Greenland and Nunavut Geoscience Workshop 2014, Nuuk, Greenland

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Abstract

The Geological Survey of Denmark and Greenland (GEUS) and the Canada-Nunavut Geoscience Office (CNGO) recently held a workshop in Nuuk, Greenland focused on exchanging information about mineral and petroleum resources and discussing geoscience questions common to both jurisdictions. This workshop included participants from the CNGO, Government of Nunavut Department of Economic Development and Transportation, Aboriginal Affairs and Northern Development Canada, the Geological Survey of Canada, Government of Greenland Ministry of Industry and Mineral Resources, and GEUS. Valuable perspectives were also shared by both Greenland and Nunavut on the value of geological surveys as important institutions for managing natural resources. The workshop consisted of 23 presentations and a field trip in Godthåbsfjord.

Discussions during the workshop confirmed that increased collaboration between Greenland and Nunavut could help solve a range of geoscience-related questions and help build competencies on both sides of Baffin Bay. Important scientific outcomes of increased collaboration would include better understanding of the oil and gas resource potential, tectonics and mineral occurrences in the area. Specific outcomes linked to this goal include: 1) having staff exchanges between the two jurisdictions; 2) exchanging information regarding the establishment and operation of geological survey offices and local capacity building; 3) meeting annually during the Prospectors and Developers Association of Canada (PDAC) conference in Toronto; and 4) co-ordinating another similar workshop in Nunavut in 2 to 3 years.

Résumé

Le Service géologique du Danemark et du Groenland (GEUS) et le Bureau géoscientifique Canada-Nunavut ont récemment tenu un atelier à Nuuk, au Groenland, dans le cadre duquel l’accent a été mis sur des échanges d’information au sujet des ressources minérales et pétrolières et sur des discussions relatives à des questions d’ordre géoscientifique touchant les deux compétences. Des représentants du ministère du Développement économique et des Transport du gouvernement du Nunavut, d’Affaires autochtones et Développement du Nord Canada, de la Commission géologique du Canada, du ministère de l’Industrie et des Ressources minérales du gouvernement du Groenland et de la GEUS ont aussi pris part à cet atelier. Il s’est également agi pour le Groenland et le Nunavut d’une occasion de faire valoir leurs points de vue respectifs au sujet de la pertinence d’organismes tels les levés scientifiques en tant qu’institutions qui jouent un rôle important dans la gestion des ressources naturelles. Vingt-trois présentations ont été faites à cet atelier auquel est venu s’ajouter une excursion à Godthåbsfjord.

Les discussions qui ont eu lieu au cours de l’atelier ont permis d’établir que des efforts de collaboration accrue entre le Groenland et le Nunavut pourraient contribuer à résoudre toute une gamme de questions de nature géoscientifique et pourrait également contribuer à renforcer les compétences des deux côtés de la baie de Baffin. D’importantes réalisations scientifiques pourraient découler de cette collaboration, y compris une meilleure compréhension du potentiel en ressources

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pétrolières et gazières, de la tectonique et des venues minérales de la région. Parmi les réalisations spécifiques susceptibles d’aider à atteindre cet objectif, on note 1) l’échange de personnel entre les deux compétences; 2) l’échange d’information au sujet de l’établissement et du fonctionnement de bureaux relevant des services géologiques et le renforcement des capacités locales; 3) la tenue d’une rencontre annuelle prévue à l’occasion du congrès de la Prospects and Developers Association of Canada à Toronto; et 4) la tenue d’un atelier semblable à Nunavut dans 2 à 3 ans.

Introduction

This paper provides a summary of a recent workshop for geoscience staff from Greenland and Nunavut that focused on exchanging information about geology and mineral resources and also on discussing geoscience questions affecting both sides of Baffin Bay. Topics related to petroleum resources were discussed more briefly, and a more thorough discussion could be a suitable topic for a future workshop. The workshop was a valuable professional development opportunity for geoscience staff from both jurisdictions and helped develop a collaborative dialogue between Nunavut, Greenland, Denmark and Canada. Natural resource management in the Arctic, and geoscience training and capacity building activities were also discussed. In addition, valuable perspectives were shared on how both Greenland and Nunavut view geological surveys as institutions that support natural resource management. The workshop was co-organized by the Canada-Nunavut Geoscience Office (CNGO) in Iqaluit and the Geological Survey of Denmark and Greenland (GEUS) branch office in Nuuk.

Geology of Greenland

Greenland is the largest island on Earth, comprising a total area of 2 166 000 km² of which 410 000 km² are ice-free. The geological history of Greenland spans more than 3800 m.y. and represents a large variety of geological environments. The oldest areas constitute a basement shield composed mainly of deformed gneissic rocks representing root zones of Archean and Proterozoic orogenic belts. These belts are welded together to form a stable coherent block of which the North Atlantic craton and the Rae craton constitute two main components. Two prominent Proterozoic orogens, the Ellesmere–Inglefield mobile belt in North Greenland and the Makkovik–Ketilidian Orogen in South Greenland can be correlated to eastern Canada. Sedimentary basins developed adjacent to the basement shield during the following three time periods: 1) from the Meso- to Neoproterozoic, 2) from the Cambrian to Silurian, and 3) from the Devonian to Neogene. In the early Paleozoic, two distinct coast-parallel mountain belts formed: the Caledonian Orogen in North–East Greenland, and the Ellesmerian Orogen in North Greenland. Paleogene volcanic rocks related to the opening of the North Atlantic are represented as a flood basalt province in West and East Greenland. A geological map of Greenland is presented in Figure 1.

