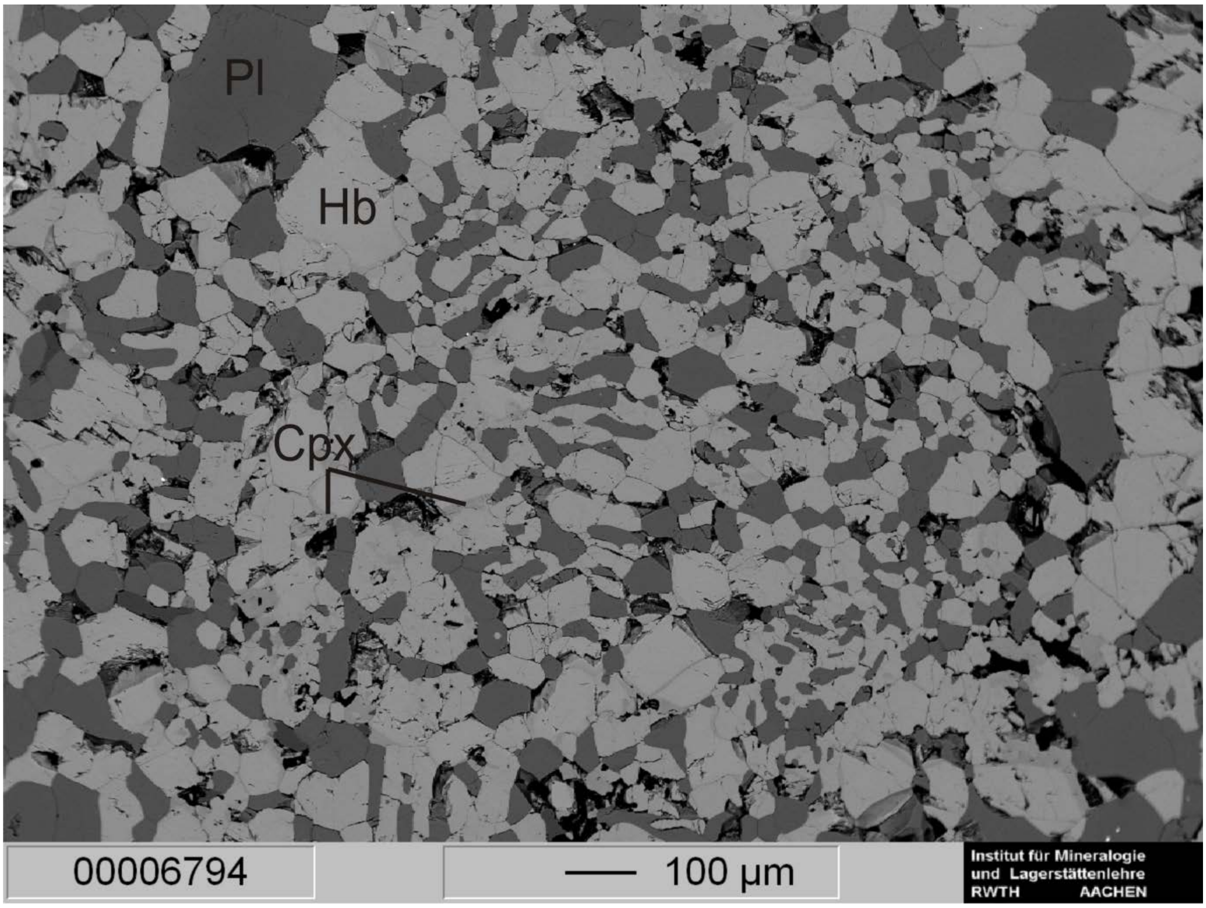

Figure 2 *Clinopyroxene-subdomain consisting of clinopyroxene (Cpx) intergrown with hornblende (Hb) and plagioclase (Pl).*

The worm-like structures and mineral assemblage in this subdomain are typical of a symplectite after omphacite that forms during exhumation: omphacite, as an eclogite-facies mineral is moved out of its stable PT-range during isothermal decompression and disintegrates into plagioclase and Na-poor diopside. While this process might proceed isochemically within the clinopyroxene subdomains, it is more likely that the reaction products in former omphacite domains have formed due to the interaction with the matrix and garnet subdomains.

The other subdomain consists almost entirely of garnet, plagioclase and hornblende and also show disequilibrium textures (Fig. 3). Similar to omphacite, garnet becomes unstable during decompression and is replaced by plagioclase. Garnet, however, is a refractory mineral and as such much more resistant to alteration than omphacite, which is the weaker phase in eclogites. Consequently, garnet is not being transformed to plagioclase entirely but rather is replaced by plagioclase-coronas around its centre, followed by smaller hornblende and quartz coronas. Plagioclase reaction rims around the garnet core replace the eclogite-facies mineral to different degrees, as diffusion and net-transfer reactions result in further corona growth, ultimately leading to pseudomorphs after garnet. Except for garnet, which shows a fine retrograde diffusion zoning (Mn- and Fe-rich rims), all minerals are unzoned.

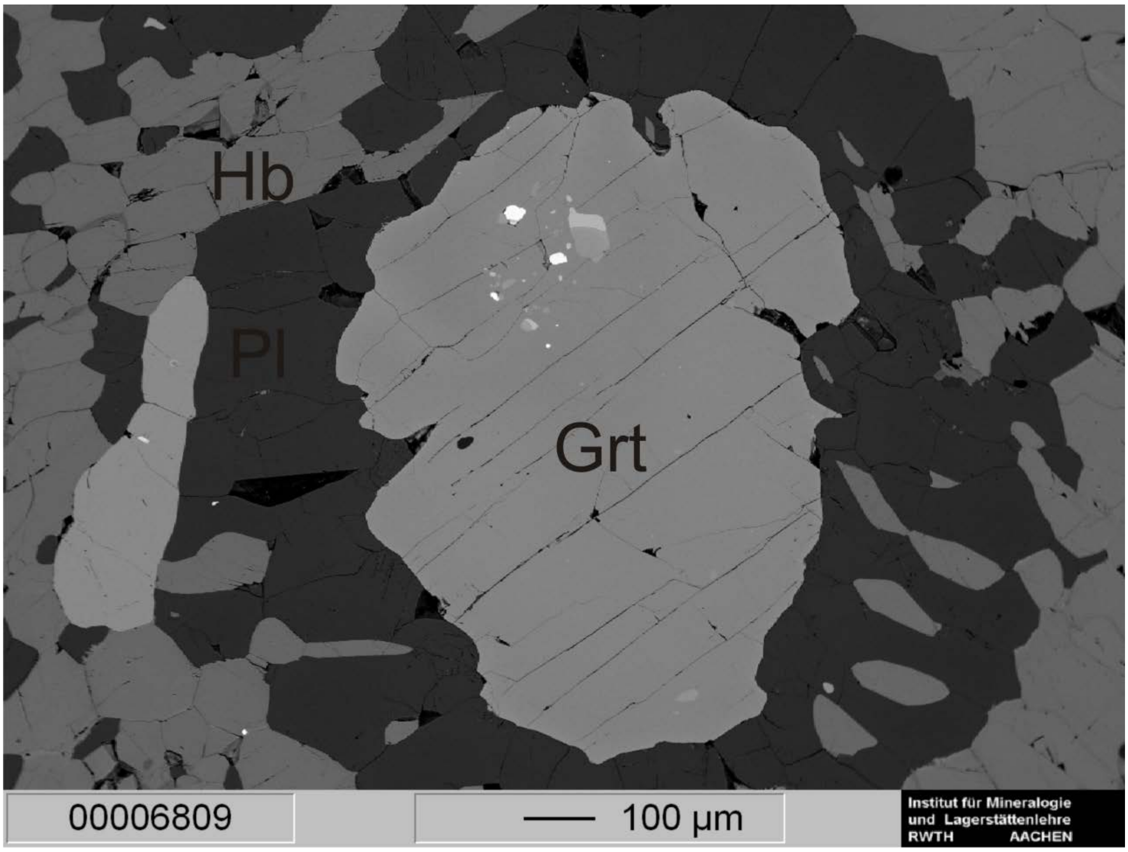

Figure 3 *Garnet-subdomain consisting of garnet-cores (Grt), surrounded by plagioclase- (Pl) and hornblende-coronas (Hb).*

Apart from variable mineral parageneses, bulk rock major- and trace-element data of the mafic dykes also show a large range in compositions. The samples have a basaltic, tholeitic composition based on their bulk-rock major element contents. An island arc setting has been determined as the tectonic origin of these rocks via bulk-rock trace element chemistry.

Pressure and temperature conditions during metamorphism were determined using conventional geothermobarometry, the THERMOCALC average P-T-method and pseudosection modelling.

The average P-T-method yields PT-conditions of 893-938°C, with a maximum error of 110°C, and 12,2-14,4 kbar, with a maximum error of 3,1 kbar. Pseudosection modelling yields more precise PT-ranges with 820-870°C and pressures of 9-12 kbar. These data are generally consistent with the mineral assemblages observed, but the estimated temperatures are about 100-200°C higher than those estimated using conventional geothermometry (600-800°C). The difference in estimated temperatures is most likely due to the fact that the rocks had a reduced fluid content during retrogression, whereas the pseudosections were calculated with water in excess.

Estimated pressures and temperatures of the retrogressed eclogites are in agreement with calculations of previous authors working in the Nagssugtoqidian Orogen (Nutman et al. 2008). The data show that the mafic dykes were exhumed from the mantle into the lower continental crust (about 35-40 km).

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Characterisation of the South East Greenland basement – a CCSEM heavy mineral investigation

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The analysis of stream sediments samples provides a way to characterise the local bedrock geology in an area and can therefore be used to give a first insight to the geology of a relatively unknown area, but also as a provenance tool for palaeogeographic reconstructions and basin analyses. Kalsbeek et al. (1974) describe that a change in composition of the sand reflects changes in the local bedrock geology of the area, while reworking of glacial materials and other sedimentary processes only play a minor role, as long as drainage areas of moraine deposits are avoided for sampling. Heavy mineral analysis provides information on the nature of the basement or its sedimentary cover, like the composition (felsic, mafic), metamorphic grade, and in case of sediments, the maturity. The method profits from a combination with an ICP-MS detrital zircon investigation (Thrane, this volume; Thrane & Keulen, in revision).

Method

Computer-controlled Scanning Electron Microscopy (CCSEM) as an analysis tool for a wide range of geological or non-geological materials has been developed at the Geological Survey of Denmark and Greenland (GEUS) as a fast and reliable method to determine the chemistry of individual minerals and bulk samples with a scanning electron microscope equipped with an energy dispersive spectrometer.

Samples have been analysed for the following elements: Na, Mg, Al, Si, P, S, K, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Y, Zr, Nb, Sn and Ce.. The chemical analysis is combined with measurements of the two-dimensional size and morphology of every single grain. Further details of the technique are discussed in Keulen et al. (2008, 2012). The following minerals are currently identified in the database: Ilmenite, leucoxene, rutile, Ti-magnetite, magnetite, chromite, spinel, garnet, sillimanite-kyanite, staurolite, dark mica, white mica, feldspar, quartz, epidote, chlorite, olivine, clino-amphibole/pyroxene, ortho-amphibole/pyroxene, other silicates, corundum, pyrite, monazite, xenotime, phosphates, carbonates, and other minerals (unclassified). Additional minerals can be added when necessary. To characterise the garnets, the garnet classification described by Keulen & Heijboer (2011) has been used.

Here, the CCSEM technique was applied to heavy mineral fraction (□>2.9 g/cm3) samples and 19 stream sediment samples collected from South-East Greenland (Figure 1). Most of the stream sediment samples are derived from Archaean and Proterozoic basement rocks, some also dewater late (Palaeogene and Mesozoic) intrusions.

Results

The results for the modal heavy mineral analysis on these samples are discussed below. Since clino-pyroxene/clino-amphibole is the main heavy mineral in the region, an attempt to further classify these minerals was made, based on their major and minor element contents.

