Uranium potential in Greenland
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Uranium is almost entirely used for generating electricity. As of January, 2015, a total of 437 commercial nuclear reactors were connected to the grid worldwide, generating 377 GW and requiring c. 56,600 tons of uranium annually. At the same time, 70 new reactors were under construction in 15 countries. The world nuclear power capacity in 2035 is projected to grow to 418 GW in the low demand case and 683 GW in the high demand case. Accordingly, world annual reactor-related uranium requirements are projected to rise to between 66,995 and 104,740 tons of uranium by 2035.

Uranium supply has been adequate to meet the demand for decades with no supply shortages. Sufficient proven uranium resources also exist to support continued use of nuclear power including the maximum projected growth case in the foreseeable future. However, new mining projects have to be initiated in a timely manner to make up for mines that will be shut down due to resource exhaustion and to satisfy the expected increasing demand. The demand for uranium has been predicted to rise for several years as nuclear power is projected to grow considerably with a large number of new nuclear reactors in the pipeline. This reflects an increased demand for electricity combined with more focus on clean air and zero CO2 emission production. The East Asia region is projected to experience the largest increase in nuclear power plants, a movement that is already underway. However, the projections for the global demand for uranium are subject to great uncertainty, especially following the Fukushima Daiichi accident and the decisions of several countries to phase out nuclear power. As such, the projections for demand for uranium in the European Union vary from a minor increase to a large decrease.

Denmark, including Greenland, joined the European Economic Community in 1973 when uranium exploration was encouraged in member states to secure the community’s uranium resources. The government institutions, Geological Survey of Greenland and Risø National Laboratory, conducted exploration in Greenland until 1985, when the Danish government decided to exclude nuclear power from its energy supply policy. Soon after, Greenland introduced a ban on uranium exploration. In 2013, the Greenland government lifted the ban, which created a renewed interest in assessing Greenland’s uranium resources.
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Table 1. Significant uranium occurrences in Greenland (Fig. 2). Three types are encountered: large, low-grade magmatic deposits, small syn- to epigenetic carbonatite and fenite and pegmatites. Known uranium occurrences and areas are all situated in areas outlined as high radiations over the Kvanefjeld plateau within the Ilímaussaq intrusion.

In November 2016, a workshop on the ‘Assessment of the uranium potential in Greenland’ was arranged jointly by the Geological Survey of Denmark and Greenland (GEUS) and the Ministry of Mineral Resources (MMR), Government of Greenland with the purpose of: 1) presenting and discussing known uranium occurrences in Greenland and 2) estimating the probability for the existence of undiscovered and hidden uranium deposits. Three uranium deposit types were chosen for the assessment: intrusive, sandstone-hosted and unconformity-related. The main conclusion of the workshop was that the intrusive and unconformity-related deposits have the highest probability of having formed uranium deposits in Greenland, and that South Greenland has the best potential for hidden deposits (Thrane et al. in press).

This edition of Geology and Ore provides an overview of: 1) surveys concerning uranium, 2) known uranium occurrences and 3) the main results from the workshop. A GEUS report documenting results from the workshop will be available at the end of 2017.

Uranium exploration and multi-element geochemical mapping including uranium

Most of Greenland has been covered by drainage geochemical surveys with uranium as one of the elements determined routinely in stream sediment samples. In addition, large areas in East, South and West Greenland have been surveyed by airborne gamma-spectrometry (Fig. 1). Follow-up exploration in anomalous areas has verified a number of uranium-mineralised occurrences.

The earliest uranium exploration by means of Geiger counters over selected areas of South Greenland (1955–1956) located the highest radiations over the Kvanefjeld plateau within the Ilímaussaq intrusion. Uranium enrichment took place during exploration between 1955 and 1985 are listed in Table 1, and their location shown in Fig. 2. In addition, a large number of showings with samples yielding above 100 ppm U are known.

South Greenland

South Greenland is underlain by Archaean, Palaeoproterozoic and Mesoproterozoic rock complexes (Fig. 3). Uranium enrichment took place during the Palaeoproterozoic Ketilidian orogeny, and during the Mesoproterozoic alkaline magmatism. The latter resulted in uranium mineralisation in rift-related faults and accumulation of uranium in the most evolved peralkaline magmas.

Palaeoproterozoic uranium mineralisation

The Ketilidian orogen (formed 1850–1730 Ma) includes the Julianehåb igneous complex dominated by granite and granite as well as large volumes of supracrustal rocks of sedimentary and volcanic origin that are moderately to strongly folded, thrusted and partially melted. The Ila plutonic suite (1755–1730 Ma) represents the last intrusive event in the orogeny.

Intrusive and unconformity-related uranium occurrences are all situated in areas outlined as high radiations over the Kvanefjeld plateau within the Ilímaussaq intrusion.