Geology of Nunavut

Nunavut is a vast territory, comprising almost a quarter of Canada, and its geology and natural resource potential are diverse. Geological provinces within Nunavut include the Churchill, Slave and Bear along with the Arctic Platform and Hudson Bay Lowlands. Several major tectonic events occurred in the past and include the Wopmay, Thelon, Trans-Hudson and Innuittian orogenies. Archean rocks are exposed throughout Nunavut and are characterized by granite-greenstone terranes. Siliciclastic rocks are common throughout, and Proterozoic and Phanerozoic rocks cover approximately one-third of Nunavut. A simplified geological map of Nunavut can be seen in Figure 2.

The landscape of Nunavut has been modified by past glaciations. During the last glaciation (Wisconsinan) the Laurentide Ice Sheet covered most of Nunavut with the thickest accumulation of ice centred over western Hudson Bay. The resulting erosion and deposition of glacial sediments has resulted in numerous aggregate deposits as well as the burial of mineral deposits and dispersal of their indicator minerals. Therefore, drift prospecting has now become an important exploration tool for large regions of the territory. Knowledge of permafrost, coastal sensitivity and marine geology are also becoming critical for infrastructure, resource and community development.

Workshop program and participants

This workshop was held in Nuuk, the capital of Greenland, from September 9 to September 11, 2014. It was hosted by GEUS at the Greenland Institute of Natural Resources. The program included two full days of presentations (Table 1). In total, 23 different presentations were given on a diverse range of topics including mineral exploration overviews of both jurisdictions; ruby discoveries in Greenland; Paleozoic xenoliths from kimberlite pipes on southern Hall Peninsula and implications for the petroleum potential in Baffin Bay; and the national mineral hunt in Greenland. On September 11 a geological field trip was taken in Godthåbsfjord.

Ten participants from Canada including eight from Nunavut, seven from Greenland and four from Denmark attended the workshop (Figure 3). Canadian participants represented the CNGO, Government of Nunavut Department of Economic Development and Transportation (GN), Aboriginal Affairs and Northern Development Canada...
Figure 1: Geological map of Greenland with interpretation of sub-ice bedrock in terms of major provinces. Insert shows Canadian-Greenland correlations in the Precambrian shield (from Henriksen, 2008).
(AANDC), and the Geological Survey of Canada (GSC). Four participants from Denmark represented GEUS, while seven participants from Greenland represented the Government of Greenland Ministry of Industry and Mineral Resources (MIM) and the GEUS branch office in Nuuk.

**Program Abstracts**

Abstract summaries for all presentations are provided below in chronological order. Please refer to Table 1 for the presenters name, title and organization.

**GEUS in Greenland (A1)**

The overall mission of GEUS is to provide, use and disseminate geoscience knowledge that is important for the use and protection of geological resources in Denmark and Greenland. Part of this mission is to support the governments of Denmark and Greenland, by providing state-of-the-art geoscienctific knowledge of international standard. The activities of the geological survey are organized into five main program areas:

- data banks, information technology, and information for the general public
- water resources
- energy resources
- mineral resources and Greenland mapping
- nature and climate

Some of the core activities for GEUS are to assist Greenland in developing a sustainable mineral industry by collecting and providing basic geological data for Greenland, as well as to provide specific advice to government institutions and to the mineral and oil exploration industry about the geology of Greenland. To make GEUS activities more available to the people of Greenland and to help facilitate
capacity building and public outreach in Greenland, a GEUS branch office was opened in Nuuk in 2013. The office assists the Greenlandic administration, public and companies with geological advice and scientific knowledge about mineral resources, energy resources and climate.

Canada-Nunavut Geoscience Office: an evolving Arctic geological survey (A2)

The Canada-Nunavut Geoscience Office (CNGO) is formally co-managed by the Government of Nunavut (GN), Natural Resources Canada (NRCan), and Aboriginal Af-
fairs and Northern Development Canada (AANDC). Nuna-
vut Tunngavik Inc., which represents the Inuit of Nunavut,
also sits on the management board as a nonvoting member.
The mandate of the office is to provide Nunavut with acces-
sible geoscience information and expertise to support 1) re-
sponsible resource exploration and development, 2) re-
sponsible infrastructure development, and 3) geoscience
capacity building and outreach. The office delivers a di-
verse suite of activities in collaboration with universities,
industry and other government organizations, including
NRCan’s Geo-mapping for Energy and Minerals (GEM)
program.

Nunavut mining and resource potential: 2014–
2015 status update (A3)

Nunavut may potentially hold a quarter of Canada’s natural
resources, however, the geoscience knowledge-base for
much of its land-mass is insufficient to support mineral ex-
ploration. The Government of Nunavut remains committed
to public geoscience, and works collaboratively with the
CNGO to deliver and carry out geoscience research.