483291 and 483292 have garnet as their major heavy mineral. Clino-pyroxene/clino-amphibole, biotite and ortho-pyroxene/ortho-amphibole are common. Less abundant are sillimanite-kyanite, muscovite, epidote and ilmenite-Ti-magnetite. The clino-pyroxene/clino-amphibole in these samples probably has an augite composition. The garnets in these samples were derived from felsic rocks that recrystallised at high to intermediate metamorphic grade.

483297, 483298, 552661 and 552670 show a very similar heavy mineral suite: clino-pyroxene/clino-amphibole, ortho-pyroxene/ortho-amphibole, Ti-magnetite and biotite are the most common minerals. Iron-oxide (probably magnetite) is found abundantly as well. The clino-pyroxene/clino-amphibole minerals in the four samples are probably hornblende (of edenite-hastingite composition) and augite or diopside-augite. The ortho-pyroxene/ortho-amphibole in samples 483297 and 483298 might possibly be. The retrograde mineral epidote was observed, especially in sample 552670.

552653, 550895, 550686 and 550886 yield abundant garnets that mainly are derived from intermediate to mafic composition rocks that were metamorphosed at intermediate temperature conditions. Sample 550686 additionally has garnets that were derived from a more felsic rock. The latter three samples yield more garnet, dark mica and white mica than the previous four samples. Some sillimanite-kyanite was observed in sample 550686. Investigations of the heavy mineral suite's clino-pyroxene/clino-amphibole minerals seem to indicate a strong presence of hornblende (mainly hastingite, some of more kærsutite and edenite compositions) and some augite-diopside.

550903 derived from a stream dewatering the large body of diorite and tonalite. Ortho-pyroxene/ortho-amphibolite is the most common heavy mineral in this sample, clino-pyroxene/clino-amphibole occurs abundantly as well. The ortho-pyroxene/ortho-amphibolite is probably pigeonite.

552708 and 552530 yield abundant garnet, biotite and some sillimanite/kyanite in their heavy mineral suite. Ortho-pyroxene/ortho-amphibole is more abundant than clino-pyroxene/clino-amphibole. Pigeonite might be present in sample 552708. The garnet distribution for these two samples shows clearly that the samples were derived from rocks with a felsic composition. Most of the garnets in sample 552730 were derived from a felsic rock metamorphosed at high temperature conditions, while sample 552708 also has a small component of garnet formed at intermediate metamorphic temperatures.

552564, 552620, 550662, and 552607 consists of a heavy mineral suite of mainly clino-pyroxene/clino-amphibole, and ortho-pyroxene/ortho-amphibole, biotite, epidote, sphene and garnet also have been observed. Hastigite hornblende, locally with a more edenite-hornblende composition seems to be the common most clino-pyroxene/clino-amphibole.

550645 and 550120 have a heavy mineral suite that is dominated by clino-pyroxene/clino-amphibole; the samples show epidote and biotite, and some sphene, garnet, muscovite, ortho-pyroxene/ortho-amphibole, epidote and biotite. The clino-pyroxene/clino-amphibole minerals in these two samples mainly seem to be hastingite hornblende with a little augite in the samples. In sample 5504645, the hornblende composition ranges so broadly that some of the minerals are of tremolite composition. Locally augite was observed.

550052, 550148 and 550512 yielded a heavy mineral suite that consists of roughly similar portions of clino-pyroxene/clino-amphibole and ortho-pyroxene/ortho-amphibole, a large fraction of Ti-magnetite, some biotite, ilmenite, and some minor amounts of garnet, muscovite and epidote. Clino-pyroxene/clino-amphibole and ortho-pyroxene/ortho-amphibole probably have a pigeonite and augite composition and the samples yield abundant iron-oxide, probably magnetite. Sample 550512 shows less ortho-pyroxene, magnetite, and Ti-magnetite, and more hornblende and biotite.

550272 resembles 550120 with mainly clino-pyroxene/clino-amphibole and common ortho-pyroxene/ortho-amphibole, biotite, epidote and garnet. The clino-pyroxene/clino-amphibole seems to consist of mainly hastingite-edenite hornblende, and some augite. The garnets in this sample were derived from a felsic rock type that has been metamorphosed under high-temperature conditions, while some garnets are derived from a calc-silicate rock.

Provenance characteristics of the Eastern Greenlandic basement between 68° and 62° N.

The orthogneiss in the area between 68° and 62° N can be divided into five different zones (Figure 1). Within these zones six analysed stream sediment samples can be group as special inclusions, covering two intrusive complexes and two areas rich in supracrustal rocks. The orthogneisses comprise, from North till South:

Orthogneiss A: The heavy mineral assemblage of this orthogneiss was interpreted as ortho-pyroxene, clino-pyroxene, Ti-magnetite and magnetite-bearing. This mineral assemblage suggests that peak metamorphic temperatures were up to granulite facies conditions. Other characteristic minerals for this orthogneiss, e.g. for provenance purposes, are biotite, ilmenite and hornblende. Epidote was observed locally, which is resulting from retrograde reactions in the orthogneiss.

The high metamorphic conditions are confirmed by the presence of felsic Al-rich rocks in the northern part of the study area (marked with 1 in Figure 1). Here, garnets are the major part of the heavy mineral suite and those indicate a felsic rock composition, and metamorphic peak conditions at high-temperatures. Augite, biotite, ilmenite, Ti-magnetite and minor sillimanite-kyanite are further defining the heavy mineral suite.

Orthogneiss B: The heavy mineral suite of the orthogneiss B has been interpreted as amphibolite facies, with hornblende, clino-pyroxene, biotite and garnet. Muscovite, sphene and Ti-magnetite form minor but distinctive contributions. The exact boundary between orthogneiss A and B is unknown, in Figure 1, we followed the boundary indicated by Myers et al. (1988) and Escher (1990). Some of the clino-pyroxene in this sample is richer in Na than usual augite is (ca. 4 wt%), which indicates a composition between omphacite and augite. Omphacite is indicative for high-pressure during metamorphism. Slightly higher pressures than usual for Archaean grey gneisses might have occurred in the area. Nutman & Friend (1989) describe "eclogitic" cores in dykes (their quotation marks) with sodic clinopyroxene. They interpret these "eclogitic" cores as indicative for an early high pressure deformation phase.

Garnets in orthogneiss B, probably derived from incorporated bodies of supracrustal rock, indicate that they were derived from a mafic to intermediate composition rock that was metamorphosed at intermediate temperatures.

In this area, a large post-tectonic, Palaeoproterozoic intrusive body of diorite and tonalite has been sampled, which is a major source for the ortho-pyroxene.

Orthogneiss C has also been interpreted as an amphibolite facies orthogneiss. However, its mineral assemblage is slightly different from orthogneiss B. Here hornblende and biotite, ortho-amphibole/ortho-pyroxene, epidote, biotite, Ti-magnetite and sphene are the major contributors to the heavy mineral suite. The hornblende in these samples is rather rich in aluminium and mainly of a hastingite composition. The amount of Al in hornblende increases with increasing pressure (Ernst & Liu 1998). Thus here as well as in orthogneiss B, slightly higher pressures during metamorphism might have occurred.

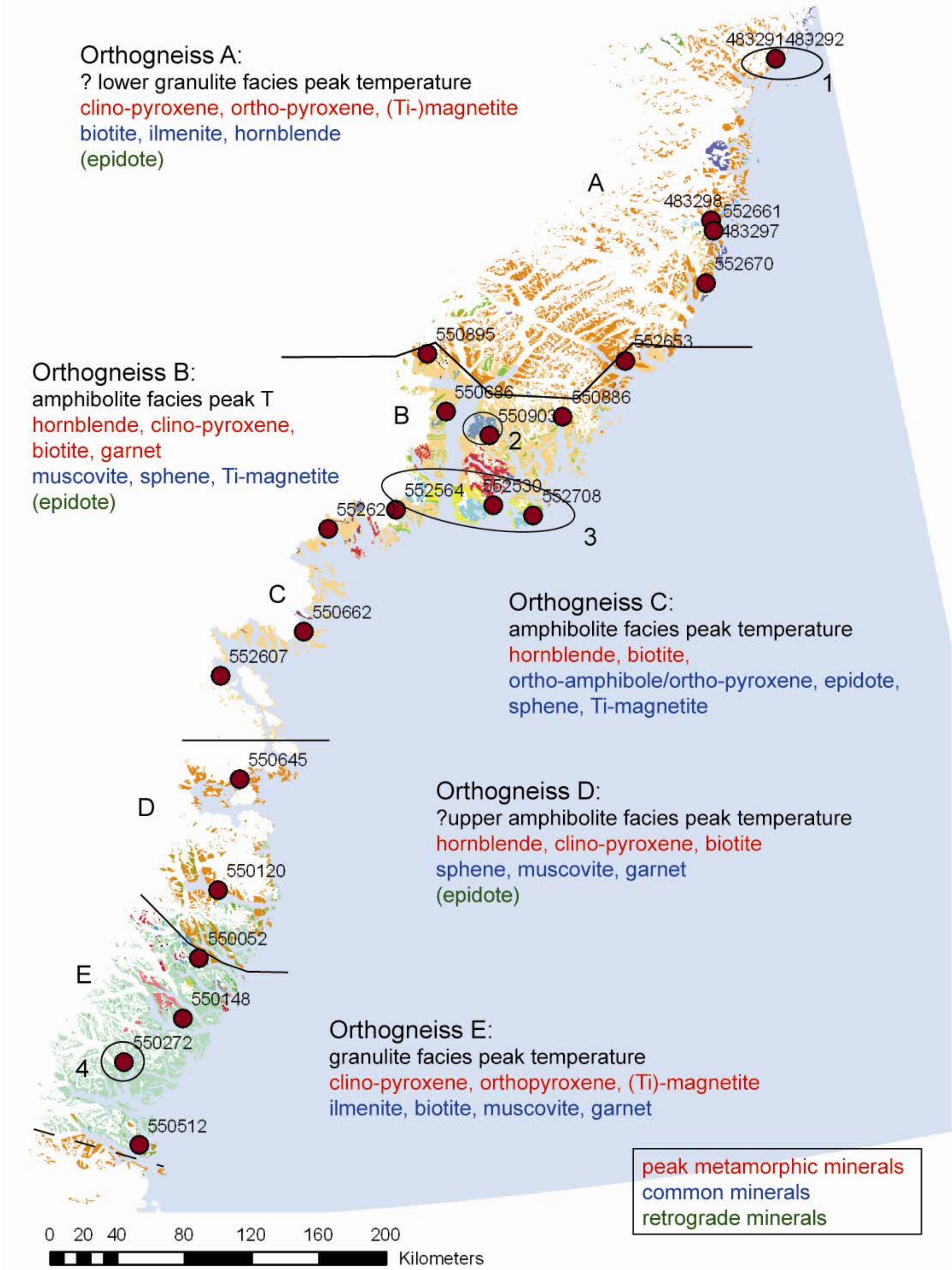

Figure 1 *Overview map for the results of the CCSEM samples collected between 68° and 62°N. Five different zones with orthogneiss and four special areas have been defined by their mineralogy. Map modified by T.F.D. Nielsen (2010) after the three original 1:500 000 scale maps produced by the Geological Survey of Greenland (now Geological Survey of Denmark and Greenland, GEUS): Skjoldungen (Escher 1990), Kangerdlugssuaq (Myers, Dawes & Nielsen 1988) and Sydgrønland (2nd edition, Garde 2007).*

Between orthogneiss B and orthogneiss C the Ammassalik Complex intrusive rocks and high-grade anatexites is observed. These anatexites are garnet-bearing graphitic semi-pelitic and psammitic metasediments that were metamorphosed at high temperatures. Apart from garnet, sillimanite-kyanite, ortho-pyroxene, biotite, and muscovite were found in these rocks, resulting from contact metamorphism. So even though the surrounding orthogneisses might not have reached metamorphic conditions higher than amphibolite facies, higher temperatures seemed to have occurred related to the large intrusions in the Ammassalik area. Friend & Nutman (1989) describe that the presence of these sediments might be related to an unconformity, but mention that these play a major role in thrusting and folding of the area.