Investigations of the strongest of many aeroradiometric uranium anomalies recorded in these environments led to the identification of uranium mineralisation

<table>
<thead>
<tr>
<th>Area</th>
<th>Name</th>
<th>Mineralisation setting</th>
<th>Mineralisation age</th>
<th>Host rock age</th>
<th>Host rock lithology</th>
<th>Mineralogy</th>
<th>Grade U %</th>
<th>Tonnage</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Greenland</td>
<td>Søndermark</td>
<td>Intrusive</td>
<td>Palaeoproterozoic</td>
<td>1850 Ma</td>
<td>Granite</td>
<td>Uraninite</td>
<td>0.5-1</td>
<td>1-2</td>
<td>Additional resource</td>
</tr>
<tr>
<td>South Greenland</td>
<td>Kvanefjeld</td>
<td>Intrusive</td>
<td>Palaeoproterozoic</td>
<td>1850 Ma</td>
<td>Granite</td>
<td>Uraninite</td>
<td>0.5-1</td>
<td>1-2</td>
<td>Additional resource</td>
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<td>Nordmark</td>
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<td>0.5-1</td>
<td>1-2</td>
<td>Additional resource</td>
</tr>
</tbody>
</table>
within rafts of metasediment enclosed by granitoids at Illorsuit and Nunatak (Fig. 3). In both places, the mineralisation is described as stratiform and the original mineralisation is interpreted as syn-sedimentary/syn-volcanic, although locally mineralisation is situated in folds and veins, due to tectonic and metamorphic processes. The uraninite at Illorsuit in the Southern Domain of the orogen yields a U-Pb isotopic age of c. 1740 Ma, which is within the age span for the flua plutonic suite surrounding the metasediments (Fig. 3). The highest grade uranium mineralisation is about 50 m long and up to 5 m wide with grades up to 7 % U. It is estimated that the Illorsuit prospect contains 17,000 tons of uranium ore with a grade of 0.31 % U. The known mineralisation at Nunatak is much smaller and less well documented, but it is believed that a number of unchecked gamma-spectrometric anomalies in the same area reflect similar uranium mineralisation.

The anatectic melting of metasediments in the Southern domain of the Ketilidian orogen created pegmatites and migmatitic veins that host scattered, small uraninite occurrences that were investigated cursorily at Tasermiut (Table 1, Fig. 4).

Mesoproterozoic fault-zone related uranium mineralisation

Large parts of the Julianehaab igneous complex, Central Domain of the Ketilidian orogen (Fig. 3), are strongly faulted and fractured in response to Mesoproterozoic rifting. The faulted region is outlined as strongly enriched in uranium by an abundance of stream-sediment and stream-water uranium anomalies (Fig. 4), and over 200 occurrences with more than 100 ppm U were discovered during ground exploration. Uranium occurrences are commonly small lenses or veins, but they occur along fractures traceable for up to 10 km. They comprise two types: (1) pitchblende associated with faults, fractures and related joints and (2) brannerite, also associated with fractures and disseminated in altered granite along them. This latter type occurs mainly in the southern part of the Julianehaab igneous complex.

Uranium vein mineralisation occurs in NE-SW-striking tension fractures and is typically accompanied by alteration, such as desilicification, introduction of iron oxides and calcite, decomposition of plagioclase and its replacement by albite. Pitchblende or brannerite may be accompanied by secondary uranium minerals, galena, pyrite and chalcopyrite, whereas
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Figure 3. Main lithostratigraphic units within South Greenland together with known uranium occurrences. Uranium mineralisations are documented by rock samples (see Fig. 4); prospects have been investigated in detail. From the workshop presentation by A. Steenfelt.

Figure 4. Summary of results of uranium exploration 1979–1984 in South Greenland. Elevated to high uranium contents of stream sediment and rock samples displayed on top of gridded data for equivalent uranium (eU) recorded during helicopter-borne gamma-spectrometry. From the workshop presentation by A. Steenfelt.
gangue minerals commonly include calcite, quartz and fluorite. Isotopic data indicate an age of about 1180 Ma for pitchblende. The most studied occurrences, Qasianuk, Pursatqat and Vatnahverfi (Fig. 4), yielded grades in the range 1–2 % U.

**Mesoproterozoic peralkaline intrusions**

The Mesoproterozoic (1300–1140 Ma) igneous rift-related province, the Gardar Province, covers large areas of South Greenland. The province comprises sandstones, lavas, numerous dykes and 14 intrusive complexes. The most evolved magmas have been enriched in alkali metals, high-field-strength elements, rare-earth elements (REE) and actinides (U and Th) to a degree where they constitute multi-element deposits.

The Ilímaussaq complex (1160 Ma) is one of the youngest intrusions of the Gardar Province (Fig. 5). The earlier intrusive phases formed augite syenites and alkali granite. The main phase was peralkaline, very rich in chlorine and fluorine and differentiated into the nepheline-syenite units pulaskite, foyaite, naugite, kakortokite and aegirine lujavrite. The last phase, arfvedsonite lujavrite with agpatic to hyper-agpatic composition, features very high concentrations of Li, Be, F, Zn, Y, Zr, Hf, Nb, Ta, Th, and U and is the basis for the Ilímaussaq deposit and additional prospective zones.