Sustainable development in Nunavut will likely involve the
responsible development of natural resources in order to in-
vest in the territory and develop human capital with the aim
to evolve beyond a reliance on resource development. In
this context, the CNGO has recently begun delivering a
new two-year (2014–16) geoscience program. It intends to
deliver applied geoscience projects that support responsi-
ble natural resource development, protect investments in
infrastructure and disseminate geoscience data to users and
decision-makers. The intent of this presentation is to
provide an overview of the CNGO and its activities.

Figure 3: Participants at the workshop held at the Greenland Institute of Natural Resources. Bottom from left: D.J. Mate, M. Sanborn-
Barrie, M.D. Poulsen, L. Ham, S. Pehrsson. In the middle from left: K. Costello, H. Steenkamp, K. Thorsøe, A. Juul-Nielsen, K. Hanghøj,

Nunavut is geologically diverse, and a wide range of com-
modities including gold, zinc, copper, iron, uranium and di-
amonds, are current exploration targets. Nunavut has one
settled land claim that makes Inuit beneficiaries the major
recipients of any resource development. It also clearly de-
fines the environmental regulations and processes for re-
source development. Additionally, the potential for petro-
leum prospects within Nunavut remains high.
Status of mineral exploration in Greenland (A4)

In Greenland, the number of exploration licences granted has been steadily increasing since 2002. In addition to the traditional licences (exploration, prospecting and exploitation licences), a new type of licence has recently been introduced: the small-scale mining licence.

A persistent marketing of the Greenlandic mineral potential in several countries has led to the positive development of several mineral projects. As a result of this, the Government of Greenland’s objective is to license the opening of three to five mines on an environmentally and socially sustainable basis over the next five years. These mining projects may include the following:

- Isukasia (Isua) iron project, northeast of Nuuk, West Greenland
- Aapaluttoq ruby-sapphire project, south of Nuuk, West Greenland
- Killavaat Alannnguat/Kringlerne rare-earth element (REE) project, South Greenland
- Kvanefjeldet REE project at Narsaq, South Greenland
- Citronen Fjord zinc-lead project, North Greenland
- White Mountain anorthosite project, West Greenland

In the future, the Government of Greenland will focus on the potential for occurrences of new major deposits of iron and base metals, rare-earth elements, gold and gemstones. Furthermore, the analysis of the zinc potential of North Greenland is an area that will receive special attention.

Mineral exploration in Nunavut (A5)

The territory of Nunavut was created on April 1, 1999 through the Nunavut Land Claims Agreement, along with a co-managed regulatory regime involving the governments of Canada and of Nunavut, Inuit organizations and the Inco-managed regulatory regime involving the governments through the Nunavut Land Claims Agreement, along with the Inuit organizations. The territory of Nunavut was created on April 1, 1999.

Mineral exploration in Nunavut has been steadily increasing since 2002. In addition to the traditional licences (exploration, prospecting and exploitation licences), a new type of licence has recently been introduced: the small-scale mining licence.

Other advanced projects that are actively progressing through the regulatory process include Agnico-Eagle Mines Ltd.’s advanced stage Meliadine gold project, Sabina Gold and Silver Corp.’s Back River gold project and AREVA Resources Canada Inc.’s Kiggavik uranium project.

Uranium exploration in Greenland (A6)

Uranium exploration in Greenland was initiated in the 1950s by GEUS at the Kvanefjeld in South Greenland. Regional airborne radiometric surveys have been conducted in West and East Greenland, resulting in the identification of several areas with uranium mineralization (i.e., the Sarfartoq carbonatite in West Greenland).

Since 2007, Kvanefjeld has been investigated in detail by an Australian company, Greenland Minerals and Energy Ltd. (GME), who is conducting exploration on rare-earth elements and uranium deposits at the northern part of the Ilímaussaq complex. The Ilímaussaq complex is a Meso-proterozoic alkaline intrusive complex that hosts several multi-element deposits. The upper parts of the intrusive complex are represented in the northern part of the complex at the localities Kvanefjeld, Sørensen and Zone 3, which host REE-U-Zn-F deposits. Overall total resources of the northern part of the Ilímaussaq complex, as reported by GME, are 956 Mt containing 575 Mlbs. U3O8, 10.33 Mt total rare-earth elements (TREO, includes 0.37 Mt heavy rare-earth oxide), 2.25 Mt zinc and 0.84 Mt yttrium oxide.

Kvanefjeld is the largest of the known uranium occurrences in Greenland. It is a unique type of uranium deposit where the majority of the uranium is hosted by the mineral steenstrupine, containing 0.2–0.5% UO2. The hostrock, lujavrite, contains 200–400 ppm U and 600–800 ppm Th, the typical Th/U ratio lies between 2 and 3. The enrichment of uranium (and thorium) is thought to have occurred during crystallization and differentiation of the agpatic rocks.

The mid-Proterozoic Gardar Province, South Greenland: geology and rare-earth element potential (A7)

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

Geochemical investigations of mafic dykes indicate a time dependent compositional change within the Gardar magmatism, providing evidence for the involvement of two geochemically distinct mantle components. A first depleted source, re-enriched by fluid metasomatism and a second more enriched source possibly intermixed with phlogopite and apatite components. The geochemical fingerprint of dykes, associated with the older Gardar magmatic period, shows remarkable similarities to penecontemporaneous dykes in South-East Greenland and North America indicat-
ing a much more widespread magmatism. Recent plate reconstructions (Evans and Mitchell, 2011) give rise to the assumption that these dyke swarms were formed behind a long-lived orogenic belt in response to back-arc basin formation.