Chadwick et al. (1989) describe that the area covered by orthogneiss B and C and their intrusive rocks form the Proterozoic mobile belt of Ammassalisk. They indicate that the boundary between orthogneiss B and orthogneiss C indicates the transition between an area of reworking, retrogression (from granulite to amphibolite facies) of gneisses and of acid and basic intrusive rocks to the north and reworked amphibolite facies gneiss to the south. This reworking however, is not obvious from the obtained heavy mineral suites.

Orthogneiss D has been indicated as retrogressed from granulite facies according to Escher (1990). Chadwick et al (1989), however, describe the gneiss as amphibolite facies. The heavy mineral suite does not give much evidence for granulite facies relict minerals. Hornblende, clino-pyroxene and biotite define the peak metamorphic assemblage, which is typical for amphibolite facies conditions. Other minerals in the heavy mineral suite include epidote and small amounts of sphene, muscovite, and garnet.

Orthogneiss E has a high temperature mineral assemblage including of orthopyroxene, clinopyroxene, magnetite and Ti-magnetite, which indicate that temperatures might have been up to granulite facies conditions. Other common minerals are ilmenite, biotite, muscovite and garnet. The assemblage is distinctive by its high amount of ortho-pyroxene. Escher (1990) indicated granulite facies for the northern half of the area covered by orthogneiss E and amphibolite facies for the southern half. A temperature gradient in the gneisses might exist from north to south, visible in the decreasing amount of orthopyroxene, magnetite and Ti-magnetite. Kolb et al. (2013) on the other hand, interpretate the whole area as granulite facies rocks and the orthogneiss as charnockitic.

Sample 550272 yields a more intense retrogression from granulite facies to amphibolite facies than in the other three samples from the orthogneiss E. Its mineral assemblage resembles orthogneiss D. No difference between this area and the surrounding orthogneiss has been indicated on the map (Escher 1990).

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Zircon geochronology from the Skjoldungen region

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Introduction and database strategy

We present zircon U/Pb geochronological data from the Archaean Skjoldungen region, South East Greenland. The samples include a regional coverage of the agmatitic gneisses and granites, meso- to leucocratic alkaline intrusions of the Skjoldungen Alkaline Province (SAP) as well as leucosome veins in gneisses and late granitic pegmatites. The database includes age data from 90 samples. For the setup of a SE Greenland geochronological database, the ages have been classified into five tentative categories: (1) Skjoldungen intrusive ages, (2) protolith intrusive ages, (3) inherited ages, (4) metamorphic ages, and (5) uncertain. In relation to the regional geological interpretation of the area, "(1)" can be ascribed to the Skjoldungen Orogeny (2750-2700 Ma), whereas "(2)" belongs to the older intrusive events (up to ca 3.2 Ga), including the Timmiarmiut Orogeny (ca 2800 Ma), as defined by Kolb et al. (2013).

The basement rocks in the Skjoldungen region can largely be described as gneisses with an agmatitic texture, these are however variously deformed and some are better described as granitoids rich in xenoliths, or as mafic units broken up by leucocratic melts. These rock types occur throughout the area but are dominating south of Lange Næs (Figure 1). North of Lange Næs gneisses or migmatites are more common. The classification of zircon ages obtained from these igneous and metamorphic rocks are not always straight forward. For instance, as have been shown in Kolb et al. (2013), xenoliths within granitoids or agmatitic gneisses may contain a zircon population with the same age as obtained from the granitic or gneissic matrix. Similarly, in some migmatitic gneisses the main zircon population in both the leucosome and the ambient gneisses are similar. At this stage we have decided to classify the zircon ages from such lithologies to reflect the latest intrusive stage, thus reflecting the granite intrusion age or the age of infiltration of leucocratic melts. Such a classification is likely justified in most instances, however, in some cases the leucosome is demonstrably locally derived by in situ partial melting, and such ages should sensu stricto be classified as metamorphic age. Also we have decided to classify the main ages from gneisses with agmatitic texture as "intrusive", although it might be argued that "protoliths intrusion age" would be a more correct term at least for the most deformed varieties.

Finally there are a number of samples that are basically too young to be understood within the tectono-metamorphic frame work of the area as presented by Kolb et al. (2013). This concerns samples with ages ranging from ca 1800 up to 2600 Ma, and particularly the few rocks with age components from 1800 to 2000 Ma. The primary reduction of data seems reliable, and the most likely explanation is that these younger ages reflect Pb-loss by resetting of individual zircon grains, or discrete domains within grains. This however requires that geological events, like e.g. heating, fluid infiltration or uplift have caused the zircon domains to act as open systems.

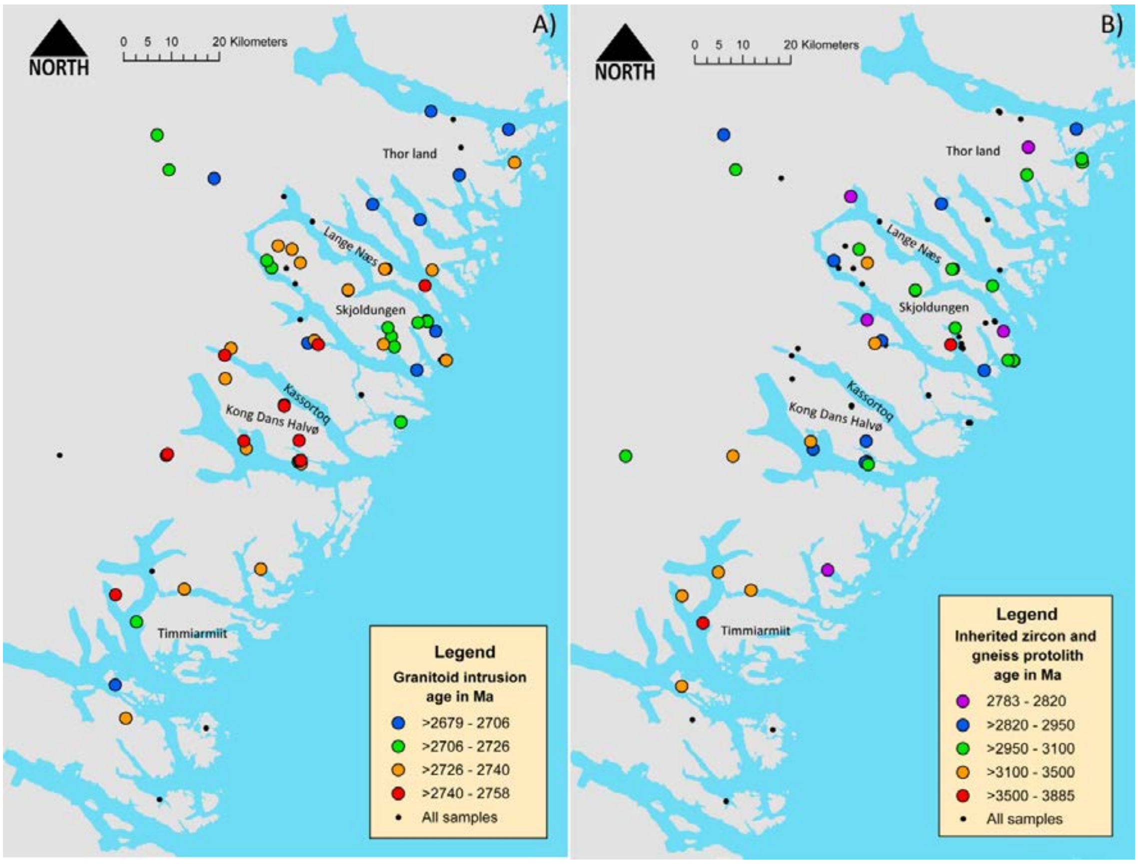
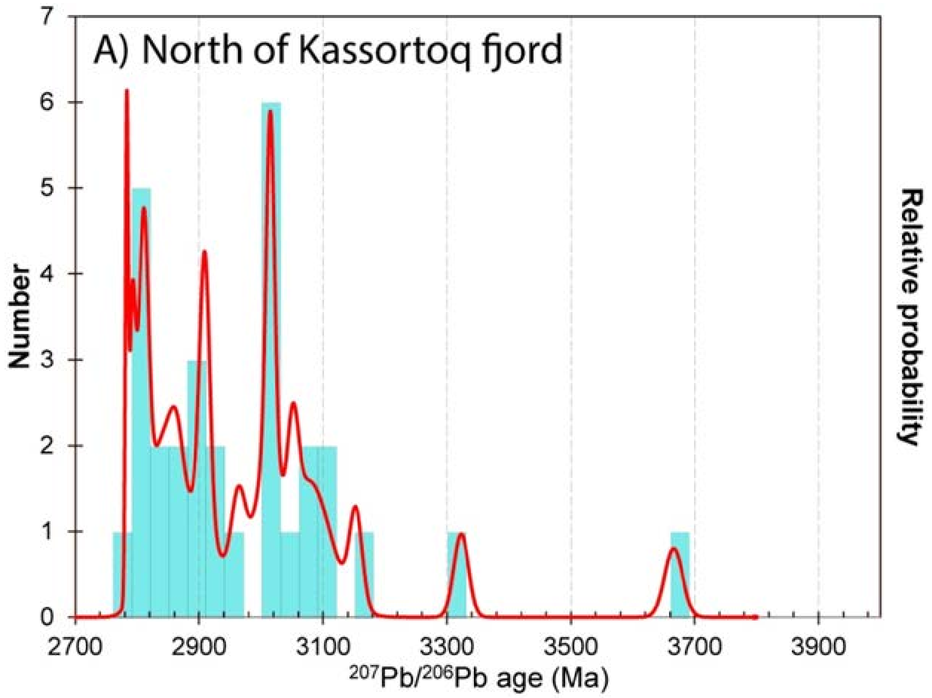


Figure 1 *Map of the Skjoldungen region of southeaster Greenland. A) Granitoid intrusion ages. B) Inherited zircon ages and gneiss protoliths ages.*

Results

Figure 1 shows the distribution of granitoid intrusion ages in the SAP region. As discussed above, these ages include data from the SAP granitoids, leucocratic granites, granitic sheets within mafic belts, deformed granitoids (agmatitic gneiss) and leucosome in migmatites, but exclude pegmatites. The intrusive ages show a continuous range from 2679 ± 4 Ma to 2758 ± 7 Ma with two main age clusters around 2715 and 2735 Ma. These intrusive ages are thus similar in age to the whole rock Sm-Nd age obtained from intrusive rocks of the SAP (2721 ± 24 Ma) (Blichert-Toft et al., 1995). The geographical distribution shows systematic variations (Fig. 1), overall intrusion ages are older towards the south and younger towards the north. In more detail, the area north of Lange Næs mainly has ages below 2706 Ma (blue). On Skjoldungen Island, where the highest density of dated samples occurs, there is seemingly the opposite age distribution compared to the regional picture, as younger ages (green) occur to the south and older ages (orange) to the north. In the area around Kong Dans Halvø, the oldest granotoid intrusion ages occur (red), ranging up to 2758 Ma. Further to the south, there seems to be a younging of the intrusive ages south of Timmiarmiit Island, although only few data have been obtained from this region.



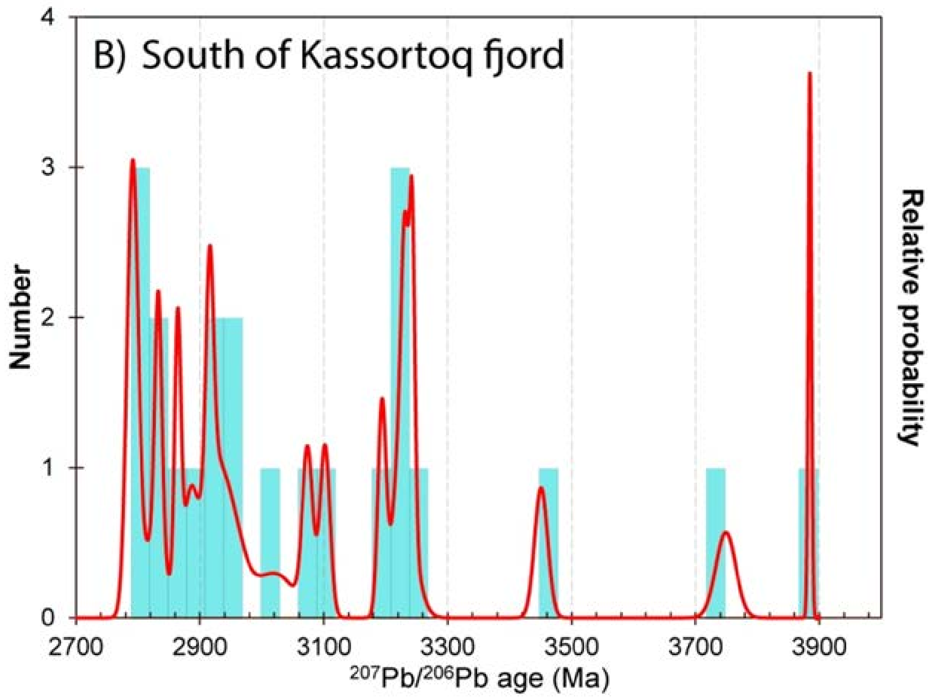


Figure 2. I*nherited zircon and gneiss protoliths ages shown in histograms and as relative prob-ability plots. A) and B) contain data from rocks north and south of the Kassortoq fjord, re-spectively.*

Inherited zircon ages from orthogneisses, migmatites and granitoid rocks are presented together with a limited amount of gneiss protoliths ages (N = 8) (Fig. 1B and 2). These data are more difficult to present geographically as many samples contain more than one inher-ited zircon population. However highlighting the oldest inherited ages in each sample (Fig. 1B), we suggest to divide the region into two areas, (1) a northern area showing a rather mixed age pattern and with a maximum age of about 3100 Ma, and (2) a southern area with a high proportion of inherited zircon ages from >3100 up to 3885 Ma. The transition zone occurs approximately around Kassortoq fjord. This strict division into two areas are in part only apparent as many samples contain a range of inherited ages, as can be seen when plotting the age data from the northern and southern terrane in histograms (Fig. 2). The age histogram plots show that both the northern and southern areas are characterised by a main age-cluster from 2800 to 2940 Ma. However a distinction between the two areas is still evident as the northern area is characterised by an age cluster at ca. 3000 to 3100 Ma and the southern area by an age-cluster at ca. 3200 to 3260 Ma.

Summary

The compilation of data and interpretation of ages as discussed above reflects work in progress and are still preliminary observations as the age database is still growing. However the intrusive ages clearly demonstrate that the region from north to south either represented by granitoids intrusions, agmatitic gneisses, granitic melts infiltrated in the basement rocks and leucosome in migmatites, all have ages in the range from ca 2760 to 2700 Ma. Moreover the intrusive ages show a northwards younging, with the oldest ages around Kong Dans Halvø and the youngest ages north of Lange Næs.

From the inherited zircon data, it is apparent that the younger granitoid units intrude into or were sourced from a much older basement, and that this basement might be subdivided into a southern and a northern part. The southern part has a large population of inherited zircons with ages from 3200-3260 Ma, and this has so far not observed in the northern part. The northern area, on the other hand, contain a large population of inherited grains with ages from 3000-3100 Ma that are rarer in rocks from the southern area. For both areas the main population of inherited grains, however, have ages in the range from ca 2800 to 2940 Ma. This seems to suggest that the granitoids of the southern and northern areas have sampled a basement with a distinct early geological history prior to ca 2940 Ma. Younger Archaean geological events (<2940 Ma), as documented by inherited zircon ages, are however found throughout the entire region.

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Results in South-East Greenland from Ujarassiorit-program.

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Ujarassiorit, the public mineral hunt competition program in Greenland has run for 25 years and more than 20.000 rock-samples have been submitted for the competition. Majority of the submitted Ujarassiorit-samples have been collected in the vicinity of towns and settlements where the seagoing traffic is greatest. Thus, the majority of mineral hunt program samples from South-East Greenland are mainly from the Tasiilaq-region and are concentrated mostly along the coastlines from Ikertivaq (65°25'N) in south to K. J. V. Steenstrup Søndre Bræ (66°26'N) in north.

Submitted Ujarassiorit samples are inspected and described by geologists. Gemstones and mineralized samples advance in the competition. Since 1989 more than 450 of Ujarassiorit samples from Tasiilaq-region have been assayed geochemically to determine contents of economically interesting precious and base metals.

Different rock types with different anomalous element contents have been awarded. Samples with elevated contents of gold, silver, copper, nickel, palladium and platinum have been selected as winners in the Ujarassiorit mineral hunt competition. Samples described below have been awarded in the recent years.

- First prize winner sample in 2009 is an coarse grained amphibolitic rock with centimetre sized pink corundum crystals, found in Nagtivit, a peninsula, 40 km west of Tasiilaq. A follow-up fieldwork in 2010 in the area has failed to relocalize the corundum occurrence.

- In 2011 the first prize winner sample is an graphite-garnet-gneiss with 11,1 ppm Au, found in Aappaluttoq on western coastline of Sermilik-fiord, 26 km north-west of Tiniteqilaaq.

- In 2013 the 3rd prize winner sample has been collected near Kuugaarmiit, 5 km east to Tiniteqilaaq. The sample is a molybdenite rich altered granitic rock and is found within contact-zone between a palaeoproterozoic granitic intrusion and surrounding gneisses.

- The 4th prize winning sample in 2013 Ujarassiorit campaign has been collected in Sermiligaaq. The sample is a sulphide-rich quartz-vein sample with 4 ppm Au, 0,37% Cu, 320 ppm Ag and 0,69% Pb.

Follow-up fieldworks in Tasiilaq-region have been carried out serveral times by GEUS and geologists from Government of Greenland in order to gain more information about the selected Ujarassiorit sample locations. In the most recent follow-up fieldwork in 2010, about 10 localities have been visited.

It is recommended the localities mentioned above are visited in 2014 follow-up work.

Reactivation of Proterozoic structures along the South-East Greenland margin (Skjoldungen)

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The Archaean basement of Skjoldungen in South-East Greenland is cross-cut by brittle structures consisting of dike swarms of Proterozoic age and faults. Pseudotachylites sampled along brittle faults, related to injection veins with irregular orientation, show coherent Paleoproterozoic age (1900-2000 Ma) with large errors due to the old age and to the presence of excess Ar that differs from the age of the country rock by 600 Ma.

In this area pronounced ENE-WSW and NE-SW trends are visible from the aerial photographs and digital elevation models. The more than 50 km-long morphological lineaments parallel Proterozoic dike systems. Structural mapping along these structures revealed the presence of strike-slip deformation overprinting and reactivating the former dike trends. Paleostress analysis of fault-slip data, combined with the pseudotachylites analysis and cross-cutting relationships with dikes allowed to separate five distinct tectonic events where three of them are characterized by extension and dike intrusions and two by strike-slip brittle faulting. The youngest strike-slip event is interpreted as Paleocene and related to the Northeast Atlantic rifting. The estimated left-lateral offset along the major structure is about 15 km and its offshore prolongation cut through the Tertiary basalts encountered by the ODP Leg 152 along the SE Greenland shelf.

The multiple brittle deformations in the craton together with the cross-cutting relationships between faults and dikes show the potential of reactivation of pre-existing structures in particular during rifting processes addressing the problem to combine structural data of different age into a single data set.

Relocated local earthquakes in Southeast Greenland align on old geological structures

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In the Ammasalik region in Southeast Greenland 62 local earthquakes have been analyzed and re-located. Some of the events had formerly been located from distant stations by using a universal earth model. The result of this localization was a scattered distribution of the events in the region. The locations have now been improved by using a local earth model along with phase readings from two local stations not previously included; ANG in Tasiilaq and ISOG in Isortoq. From relocating the events two zones with a higher degree of seismicity than in the rest of the region are observed. The first zone is located by felsic intrusions. The second zone is at the boundary between the Archaean Craton and the Ammasalik region where reworked Archaean gneisses are dominating the geology.

During the analysis it was observed that the additional information from the local stations are of great importance for the result. When the earthquakes were located by using the local earth model, but without these additional information, the result did not differ significantly from the one obtained by the universal earth model. The data was analyzed using SEISAN software (Ottemöller and Havskov, 1999). P-, S- and azimuth phases were read in the waveform data along with readings of the amplitudes for magnitude determination. The events were first located with the hypocenter locating program HYP and thereafter verified by a grid search.

Aeromag 2013 (and Aeromag 2012)

Peter Riisager

Geological Survey of Denmark and Greenland (GEUS)

The new Aeromag 2012 and Aeromag 2013 aeromagnetic surveys cover the remote and relatively under-explored coastal regions in South-East Greenland. In combination the two surveys stretches from 61°45'N and northward to 67°30'N (see Fig. 1).

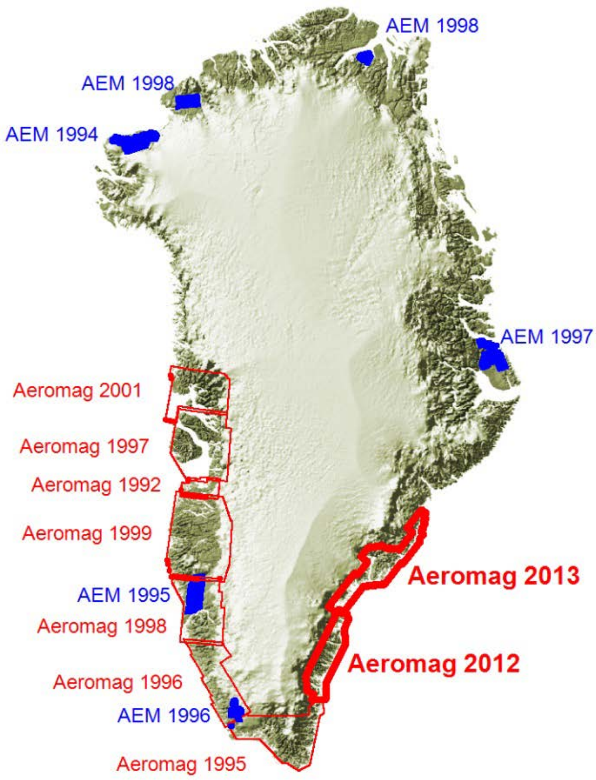

Figure 1 *Location of government-financed high-resolution airborne geophysical surveys in the period 1992-2014. Aeromagnetic surveys (Aeromag) are outlined in red and combined electro-magnetic and magnetic surveys (AEM) are outlined in blue. The new Aeromag 2012-2013 data are marked in bold.*

The Aeromag 2012 survey represents a total of 48 493 line-kilometers, while the Aeromag 2013 survey comprise a total of 65 492 line-kilometers. For both surveys, the flight-lines were aligned parallel to the coast line, and with a separation of 500 m, while orthogonal tie-lines were flown with a separation of 5000 m. Total magnetic field data were recorded with a sampling rate of 0.1 second which corresponds to a sample distance of 7 m along the survey lines. The surveys were carried out by flying along a gently draped surface of 300 m above the ground and sea level. Due to the severe topography the average height above ground is somewhat higher than 300 m. These dull and rather trivial sounding parameters are important to consider when interpreting the data, particularly line spacing and sensor heights. In the across-line direction only magnetic anomalies with wavelengths larger than twice the line-spacing (e.g. 1000 meter) can be resolved. Both surveys was financed by the Government of Greenland and flown by EON Geosciences Inc. Further details on the survey operation and equipment can be found in the reports of EON Geosciences (2013, 2014) available in the online DODEX database (Riisager et al., 2011).