Current REE exploration studies within the province are focused on highly evolved apparitic nepheline syenite within the Ilímaussaq intrusion. In addition, significant REE enrichment is described for the Motzfeldt, Ivigtut and Paatusoq intrusions, but no detailed exploration studies have been conducted.

A geomorphological transect across eastern Nunavut (A8)

The effect of Quaternary glacial erosion on the landscape of central and eastern Nunavut is variable in its spatial distribution and intensity. Vast regions affected by glacial erosion are characterized by exposed fresh bedrock, till cover and evidence of glacial scouring, indicated by the presence of lakes over crystalline bedrock. Undulating terrain covered with a mantle of regolith preserves original Neogene landscapes on the plateaus of Boothia, Melville and Hall Peninsulas. These Neogene landscapes are preserved in cold-based glacier zones, where glacial erosion was minimal because the glacier was frozen to its base. The composition of the Neogene regolith depends on hostrock, ranging from boulder fields with little sandy matrix over tonalite rocks, to kaolinite-bearing orange clayey sands with minor boulder content over weathered garnet- and plagioclase-rich metasedimentary rocks. Satellite images and field studies illustrate the difference between the dendritic, organized fluvial landscape dating from the Neogene and the deranged fluvial landscape dating from the Quaternary. The increasing intensity of glacial erosion and transport is transitional from Neogene regolith (cold-based glacial terrain) to areas of till cover (warm-based glacial terrain). The surface material composition (geochemistry, sedimentology and heavy mineral content) informs us about the type of glacial transport and weathering processes that occurred across the transition zone from cold-based to warm-based glaciation.

South-East Greenland Mineral ENDowment Task, SEGMENT (A9)

The SEGMENT project is financed jointly by GEUS and the Ministry of Industry and Mineral Resources (MIM), Government of Greenland. The aim of SEGMENT is to provide better and more precise evaluations of the mineral endowment of the North Atlantic craton, the Ammassalik mobile belt and the Paleogene magmatic suite of South-East Greenland, between 62 and 67°N.

The project started in 2009 and 2010 with a regional fine-fraction stream sediment, fresh water and till sampling program. At the same time regional geological reconnaissance work was carried out. These datasets were used to plan more targeted geological research in the following years. Furthermore, regional aeromagnetic surveys were conducted in 2012 and 2013.

The focus region in 2011 and 2012 was the North Atlantic craton of South-East Greenland (62–64°N), centred on the Skjoldungen area. The work involved detailed mapping, tectonometamorphic and petrological studies, geochronology and isotopic mapping.

In 2014, the focus area for SEGMENT was the Tasilaq region (64–67°N). Extensive petrological investigations were conducted on different intrusive complexes in the area and work on establishing a tectonometamorphic model and the lithostratigraphy of mafic and supracrustal rock units was undertaken.

Nunavut’s soapstone: defining the supply for the community commodity of Arctic Canada (A10)

The Government of Nunavut has been evaluating carving stone sites since 2010 through the Nunavut Carving Stone Deposit Evaluation Program. The primary goals of the program are to verify the quality and size of traditional carving stone sites and identify new resources. The program relies on guidance from carvers and local community members to identify and assess traditional carving stone sites.

A total of 77 carving stone sites have been categorized for artisan suitability, tonnage and composition. A talc-rich rock type rarely found in Nunavut, ‘soapstone’, is a generic misnomer used in place of ‘carving stone’ by many Inuit carvers. Artisan serpentinite and artisan marble that can be shaped by carbide tools are Nunavut carvers’ preferred choice of carving stone.

Nunavut’s carving stone deposits range in size from tiny occurrences up to deposits containing 1 000 000 tonnes. The larger the resource, the more it is shared by carvers. A community-sized quarry or undeveloped deposit contains up to 1000 tonnes or more of material, while a regional-sized quarry or undeveloped deposit is 10 000 tonnes or larger in size. Deposits containing up to 1000 tonnes of material can supply average community use, while deposits containing up to 10 000 tonnes of material can provide carving stone to a much broader region. The Kangiqsuk-utaaq quarry on southern Baffin Island is Nunavut’s only regional producer. This 1970s tidewater discovery has yielded a lifespan-averaged 450 tonnes per year, supplying one-third of Nunavut’s carvers with excellent-quality carving stone.

The territory is now known to have 15 undeveloped carving stone deposits and 11 quarries able to provide several decades worth of carving stone to nearby communities. Of Nunavut’s 25 communities, 17 have access to local carving stone deposits and 11 quarries able to provide several decades worth of carving stone to nearby communities.
stone resources adequate for their long-term needs. Substantial high-quality resources await further study and future development.

**Greenlandic rubies (A11)**

During the past 15 years there has been considerable international and local interest in exploiting the Greenlandic occurrences of gemstone variants of corundum (sapphire and ruby). This has resulted in MIM issuing a number of exploration and small-scale licences and one full-scale exploitation licence for these commodities.