With the completion of the Aeromag 2012 and Aeromag 2013 projects, a total of 633.500 line-kilometres of high-resolution aeromagnetic data and approximately 75 000 line-kilometres of multi-parameter data (electromagnetic, magnetic, and partly radiometric data) have now been gathered. Further details on previous surveys and the Greenland database of available aeromagnetic data is summarized in Rasmussen et al. (2013) (see also Fig. 1).

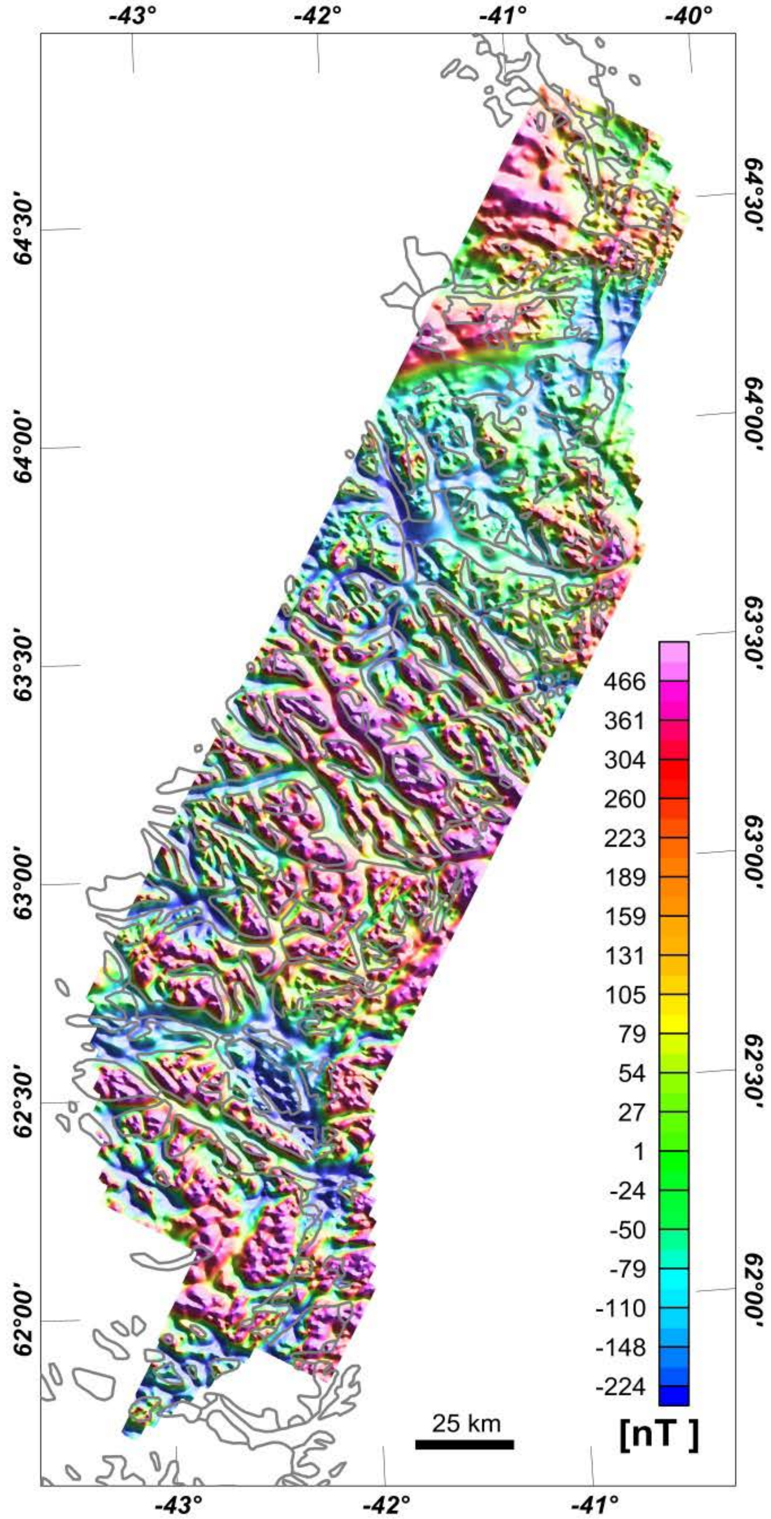

Figure 2 *Magnetic anomaly with shaded relief for the Aeromag 2012 survey. The magnetic anomalies range in amplitudes between -451 and +1773 nT. The topography has a strong effect on the magnetic anomaly map (coast line is the grey line).*

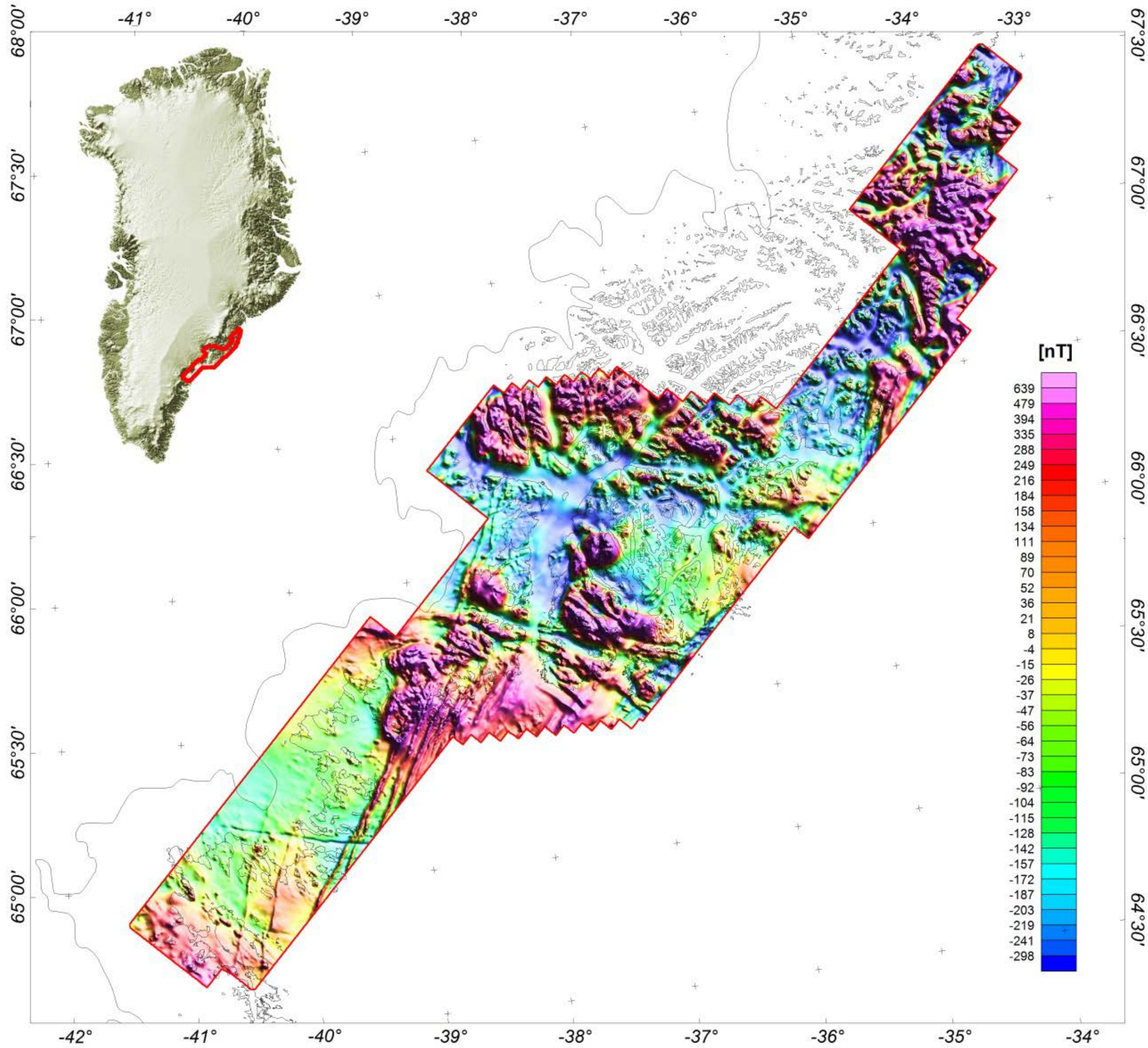

Figure 3 *Magnetic anomaly map for the Aeromag 2013 survey. The magnetic anomalies range in amplitudes between -1318 and +3270 nT, where both the highest negative and positive values relate to mapped intrusions.*

The new Aeromag 2012-2013 aeromagnetic data (Figs. 2-3) are in reasonably good accordance with the geological maps of the region. In the presentation we will focus on, and discuss a few magnetic anomalies of regional extent.

The two surveys have been merged (grid-knitting) and data have been processed to aid the interpretation. All the data will be included in an ArcGIS project that will be made available for the entire SEGMENT workgroup. The data can also be obtained in other formats if needed. The presentation will present some of the processed maps and discuss their potential use.

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A W-Mo quartz vein and W-rich amphibolite horizons from the Thrudvang peninsula, Skjoldungen, SE Greenland

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[2]Department of Geoscience, Aarhus University, Denmark.

Background and Geological Setting

Background and Geological Setting
During the SEGMENT expedition of 2012, a quartz-wolframite-molybdenite vein with phyllic alteration was identified in the north-western side of the Thrudvang peninsula, by Kangerdlikajik, in the Skjoldungen region of SE Greenland (sample 446946, see Figure 1). The approximately 30 cm-wide and subvertical vein is hosted by a package of mafic granulite. However, the deformed nature of the vein and steep terrain did not allow the establishment of its extension or probable general trend.

Two rusty amphibolite horizons of the mafic granulite package hosting the vein are anomalous in W, but not in Mo (samples 446934 and 446948, Table 1). Ultraviolet light studies documented that this W is present as pale blue luminescing scheelite grains, rather than as wolframite, as in the vein. As such, these samples are reminiscent of scheelite-rich strata-bound horizons documented in the supracrustal sequences of the Nuuk fjord area, in West Greenland, interpreted by Appel & Garde (1987) to have an exhalative origin.

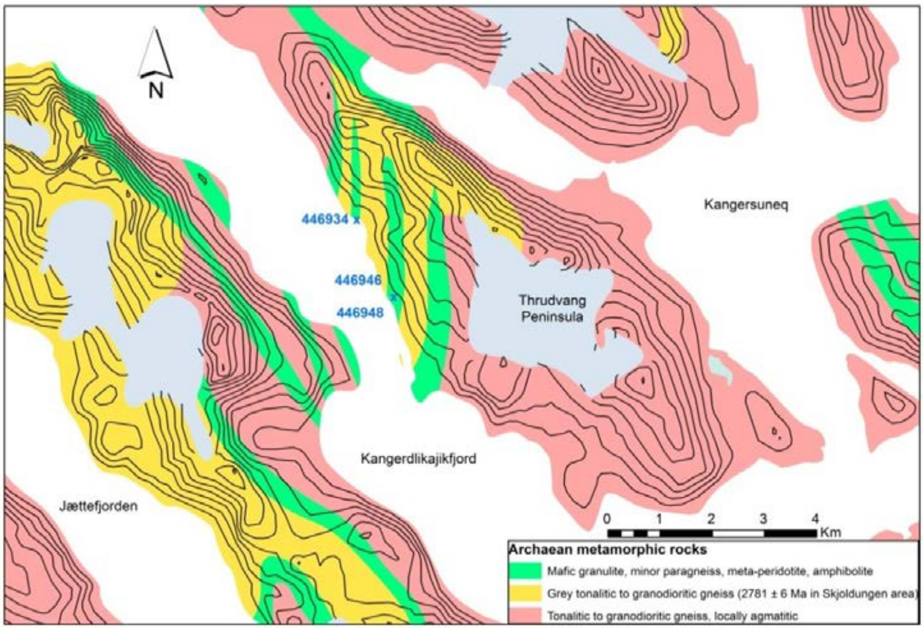

Figure 1 *Geological map of the Thrudvang Peninsula and surroundings (after Kolb et al, 2012), with location of mineralised samples (in blue). Contour line spacing is of 100 m.*

Table 1 *Whole rock geochemistry of mineralised samples, analysed at Actlabs (Canada), trough fusion ICP-OES (majors) and fusion ICP-MS (Mo and W)*

Sample No	Description	SiO2 %	Al2O3 %	Fe2O3 %	MnO %	MgO %	CaO %	Na2O %	K2O %	TiO2 %	P2O5 %	LOI %	Total %	Mo ppm	W %
446934	rusty zone in amphibolite	49.75	14.61	11.18	0.14	7.39	10.50	3.14	0.65	0.84	0.02	0.89	99.12	3	0.37
446946	W-Mo quartz vein	94.95	1.57	1.10	0.01	0.11	0.36	0.44	0.11	0.05	0.02	0.49	99.2	2630	1.60
446948	rusty zone in amphibolite	49.03	13.99	13.05	0.16	4.77	12.15	2.81	0.30	0.74	0.23	2.18	99.4	5	0.55

Geochronology

A molybdenite concentrate from the identified vein was dated (Table 2), which provided a Neoarchean age of 2749±11 Ma. This age is similar to the ~2740 Ma porphyritic granitic rocks and the 2753±5 Ma Skirner Bjerge syenite of the SAP, interpreted to have been emplaced during the first DS1 stage of regional transpression of the Skjoldungen Orogeny (Kolb et al, 2013).

This vein documents a previously unknown tungsten-molybdenum mineralising event in Greenland, in addition to the previously known molybdenite occurrences of East Greenland, related to Paleogene intrusions. Furthermore, this date fits into the earliest of five Mo mineralising pulses, which correspond to supercontinent assembly events, according to Golden et al (2013). In the case of the Neoarchean Mo mineralising pulse, it can be linked to the assembly of Kenorland, also known as Superia (Golden et al, 2013).

Table 2 *Results of the Re/Os dating of molybdenite, carried out at ALS Minerals (Canada), using isotope dilution mass spectrometry using Carius-tube, solvent extraction, anion chromatography and negative thermal ionization mass spectrometry techniques.*

Sample No	Re ppm	± 2σ	^{187}Re ppm	± 2σ	^{187}Os ppb	± 2σ	Model Age (Ma)	± 2σ (Ma)
446946	54.02	0.14	33.95	0.09	1591	1	2749	11

Mineral Potential

The analysed molybdenite, as is typical of Archean molybdenite, has a relatively low Re concentration (Table 2), which likely reflects the limited mobility of this element in the reducing subsurface environment prevailing prior to oxidation of the atmosphere (Golden et al, 2013). Notwithstanding the reported secular variation of Re concentrations in molybdenite, these can be used to establish mineralisation type and economic potential, according to Stein (2006). However, the analysed sample has a Re concentration which is intermediate between that of likely sub-economic molybdenite occurrences formed by local dehydration melting of biotite gneiss (<20 ppm, even sub-ppm Re), and that of molybdenite of possible economic interest with a porphyry-style intrusion-related origin (100s-1000s ppm Re). Therefore, discrimination between the two mineralisation types remains unclear and an assessment of the economic potential of this showing cannot be achieved, using this criterion. As such, the possibility that the studied vein can be linked to an intrusion and could be part of a wider system with economic potential remains possible.

Finally, it is considered that the mineralisation in the rusty amphibolite horizons is contemporaneous with the dated vein, rather than of exhalative or syn-genetic nature. In this case, the scheelite of the amphibolite horizons precipitated in the previously carbonatized mafic to ultramafic horizons in the host package, due to their enhanced reactivity to vein-derived mineralising fluids. This type of reaction can yield skarn-like showings, but which are probably not of economic interest, in contrast to the vein mineralisation, which could be of economic interest.

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Palaeoproterozoic graphite mineralization in rocks of the Nagssugtoqidian Orogen, South-East Greenland

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The study area is located in the Tasiilaq area, South-East Greenland in the Palaeoproterozoic Nagssugtoqidian Orogen. The orogen extends over 250 km along the east coast of Greenland. The orogen consists of Archean rocks from the Rae Craton to the north and the North Atlantic Craton to the south, and Palaeoproterozic rocks, which are further subdivided into different terranes and intrusive complexes: the Schweizerland terrane, the Kuummiut terrane, the Ammassalik intrusive complex (AIC) and the Isortoq terrane. These different terranes have a complex structural history of metamorphism and deformation due to collision of the two cratons. The Rae craton subducted beneath the North Atlantic Craton. The Schweizerland terrane consists mainly of orthogneiss, meta-anorthosite/ -leucogabbro and amphibolite. The Kuummiut terrane is composed of diorite, tonalite, marble, meta-sedimentary rocks, orthogneiss and amphibolite. The AIC contains contact metamorphic anatectic gneiss, norite, gabbro, diorite and granodiorite. The Isertoq terrane is mainly made of orthogneiss, amphibolite, ultramafic and meta-sedimentary rocks. Graphite mineralization in the Tasiilaq area is mainly found in the Paleoproterozoic rocks of the Kuummiut terrane and the contact halo of the AIC.

Graphite in general occurs in rocks of all metamorphic grades and sometimes in silicate melts. Graphite forms flakes, lumpy crystalline and amorphous aggregates. Flake graphite is the most valued with platelet diameters from >1 to 0.018 mm. Fine-grained amorphous graphite is less valuable. A minimum of 3-5% graphite in the ore is needed to extract flake graphite, while amorphous graphite ore requires grades >45%. After refinement, graphite concentrate grades of >85% or even >90% are most preferred. Graphite is resistant to supergene alteration, which means that preserved flakes can be found in decomposed rock and even in autochthonous soil. This makes it more economically attractive to mine weathered deposits compared to high cost separation of flakes from fresh and hard rock.
. Most graphite carbon has a biogenic source or is derived from marine carbonate rocks during metamorphism, which can be investigated by stable isotope analysis. Even graphite carbon in igneous rocks seemingly has an organic source, derived from assimilation of sedimentary country rocks.

Graphite deposits mainly occur in rocks modified by orogenic or contact metamorphism. They are mainly classified as orogenic metamorphic, contact metamorphic or epigenetic deposits. In orogenic metamorphic graphite deposits, the grade of metamorphism affects the type of graphite formed. Well-ordered graphite can form at greenschist facies conditions at around 300-500°C and 2-6 kbar, while very large graphite flakes are restricted to amphibolite facies rocks. Coeval shear strain seems to boost graphite formation. Other controls on graphite formation include; type of organic precursors, the composition of the fluid phase, the available reaction time and the presence of minerals that may catalyze the reaction. Apart from major shearing, contact metamorphism graphite mineralization is controlled by the same parameters. Epigenetic graphite deposits often occur as cross-cutting veins or impregnations of shear zone material. They are formed by high PT migrating supercritical carbon-bearing fluids or fluids of fluid-rich magmas. The C is transported as CH_4 and CO_2. Precipitation can occur by fluid-rock interaction, fluid mixing and by redox-change. Graphite precipitated from these fluids is always well-ordered. The fluids are formed by metamorphism or magmatic degassing.

Five graphite deposits are known in the Tasiilaq area. The graphite occur in various types of rocks in the area; gneiss, schist, amphibolite and carbonate rocks. There appears, however, not to be a lithological control of graphite mineralization, since all rock types may lack mineralization in places. There is no petrographical difference between the same type of rock containing or not containing graphite mineralization. In most places, the graphite occurs as crystallized flakes (up to 5mm diameter), but is found in few places as amorphous aggregates. The graphite content of the rocks is mostly less than 5%, though there are a few examples of up to 15%. Biotite schist is found in particular, to contain flake graphite, while the carbonate rocks mainly contain amorphous graphite. The graphite in the area is mostly found in marker horizons, which formed by iron oxidation of garnet, biotite and locally sulfides.

The aim of this project is to map and characterize target areas of graphite mineralization. Detailed mapping at 1:500 to 1:5000 scale aided by geochemistry will outline potential areas of graphite mineralization. These studies will concentrate on mapping of shear zones in biotite schist as the most promising target areas. The main purpose of additional petrological, geochemical and isotope investigations are to understand the graphite mineral system. Where does the C come from? How did it get to the deposit site? What is the best quality graphite and where is it located? What are the conditions (P, T, Eh, etc.) of graphite formation? Petrography will additionally shed a light on the quality of the graphite. Graphite is listed on the European Union's list of critical raw materials, it is therefore important to carefully characterize the graphite deposits in the Tasiilaq area for a possible future supply.

Linking West and East coast Nagssugtoqidian

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[4]Deceased

The central part of the Nagssugtoqidian of West Greenland can be defined as lying between the suture now incorporated in the Nordre Strømfjord shear zone (NSsz) and the frontal thrust traceable from the coast south of Sisimiut till the Inland Ice east of the head of Søndre Strømfjord. Within this band juvenile supracrustals occur abundantly and form a mélange which probably is both sedimentary as well as tectonic. On the east coast the Sipalik supracrustals similarly are restricted in occurrence and likely to be a mélange as well. In the mélange of the Nagssugtoqidian of the west coast the sedimentary elements are: pelitic metasediments, marble and calc-silicate rocks and quartzites while the elements of igneous heritage comprise basic metavolcanics, a variety of ultramafics, anorthosites and layered gabbroic rocks. In addition the rocks we interpret as oceanic metasediments with no continental content (see previous contribution by Glassley et al.) which are comparable to modern day nontronitic clays (occurring on spreading ridges) with manganiferous additions. We suggest that the Nagssugtoqidian of the east coast relates to the Nagssugtoqidian of the west coast as the central Alps relate to the western Alps.

Characterisation of the South East Greenland basement – an ICPMS detrital zircon study

Kristine Thrane

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U-Pb ages of detrital zircons have been obtained from stream sediment and till samples. In total, 4 tillite samples and 19 stream sediment samples from streams that drain basement rocks in Southeast Greenland between 62-68°N were processed.

The results show that the age pattern changes from north to south commensurate with ages of the basement rocks, with an overall dominate age range from 2900-2700 Ma. Several samples also have significant amounts of 3200-3000 Ma ages, and a single sample, from the Timmiarmiut area, yield ages up to 3700 Ma. Other samples contain younger Archaean ages down to 2500 Ma. Most samples do not contain Proterozoic zircons, the exception is two samples collected in the Palaeoproterozoic Ammassalik Intrusive Complex area, which yield age patterns dominated by 1950-1900 Ma zircons, in good agreement with the intrusion age.

In addition to the U-Pb ages of detrital zircons, composition data of the heavy mineral suite and garnets was also obtained from the same samples. These results will be presented by Nynke Keulen (this volume)

Even though the age patterns of the different samples are relatively similar, there are still differences, which make it possible to divide the basement of Southeast Greenland into 3 different zones characterised by 3 different types of orthogneisses, which is disused in Thrane & Keulen (in press).

References

Keulen, N. 2014: Characterisation of the South East Greenland basement – a CCSEM heavy mineral investigation. This volume.

Thrane, K. & Keulen, N. 2014: Provenance of sediments in the Faroe-Shetland Basin: Characterisation of source components in Southeast Greenland (submitted to FIEC).

New U-Pb ages from the Tasiilaq region

Kristine Thrane

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In 2010 a reconnaissance expedition was carried out in the Tasiilaq region between 64º and 67°N, as part of the Mineral Resource Assessment Project for South-East Greenland. The main target was to obtain a regional coverage of stream sediment samples for geochemical and mineralogical analyses, but also geological reconnaissance was carried out, along with sampling for geochronology.