Rubies are found in several places in Greenland; within West Greenland this includes: the Maniitsoq area, the Nuuk area and the Fiskenæsset area. In South-East Greenland corundum occurs in the Tasiilaq area. The corundum occurrences in Greenland are found near anorthosite, amphibolite and ultramafic bodies and are often related to intruding felsic sheets. Most ruby occurrences are found within the Fiskenæsset area. The Fiskenæsset anorthosite complex is extensive and measures 30 by 70 km and contains occurrences of gem-quality corundum, especially at the Aappaluttoq locality.

Collaborative research between MIM and GEUS focuses on geochemical fingerprinting of the Fiskenæsset rubies in order to compare them to other Greenlandic and international occurrences. The Aappaluttoq samples are distinguishable from other Greenlandic and international occurrences based on oxygen isotopes and trace element ratios for Fe, Ti and Cr. The samples from Aappaluttoq have very high Cr content and lower Ti and Fe. Other Fiskenæsset occurrences share similarities in geochemical signatures with the Aappaluttoq rubies to a greater extent than to other Greenlandic and international ruby occurrences.

**Ujarassiorit: the national mineral hunt (A12)**

Ujarassiorit is an annual public mineral hunt competition that began in 1989. It is a grassroots competition that aims to contribute to knowledge of mineral occurrences in Greenland. The aim is to make use of the Greenlandic people’s traditional knowledge and connection with the land as they often visit places that are seldom visited by geologists. In this manner they can help find new areas of interest for geologists and through this create a greater interest in the geology of Greenland.

In this program any citizen in Greenland may submit samples of rocks they find on land for examination by MIM. The rock samples can be submitted by collectors at any post office in Greenland. A petrological description of and information about the rock type is made and returned to the submitter. Any mineralized samples are chemically analyzed and the results also returned to the submitter. Annually 700–1000 samples are submitted to Ujarassiorit. On average, 20–30% of the rock samples submitted are chemically analyzed. Submitted rock samples are judged based on observations and analytical results by geologists from MIM and GEUS. First place prize is C$10 000, second place is C$5000, there are two third place prizes of C$1900 and four fourth place prizes valued at C$1000 each.

**Nunavut community outreach and engagement (A13)**

One of the goals as stated in ‘Sivumut Abluqta’ (Stepping Forward Together) is for Nunavut to be self-reliant and develop its resources responsibly for the benefit of Nunavut. Recent surveys identify and forecast labour market requirements for Nunavut’s minerals industry to include up to 1800 direct mining jobs in the territory over the next decade. The Government of Nunavut’s plan is to ensure that Nunavummiut take advantage and benefit from these employment opportunities.

The strategy to achieve this is to tackle the challenges in an organized and structured way. This includes promoting awareness of careers in mining through outreach activities, creating necessary governing bodies to guide stakeholders in delivering education programs and providing effective training activities.

The shortage of skilled and/or experienced mine workers in Nunavut forces companies to bring in workers from outside the territory. Providing local skilled workers will reduce operating costs for mines and meet or exceed obligations from Inuit Impact and Benefits Agreements. Both of these outcomes will be beneficial to the industry and Nunavut.

**Geology of Greenland (A14)**

The content of this abstract is presented in the ‘Geology of Greenland’ section above.

**Correlation of geological events across Davis Strait: broadening implications of GEM geoscience through international collaboration (A15)**

Canada's Geomapping for Energy and Minerals (GEM) program targeted eastern Baffin Island for updated geoscience to advance tectonic models in support of resource assessment and exploration. Integrated GEM geoscience on Cumberland Peninsula established
- significant polydeformed Mesoarchean basement;
- discrete, foliated Neoarchean plutons;
- a central belt of Paleoproterozoic cover rocks (Hoare Bay), which include komatiite and clastic rocks, with minor marble;
- a 200 km long 1.89 Ga Opx–Grt±Bt granodiorite batholith (Qikiqtarjuaq suite); and
- cryptic Archean tectonometamorphism, penetratively overprinted by folding, tectonic imbrication and upper-amphibolite–facies metamorphism from 1.86 to 1.84 Ga.
Cumberland Peninsula’s basement/cover relationships point to Rae craton affinity, however, there are differences in lithology, age, detrital provenance and/or tectonometamorphic events that are distinct from, or not yet recognized within, the Rae craton. Main tectonometamorphism is consistent with the ca. 1.86 Ga central Nagssugtoqidian Orogen, implicating collision of North Atlantic craton as a driving force.

The GEM project is continuing its mandate of geomapping for energy and minerals across the Davis Strait through the acquisition of U-Pb age data from the Paleoproterozoic Karrat Group and Proven Igneous Complex of western Greenland. These new data elucidate the provenance and timing of deposition of cover rocks, document the extent of plutonism (1.90–1.87 Ga), and provide new insight into tectonometamorphic models for northeastern Laurentia.

**Metallogeny of Greenland (A16)**

In Greenland the North Atlantic craton is bounded by two later Proterozoic orogenies, the Nagssugtoqidian to the north and the Ketilidian to the south. Subsequent subsidence created large sedimentary basins in North and East Greenland, and rifting and volcanism created igneous provinces including the Gardar Province, and the North Atlantic large igneous province. Limited kimberlitic volcanism and carbonatite intrusions are found locally in several regions.

The diverse geological record in Greenland provides good potential for a wide variety of minerals. These include:

- iron, gold, chromium and diamonds, especially in the Archean basement (e.g., Isua banded iron formation and Nalunaq gold deposit);
- base metals in sediments and metamorphosed sedimentary rocks (e.g., the zinc-lead deposits of Black Angel and Citronen Fjord);
- platinum-group elements and nickel in igneous Proterozoic and Paleogene rocks (e.g., the Skaergaard precious-metal deposit); and
- rare-earth elements, niobium, tantalum and other specialty metals in alkaline and peralkaline intrusions and in carbonate intrusions (e.g., the Ilmaussaq, Sarfartoq and Qeqertaasaq rare-earth multi-element deposits).

Since 2009, GEUS has, in collaboration with the Government of Greenland, conducted annual workshops focused on assessing the mineral potential in Greenland for specific commodities. In 2012 the focus was on assessing the extent of undiscovered magmatic nickel deposits in the upper 1 km of the crust. Nineteen geologists with knowledge of Greenland geology, and international experts on magmatic nickel, formed a panel to conduct the assessment using the procedures and guidelines of the ‘Global Mineral Resource Assessment Project’ of the United States Geological Survey (USGS). Within 32 tracts (predefined areas) three magmatic nickel deposit types, and respective grade/tonnage models, were considered: 1) komatiite-hosted deposits, 2) contact-type deposits, and 3) deposits related to picritic and/or tholeiitic basalt dyke/sill complexes (also known as conduit-type deposits).

The statistical mean estimated number of undiscovered komatiite-hosted and conduit-type deposits were assessed to be four for each type, with no deposits of the contact-type, and at a 50% confidence level these were estimated to contain a total of 1.9 Mt of nickel. Of this estimate, 1.6 Mt of undiscovered resources were expected for conduit-type deposits (mainly the norite belt at the Mesoproterozoic Maniitsoq structure and the Paleogene flood basalt prov-
ince in West Greenland), 0.2 Mt for komatiite-hosted deposits (Ikertoq area in West Greenland), and less than 0.1 Mt related to contact-type deposits.

**Bedrock geology and economic potential of Hall and Meta Incognita peninsulas on southern Baffin Island, Nunavut (A19)**

The CNGO and GSC partnered to complete geological mapping on Hall and Meta Incognita peninsulas. These areas are underlain by Archean orthogneiss and Paleo-proterozoic para- and orthogneiss that appear to correlate with rock units previously mapped to the east and west.

On both peninsulas, new areas with economic mineral potential have been identified and include layered mafic-ultramafic intrusions with Ni-Cu-PGE mineralization potential, gossanous graphite- and sulphide-bearing meta-sedimentary rocks, semiprecious spinel and apatite gemstones associated with marble and calcsilicate units, granitic pegmatite with REE potential and marble and serpentinite carving stone deposits. The Archean orthogneiss on Hall Peninsula also hosts a diamondiferous kimberlite district with significant economic potential.

Following a final field season of mapping in 2015, southern Baffin Island’s bedrock geology will have been mapped at 1:100 000 scale. This will allow metamorphic and tectonic processes, as well as timing of events associated with the Trans-Hudson Orogen in this part of the Arctic, to be better understood. It will also provide a framework for understanding the petrogenesis of potentially economic deposits in the area.

**Mississippi Valley–type Zn-Pb mineralization of North Greenland (A20)**

The results of a zinc resource assessment indicate that the Franklinian Basin, North Greenland, is highly prospective for sedimentary exhalative (SEDEX) and Mississippi Valley–type (MVT) deposits. The Franklinian Basin is characterized by a distinct facies transition from shallow-water platform carbonate sediments in the south, to deep-water siliciclastic trough sediments to the north. While the platform carbonate sediments can host MVT deposits, the trough can host SEDEX deposits, so the whole basin is considered of interest for zinc-lead mineralization. The location of the northern margin to the Franklinian Basin in North Greenland is not established with certainty.

Deposition in the trough was ended by the mid-Paleozoic Ellesmerian orogeny, which formed the North Greenland fold belt and caused compression from north to south during the late Devonian to early Carboniferous.

Fieldwork in 2012 and 2013 revealed several new MVT showings, with sphalerite veinlets and pockets intermittently distributed within dolostone in the Turesø Formation (Upper Ordovician to Lower Silurian), of the Franklinian Basin carbonate platform. The fact that these showings are up to 200 km apart, demonstrates that a large-scale hydrothermal system, transporting zinc, operated in the eastern part of the Franklinian carbonate platform.

**Onshore oil and gas exploration in Greenland: a review (A21)**

Most of the oil and gas exploration in Greenland to date has been focused offshore. However, there are two areas of specific interest for hydrocarbons onshore, which have previously drawn attention from oil and gas companies. These two areas, the Disko/Nuussuaq area in West Greenland and Jameson Land in East Greenland, are briefly described below in terms of their hydrocarbon exploration potential.