Sixteen representative samples of gneiss, granite, metasediments etc. from the Tasiilaq region was selected for zircons U-Pb geochronology and analysed by LA-ICP-MS at GEUS. The results will be presented at the workshop.

Lu-Hf ages from garnet bearing granulite facies rocks from the Helge Peninsula in the Skjoldungen Alkaline Province, South-east Greenland

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Archean rocks from Southeast Greenland are assigned to the North Atlantic Craton, because of their agreement in tectonometamorphic and magmatic evolution with Southwest Greenland and the Lewisian Complex of Northwest Scotland. Their so far investigated magmatic ages vary between 2865 – 2665 Ma. Whether and how the Archean block of SE Greenland could be subdivided into several terranes, as it has been suggested for the terranes of SW-Greenland, remains ambiguous. Compared to the southwestern Greenlandic terranes, the geological assembly of Southeast Greenland remain poorly understood.

In southeastern Greenland amphibolite to granulite facies events overprinted the primary mineral assemblage between 2800 – 2700 Ma ago. In this study, we give a petrographic description of amphibolite to granulite facies rocks from Helge Halvø (Helge Peninsula) in the ´Skjøldungen Alkaline Province` (SAP), Thrym Complex (East Greenland), and present 176Lu/176Hf garnet ages from different rock types in order to reconstruct the geological evolution of the region. The rocks from Helge Halvø can be assumed to be an association of TTGs (Tonalit-Trondhjemit-Granodiorites) and Greenstone Belts, intercalated with supracrustal units. All samples were taken from a mylonitised area with a metasedimentary and tonalitic origin. Leucosomes can be found in pressure shadows of comparably more competent units, as well as in the mylonite itself. Three of these leucosomes as well as a competent garnet sillimanite gneiss were investigated. The results were compared to other studies and field observations.

The mineral assemblages in the thin sections show no evidence for retrogression. Garnets of all samples lack growth zonations in their major element patterns. Trace element investigations using LA-ICP-MS indicate reequilibration of the Lu-Hf systematics. The extent of this reequilibration remains unknown, but the patterns of the trace and major elements imply that temperatures were high during or after garnet growth (approximately 600-800 °C). Within the analytical uncertainties, the 176Lu/176Hf ages of the different analysed samples are equal. Interestingly, they agree with U-Pb zircon ages obtained by previous studies from the same area. Thus, in combination with the metamorphic zircon ages, subdivision into two phases (ca. 2745 and 2715 Ma) is proposed. This subdivision is based on field observations and is supported by the results of prior studies that investigated growth zonation of zircons as well as geobarometry. According to that the rocks from Helge Halvø were overprinted at granulite facies conditions during the Skjøldungen Orogeny in a first stage at ca. 2745 Ma before they were affected by syn to posttectonic melt formation which could possibly be related to the origin of the Skjøldungen Alkaline Province.

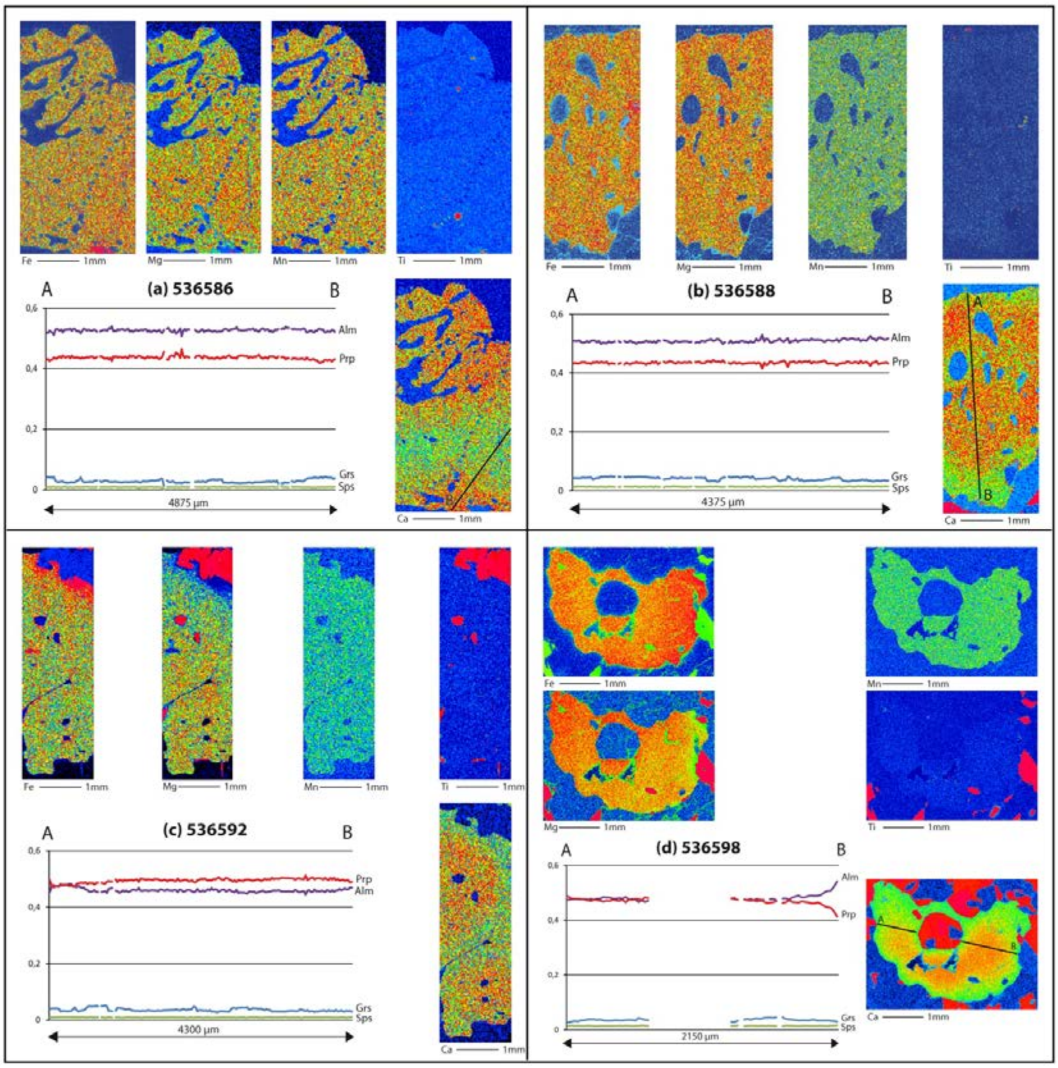

Figure 1 *Element maps from major elements and quantitative profiles over the cross sections of garnets from all samples, investigated by the microprobe.*

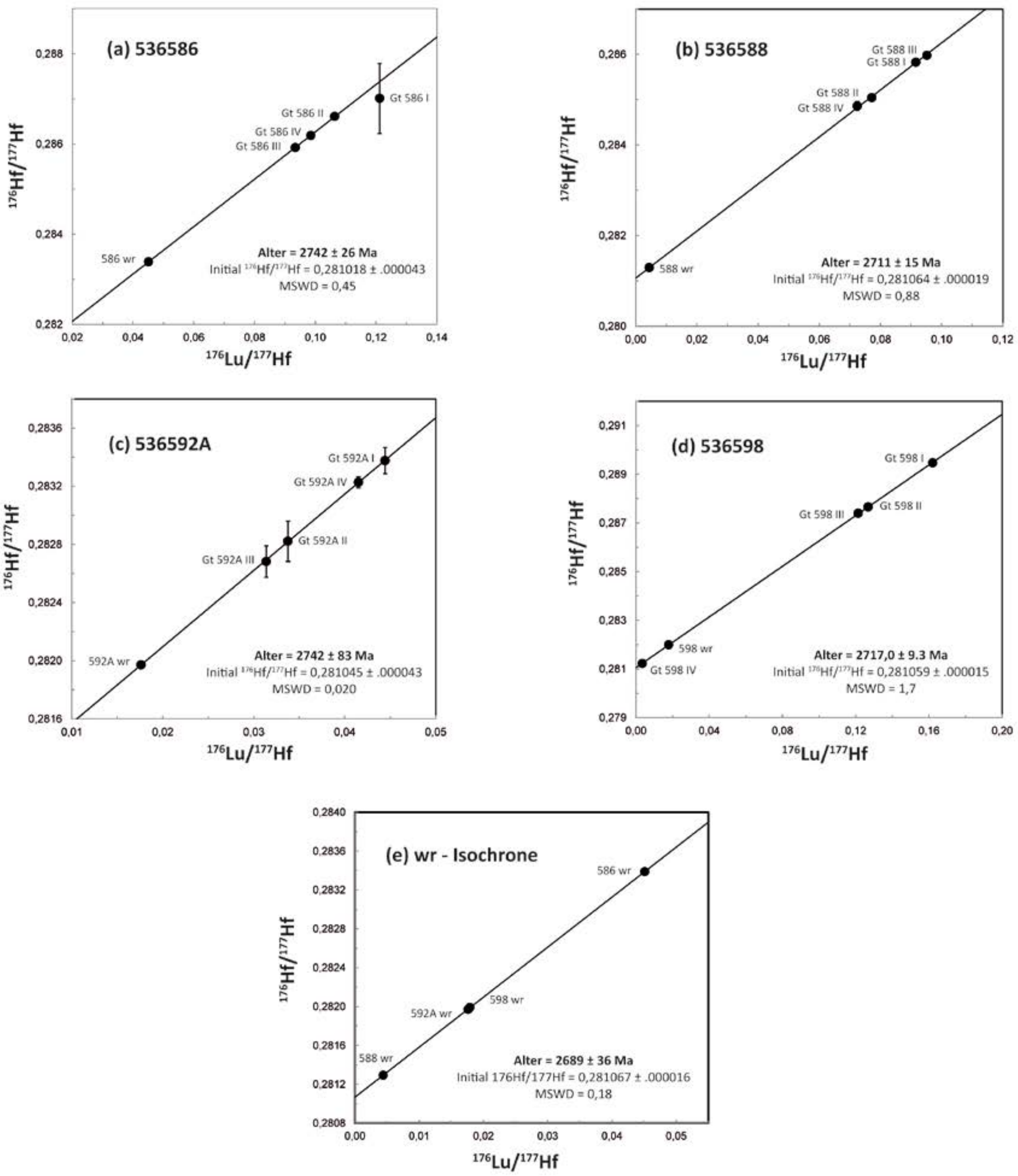

Figure 2 *Lu-Hf - Isochrons. Error bars partially smaller than the symbols.*

Skjoldungen and Tasiilaq from the air - before and after field-work

Erik Vest Sørensen

Geological Survey of Denmark and Greenland (GEUS)

Conducting fieldwork in remote places, such as the Skjoldungen and Tasiilaq areas in East Greenland, is dependent on careful planning. Traditionally, geologists prepare for fieldwork by studying relevant literature, previous field accounts, maps or images from the area of interest. In this contribution focus is on the use of stereo-imagery in both the planning pre-fieldwork phase as well as after returning from fieldwork. At the photogrammetry laboratory at the Geological Survey of Denmark and Greenland (GEUS) we have a long tradition in using photogrammetry as a tool in the geological workflow. This knowledge is here shared in order to optimize the time spent in the field and inform potential users what is possible with the method.

Prior to fieldwork

At present, black & white aerial photographs (1:150.000) are available for stereoscopic inspection at the laboratory. The images can for example be used to study or find suitable camp sites with respect to water supply and flat ground or identification of possible out-crops. Furthermore, existing GIS-data (geological map data) can be projected on to the stereoscopic models to inspect the geology in three-dimensions. In comparison to for example an ortho-image, which is also available, inspection in stereo give a much better spatial understanding of a given area. Given the scale of the aerial photographs, they are well suited to get a grasp of the overall geological and structural setting of a given area.

During fieldwork

The expedition will be equipped with a high resolution digital SLR that can be used to collect oblique stereo-images. This gives the user the possibility to document areas of interest at close-range and in three dimensions. In principle, whatever that can be seen in the images can be quantified in three dimensions (strata thickness, structural orientation, 3d mapping) providing that a set of basic rules is followed during data acquisition. The stereo-imagery is typically acquired from a helicopter, but could easily well be deployed from boat or on foot walking. This process is described as well as the basic rules in order to ensure a successful data collection.

After fieldwork

Back in the lab, the user has the possibility to work with the collected oblique imagery once the imagery has been correctly georeferenced. The process of georeferencing involves triangulation of object tie-points (common points) measured in overlapping images together with control points measured in a controlled source (B&W aerial photographs). Tie points are measured automatically while control points are measured manually. The resolution of the method typical equals the ground sampling distance (GSD) of the images and is normally between 0,1 - 0,5 m. This means that objects between 0,1 - 0,5 m can be distinguished in the images. The absolute uncertainty of the images, or how well the model is placed in real "world" coordinates, depends on how well control points can be indentified and typically amounts to around 5 m.

Typical workflow once the imagery is correctly oriented would be to draw out the geology, make correlation between areas or make structural measurements. The imagery could also be used for advanced visualizations.

The carbon cycle on early Earth recorded by the Singertât carbonatite and other carbon phases from Greenland

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The carbon isotopic compositions ($\delta^{13}C$) of the Earth's main reservoirs, including mantle and sedimentary rocks, seem to have remained constant through most of Earth's history (Schidlowsk 2001, Deines, 2002, Cartigny, 2005). While, at first sight this suggests the carbon cycle during the Archaean resembled the present day, we suggest there were different processes that maintained the isotopic balance between the reservoirs. During Earth's history carbon from the mantle has been gradually sequestered in the growing continental crust that, unlike oceanic crust, has only been recycled back to the mantle to a minor extent. Along with increased accumulation of carbon in the continental crust, the oceanic crust, which is the main inorganic carbon reservoir in the Precambrian, has decreased its role as a carbon sink through time. Both processes must have had an impact on the carbon isotopic composition of the mantle. Assuming long-term consistency in the proportion of buried organic carbon, we have developed a three-sink isotope mass balance model (Bjerrum & Canfield, 2004) that indicates the carbon isotopic composition of the mantle should increase with time. However, this observation is not consistent with the observed constancy of the mantle carbon isotopic composition. Here, we provide further evidence of the constancy of mantle carbon isotope composition since 2.664 Ga (Blichert-Toft et al. 1995) by measuring $\delta^{13}C$ of Singertât carbonatite, which represents carbon isotopic composition of the bulk mantle. We use $\delta^{13}C$ value of the Singertât carbonatites and other Greenlandic carbon phases of similar age, to test geodynamic models that would support the observed record, incorporating the effects of continental crust growth and decreased carbonatization of oceanic crust over Earth history.

The Singertât Complex from South-East Greenland is the third oldest carbonatite in the world and provides an important window into the Earth's early mantle composition. The Singertât carbonates have $\delta^{13}C$ values ranging from -4.9 to -4.4 ± 0.1‰. The narrow range in $\delta^{13}C$ values around a mean value of -4.8‰ fits well into the emerging record of mantle carbon from studies of un-degassed volcanic rocks from mid-ocean ridges, carbonatites, diamonds and other mantle xenoliths, and confirms that carbon isotopic composition of the mantle has remained constant, with $\delta^{13}C \approx -5‰$[1,2], from 2.664 Ga ago until today.

We modeled whether changes in the ratio of organic carbon burial on continents over Earth history (*f* ratio) would permit a constant carbon isotopic composition of the mantle by estimating how much organic carbon was buried ca. 2.7 Ga ago, and interpolating between the calculated *f* ratio value and an observed value of 0.16 at present. We use measured carbon isotope composition of Precambrian Greenlandic graphites ($\delta^{13}C \approx -33‰$) and marbles ($\delta^{13}C \approx 0‰$), which are proximate in age to Singertât carbonatite, to represent isotopic records of organic carbon and ocean water, respectively. Our results indicate that organic carbon accounted for only 9% of the total carbon burial ca. 2.7 Ga ago and in order to explain the constancy of the carbon isotopic composition of the mantle, a continuous increase of *f* ratio and a decrease of oceanic crust carbonatization with time are required.

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SEGMENT March, 2014 Workshop – Presentations on CD-ROM

Names of pdf-files of presentations from the SEGMENT 2014 workshop in the attached CD-ROM are given in bold. Below in italics the title of the related abstract and the full list of authors.

1_Thrane - Characterisation_of_SEG_basement - an ICPMS detrital zircon study
Characterization of the South East Greenland basement – an ICPMS detrital zircon study (Kristine Thrane)

2_Kokfelt et al - Intrusions of the Archaean Skjoldungen Alkaline Province
Intrusions of the Archaean Skjoldungen Alkaline Province, South East Greenland: Observations from the 2011-2012 field seasons and preliminary geochemical results (Thomas F. Kokfelt, Martin B. Klausen, Christian Tegner, Bjørn P. Maarupgaard, Andries Botha, Lærke Louise Thomsen)

3_Næraa et al - Zircon Geochronology Skjoldungen
Zircon geochronology from the Skjoldungen region (Tomas Næraa, Thomas Kokfelt, Kristine Thrane & Leon Bagas)

4_Keulen - Characterisation Basement SEG - CCSEM heavy mineral investigation
Characterisation of the South East Greenland basement – a CCSEM heavy mineral investigation (Nynke Keulen)

5_Tusch - LU-HF and Sm-Nd ages from garnet bearing granulite facies rocks
Lu-Hf garnet-dating on granulite facies rocks from the Helge-peninsular in the Skjoldungen Alkaline Provence, South-East-Greenland (Jonas Tusch)

6_Green - Apatite fission track analysis

6_Japsen et al - Burial, uplift and exhumation
Thermal history of outcrop samples from South-East Greenland based on apatite fission-track analysis (Paul F. Green, Peter Japsen, Pierpaolo Guarnieri & Troels F. Nielsen)

7_Guarnieri - Constraints for the Cretaceous-Tertiary geotectonic history of Skjoldungen
Constraints for the Cretaceous-Tertiary geotectonic history of Skjoldungen (Pierpaolo Guarnieri)

8_Alsen & Therkelsen - Sedimentary succession at Kap Gustav Holm
The sedimentary succession at Kap Gustav Holm, SE Greenland (Peter Alsen & Jens Therkelsen)

9_Guarnieri et al - Proterozoic structures reactivated during the NE Atlantic rifting in SE Greenland

Proterozoic structures reactivated during the NE Atlantic rifting in SE Greenland (Pierpaolo Guarnieri, Alfons Berger & P. Monie)

10_Klausen_et_al - Mafic dykes across NAC

Mafic dykes across Greenland's North Atlantic Craton: An updated record of at least seven major magmatic events between 2.5 to 0.06 Ga (Martin B. Klausen, Mimmi M.K. Nilsson, Thomas F. Kokfelt, Alexander Bartels, Riaan Bothma & Troels F.D. Nielsen)

11_Tukiainen - SAP, carbonatite intrusions in a 60 km long zone

The Archaean Skjoldungen Alkaline Province, South East Greenland - carbonatite intrusions confined to a specific 60 km long zone of the basement? (Tapani Tukiainen)

12_Justyna & Rosing - Carbon cycle on early earth recorded by Singertat carbonatite

The carbon cycle on early Earth recorded by Singertât carbonatite, South East Greenland (Justyna Wiewióra)

13_Maarupgaard et al - The Vend Om Intrusion

Petrology of the 2.7 Ga Vend Om Intrusion, Skjoldungen Alkaline Province, SE Greenland (Bjørn P. Maarupgaard, Christian Tegner, Thomas Kokfelt & Martin B. Klausen)

14_Muller - Metamorphic evolution of mafic dykes in the Nagssugtoqidian Orogen, South East Greenland

Metamorphic evolution of mafic dykes in the Nagssugtoqidian Orogen, South East Greenland (Sascha Müller & & Annika Dziggel)

15_Rosa & Ulrich - A W-Mo quartz veins and W-rich amphibolite horizons, Skjoldungen

A W-Mo quartz vein and W-rich amphibolite horizons from the Thrudvang peninsula, Skjoldungen, SE Greenland (Diogo Rosa & Thomas Ulrich)

16_Árting et al - Detailed study of a Fe-Ti oxide band in the Hjords Glacier Gabbro, Skjoldungen

A detailed study of a Fe-Ti oxide band in the Njords Glacier Intrusion, Skjoldungen Alkaline Province, SE Greenland (Tygvi Beck Árting, Thomas Kokfelt & Martin B. Klausen)

17_Kolb & Stensgaard - Nagssugtoqidian Orogens, facts, new interpretation and research needs

The Nagssugtoqidian Orogen of South-East Greenland: Facts, new interpretation and research needs (Jochen Kolb & Bo Møller Stensgaard)

18_Nielsen - Things I do not understand - and want to know more about

Things I (still) don't understand in South-East Greenland – with a focus on the Palaeogene (Troels Nielsen)

19_Glassley et al - Characteristics of the UHP metamorphic complex West Greenland

Characteristics of the UHP Metamorphic Complex In The Nagssugtoqidian Orogen Of West Greenland (William E. Glassley, John Korstgård, Kai Sørensen & S. Platou)

20_Sørensen - Nordre Strømfjord Fe-Mn rocks and where to look for them on the SE coast

Linking West and East coast Nagssugtoqidian (Kai Sørensen, William E. Glassley, John Korstgård, Kai Sørensen & S. Platou)

21_Bartels et al - The Gardar Igneours Province, SEG

The Gardar Igneous Province, South-East Greenland (Alexander Bartels, Mimi Nilsson, Martin Broman Klausen, M.B. & Ulf Söderlund)

22_Thrane - Geology of the Archaean and Palaeoprot parts of teh Tasiilaq regions - New U-Pb ages

New ages from the Tasiilaq region (Kristine Thrane)

23_Riisager - Aeromag 2013

Aeromag 2013 (Peter Riisager)

24_Stensgaard et al - New knowledge mineral potentail and new stream sediment data

[no abstract]

25_Sørensen - Skjoldungen and Tasiilaq from the air

Skjoldungen and Tasiilaq from the air - before and after fieldwork (Erik Vest Sørensen)

26_Petersen - Results from the Ujarassiorit-program

Results in South-East Greenland from the Ujarassiorit-program (Jonas Petersen)

27_Larsen et al - Earthquakes and earthquake swarms in Greenland

Earthquakes and earthquake swarms in Greenland (Tine B. Larsen, Trine Dahl-Jensen & P.H. Voss)

28_Pinna - Relocated local earthquakes in the Ammasalik region

Relocated local earthquakes in Southeast Greenland align on old geological structures (L. Pinna & T. Dahl-Jensen)

29_Danshøj & Kolb - Sulphide mineralization in the Tasiilaq intrusion

Sulphide mineralization in the Tasiilaq Intrusion, Ammassalik Intrusive Complex, South-East Greenland (Benedicte Danshøj Grøtner & Jochen Kolb)

30_Johansen et al - Nickel mineral system of the Ammassalik Intrusive Complex

The nickel mineral system of the Ammassalik Intrusive Complex, Nagssugtoqidian Orogen, South-East Greenland (Anne Brandt Johannesen, Jochen Kolb & Tobias B. Weisenberger)

31_Rosing-Schow et al - Palaeoproterozoic graphite mineralisation

Palaeoproterozoic graphite mineralization in rocks of the Nagssugtoqidian Orogen, South-East Greenland (Nanna Rosing-Schow, Jochen Kolb & Tobias B. Weisenberger)

32_Tukiainen - Highlights of geological reco on the ASTER sat data between 65-67

Tasiilaq: Highlights of geological reconnaissance on the ASTER satellite data between 65 N° and 67° 15' N (Tapani Tukiainen)