The first discovery of onshore oil in Greenland was made on the Nuussuaq peninsula in 1992. Oil stains were evident in basalts, and in the following years, many oil seeps and stains were discovered in volcanic rocks and in the fluvio-deltaic sandstone of the Nuussuaq Basin, in the Disko/Nuussuaq region. The Nuussuaq Basin formed during Early Cretaceous rifting between Greenland and Canada and is the only onshore basin analogue in West Greenland. Results from organic geochemical analyses indicate that five oil types may exist in the area.

The other onshore area of interest is Jameson Land, which forms part of a thick sedimentary basin deposited during the Upper Paleozoic to Mesozoic between eastern Greenland and western Norway. Many of the oil and gas fields offshore western Norway are producing from similar sedimentary sections as the ones found onshore Jameson Land. The subsurface of Jameson Land may prove to contain commercial hydrocarbon resources and new geological models are important in order to understand the petroleum system.

In the next phase of Greenland’s Oil and Mineral Strategy (2014–2018) both of these onshore areas are expected to be open for licence applications (Jameson Land as an Open Door policy and the Disko/Nuussuaq area as a licensing round in 2016). In terms of application policy, Open Door policy basically means that pre-defined Open Door areas can be applied for all year around (from the opening date and until the area will be closed again), whereas an ordinary licensing round generally is held every two years in different predefined areas of Greenland and holds a fixed and limited application period in the relevant year only, in this case 2016.

**Sediment source fingerprint and basement characteristics (A22)**

Analysis of age distribution patterns of detrital zircon from recent stream sediments and their comparison with Mesozoic sandstones has proven to be a powerful tool in under-
standing sandstone provenance. Fingerprints from samples representing present day drainage also yield valuable information about the basement geology in areas with scarce geological information.

In central West Greenland detrital zircons with Archean ages constitute approximately 95% of all zircons in the Nagssugtoqidian (Paleoproterozoic) Orogen. In contrast to this, the fingerprint of detrital zircons from the Karrat Group contains approximately 50% Paleoproterozoic zircons. The Melville Bay area is characterized by no detrital Paleoproterozoic zircons in recent sediment samples and a very narrow Archean age distribution pattern with a peak around 2700 Ma in the south and a broader distribution pattern with a peak around 2700 Ma in the north. In Inglefield Land two detrital zircon ages are approximately equally common, namely ca. 1750 and 1950 Ma, whereas Archean zircons are rare.

A total of 134 recent stream sediment samples and 39 Cretaceous and Paleogene sandstone samples were collected on eastern parts of Ellesmere Island, Devon Island and Baffin Island during the summers of 2012 and 2013 by GEUS as part of a collaborative project together with the CNGO.

**The discovery of an organic-rich black shale xenolith from a kimberlite on Hall Peninsula, Nunavut: implications for petroleum potential in Cumberland Sound (A23)**

Presently, Hall Peninsula lacks Phanerozoic sedimentary cover, except for unconsolidated glacial deposits. However, a great number of carbonate and a few black shale xenoliths have been recovered from the Late Jurassic–Early Cretaceous kimberlites that occur in the area. The conodont microfossils discovered from the carbonate xenoliths proved that Upper Ordovician and Lower Silurian strata were present on Hall Peninsula at least before and during kimberlite emplacement. These strata, which have a total thickness of ~300 m elsewhere on southern Baffin Island, have since been eroded off Hall Peninsula sometime between the Early Cretaceous and today (Zhang and Pell, 2013, 2014). Their conodont color alteration index (CAI) values range from 1.5 to 8, making them an excellent geothermometer for understanding kimberlite emplacement temperatures.

The black shale xenoliths represent an excellent oil-prone source rock, with average and maximum total organic carbon (TOC) values of 8.04 and 8.96%, and a possible depositional age of Early Silurian. Given the geological and geographic position of the peninsula, and the identified suspect natural petroleum seeps from uncertain source rocks in the Baffin Shelf area, especially in Cumberland Sound (Budkewitsch et al., 2013), these unique black shale xenoliths provide valuable physical evidence for inferring that the oil seeps in the region may have originated from Paleozoic source rocks overlain by Cretaceous strata thick enough to generate oil (Zhang, 2013).

**Godthåbsfjord field trip**

Nuuk is situated in the North Atlantic craton, which constitutes the oldest part of Greenland. During this workshop a field trip by boat was organized in Godthåbsfjord (Figure 4). The first stop was the Ivinnguit fault (locality 1; Figure 5a), which is a long fault zone cutting through the entire fjord and continuing toward the inland ice farther north of the map area. The structure was formed during continental collision between two (or possibly more) Archean terranes at 2.7 Ga, dividing the old Amitsoq gneiss of 3.7 Ga age (Færingehavn terrane) and the Nûk gneiss of 3.2 Ga (Akia terrane). The Ivinnguit fault was visible several times along the field trip route.

Amphibolite was seen at locality 2 and pillow lava at locality 3 (Figure 5b). The interpretation of the large amphibolitic bodies in the area is that they were formed in island arc environments. The amphibolite has been wedged between gneiss during continental collision that occurred 2.7 Ga. The deformed, but distinct Ameralik dykes were observed in the oldest gneisses in the area at Storø (Figure 5c).

An anorthosite and the gold-bearing shear zone at Storø (locality 5) were observed from distance, as they outcrop high on the almost vertical walls of Storø. The Storø gold-bearing shear zone is about 2.5 Ga old and parallel to the Ivinnguit Fault. The fault crosses rocks at localities 5 and 7. Along the route several undeformed Paleoproterozoic dykes were observed crosscutting the gneisses in the area (Figure 5d). A small glacier and moraines was observed at locality 6 along the Storø Shear Zone. The Qôrqut granite complex (locality 10 and 11; Figure 5e) is approximately 2.5 Ga. old and has three distinct units: 1) a lower more uniform and light coloured unit, 2) a middle zone of more mixed character, and 3) an upper zone with increasing amounts of pegmatite. Three soapstone occurrences were visited: one at Storø (locality 4) and on two small islands northeast of Storø; the second at Uummannaq (locality 8); and the third at Qeqertaq (locality 9; Figure 5f).

**Workshop outcomes**

The discussion and information exchange that were part of this workshop resulted in several outcomes that are expected to leave a legacy. First, it became obvious that collaboration between Greenland and Nunavut could help solve a range of geoscience-related questions on both sides of Baffin Bay, leading to a better understanding of the oil and gas resource potential, tectonics and mineral occurrences in the area. Scientific collaboration can be facilitated through staff exchanges as well as direct office to office collaboration. Second, Nunavut and Greenland together
with Canada and Denmark should exchange information regarding the establishment and operation of geological survey offices and local capacity building. Third, the two jurisdictions decided to meet annually during the PDAC in Toronto, Canada in order to continue to share information and discuss issues of mutual interest. Fourth and finally, a similar geoscience workshop will be proposed in Nunavut in 2 to 3 years and ideally biannual scientific workshops at different locations hereafter. Workshops should be fairly broad in scope and strive to have participation of relevant scientists and government officials from Greenland and Nunavut as well as Canada and Denmark. Opportunities to
Figure 5: Photographs from the field trip to Godthåbsfjord, Greenland: a) The Ivinnguit fault at locality 1; b) pillow lavas at locality 2; c) the Ameralik dyke near locality 5; d) an undeformed Paleoproterozoic dyke crosscutting the gneiss; e) the Qôrqut granite and a Paleoproterozoic dyke as viewed from the boat; f) soapstone at locality 8, Uummannaq Island.
Economic considerations

Geological surveys collect and maintain public geoscience information in order to support economic development, land-use planning and community development. Public geoscience information decreases discovery risk for industries by enabling them to focus exploration programs on areas with the greatest potential. Geological surveys are best positioned to conduct regional mapping programs and integrate diverse datasets into geological frameworks. They are also key stewards of geoscience information both digitally as well as within the expert knowledge of their government geologists. Effective geological surveys with well-maintained and publicly available geoscience data make jurisdictions more attractive to investment from the mineral, and oil and gas sectors.

The role and development of geological surveys in both Nunavut and Greenland is evolving. The CNGO represents the seed of a geological survey for Nunavut. This office was created at the same time as the territory was formed in 1999. It is formally co-managed by the governments of Canada (including the Geological Survey of Canada) and Nunavut with input from Nunavut Tunngavik Inc., which represents the Inuit of Nunavut. It strives to provide accessible geoscience information to support responsible natural resource and infrastructure development and has six permanent staff with expertise in Precambrian, Sedimentary and Quaternary geology along with GIS/cartography and data dissemination. One day the management of public lands and natural resources will be devolved by the Government of Canada to the Government of Nunavut. This devolution of responsibility has not occurred yet but when it does, it will include the transfer of the CNGO to Nunavut where it is expected to continue its growth into a full-fledged territorial geological survey.

In Greenland, the Ministry of Industry and Mineral Resources of the Government of Greenland (Naalakkersuisuit) has the authority to undertake all administration in relation to mineral, and oil and gas activities. The role as a geological survey for Greenland is provided by GEUS, which was formed when the previous Geological Survey of Denmark (DGU) and Geological Survey of Greenland (GGU) merged in 1995. The Geological Survey of Denmark and Greenland (GEUS) support Naalakkersuisuit by conducting basic geological investigations and research, and maintaining public geoscience data and information. However, the possibility of developing a GeoSurvey Greenland (GSG) in addition to GEUS is currently being discussed in Greenland, and a proposal on how such a survey could be structured was put forward by the previous Naalakkersuisuit. Similar to the CNGO and GEUS, GSG would probably be managed by a board and be capable of providing geological advice to Naalakkersuisuit related to natural resource development and regulation. If the GSG were to develop, it most likely would be in a formalized collaboration with GEUS, whose role would eventually change to that of a collaborative research partner.

Conclusion

The first ever geoscience workshop between Greenland and Nunavut was held from September 9 to 11, 2014 in Nuuk, Greenland. The intent of the workshop was to exchange information about the mineral and petroleum resources on both sides of Baffin Bay. The role of, and process for establishing, geological survey offices in the Arctic was also discussed using the CNGO and the vision for the GSG as examples. Following this workshop it is expected that collaboration between both jurisdictions on geoscience, and mineral- and petroleum-related issues will grow.

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