The Kvanefjeld deposit has an average uranium concentration of c. 300 ppm. The dominant carrier of uranium is the mineral steenstrupine, a sodium-cerium-silico-phosphate, which also carries yttrium and REE. The Kvanefjeld uranium deposit is unique and has been studied in great detail (Sørensen et al. 2011). Geological mapping and radiometric characterisation have been carried out by the government from 1956 to 1983, with 12,455 metres of core drilled, a 1 km long adit constructed and metallurgical tests.

Since 2007, Greenland Minerals and Energy Ltd. has conducted REE exploration in the Kvanefjeld area with the business concept encompassing uranium and zinc by-products. The total identified conventional mineral resource inventory for Kvanefjeld is 102,820 tons of uranium. Additional inferred mineral resources of 125,143 tons of uranium exist in Kvanefjeld, Zone Sørensen and Zone 3. This is a significant resource already identified that is likely to be much larger as the lujavrite layer extends between the identified zones.

The Motzfeldt intrusive complex within the Gardar Province contains rocks similar to those in the Kvanefjeld area but they do not attain as high concentrations of U and REE as the lujavrite of Ilímaussaq.

The Motzfeldt complex (c. 1270 Ma) is one
of the older units within the Gardar Province. It is composed of multiple intrusions of syenite and nepheline syenite, emplaced at the boundary between the Palaeoproterozoic Julianehåb granitoids and the unconformably overlying Mesoproterozoic Eriks fjord Formation. The outer intrusive unit, the Motzfeldt Sø Formation, sensu stricto, (Fig. 6) has incorporated large quantities of roof sandstones and volcanic rocks. The magma of the Motzfeldt Sø Formation underwent extreme magmatic differentiation, thereby producing a residual liquid rich in volatiles and incompatible elements that intruded the margin of the complex and formed a number of peralkaline microsyenite sheets and pegmatites.

Almost synchronous with the crystallisation of the magma, hydrothermal alteration of the Motzfeldt Sø syenite occurred along the margins and the roof. The altered syenite and microsyenite contain extensive Nb-Ta-Zr-REE-U-Th mineralisation. Uranium is mainly hosted by pyrochlore, containing 3–9 % UO₂. The microsyenite contains 100–500 ppm uranium.

East Greenland

Post-Caledonian extensional faulting

The Silurian Caledonian orogeny in northern East Greenland involved Archaean to Palaeozoic rocks (Fig. 2). Younger sedimentary and subordinate magmatic rocks are variably affected by faulting in response to post-Caledonian extension and opening of the North Atlantic Ocean. Many high values for uranium were recorded by airborne gamma-spectrometry and stream-sediment/stream-water geochemistry along the main N–S-trending post-Caledonian fault zone. Three
localities shown in Fig. 2 yielded rock samples with uranium concentrations above 0.5 % U. At Arkossedal, the fault zone transects Silurian granite whereas the uranium mineralisation at Randbøldal and Hochwacht is hosted by Devonian rhyolites close to faults.

Assessment of the potential for undiscovered uranium deposits in Greenland

A modified version of the standardised ‘Global Mineral Resource Assessment Project’ (GMRAP) procedures defined by the US Geological Survey (USGS) was applied at the workshop. The modification was required due to the absence of a grade and tonnage model for uranium deposits. Instead, predetermined regions (tracts) favourable for the formation of the selected uranium deposit types were presented and discussed. Subsequently, the members of the assessment panel made their individual estimates (bids) for the number of undiscovered deposits likely to occur within a tract, under the best circumstances and to a depth of 1 km below the surface. A consensus bid was compiled based on discussion among the panel-members.

The assessment panel consisted of sixteen experts from the USGS, IAEA, University de Lorraine, AREVA, GEUS, MMR and private exploration and consulting companies, collectively covering expertise in uranium deposits and Greenland geology.

During the workshop, a total of 35 tracts were assessed for undiscovered uranium deposits (Fig. 7).

Mineral deposit types assessed

Bruneton et al. (2014) and the IAEA classification (2014) of uranium deposits were followed, and three types were found relevant for Greenland.

Intrusive type:

Deposits of this type are hosted in intrusive rocks of various petrochemical compositions, in which uranium has been concentrated by partial melting or magmatic fractionation. The deposits tend to be low grade and comprise only 4 % of the current global production. Two main subtypes are recognised: 1) intrusive anatectic deposits associated with partial melting and contained in granite-pegmatite (e.g. Rosing and Husab, Namibia) and 2) intrusive plutonic deposits related to magmatic differentiation and subdivided into three classes: quartz monzonite, paralkaline complexes (e.g. Kvanefjeld, Greenland) and carbonatite.
Sandstone type:

Sandstone-hosted uranium deposits occur in medium- to coarse-grained unmetamorphosed sandstones deposited in continental fluvial or marginal marine sedimentary environments. Volcanic ash may represent a major uranium source within the sandstone in some regions. Uranium is precipitated by reduction processes caused by a variety of reducing agents within the sandstone. These may include carbonaceous material (mainly detrital plant debris), sulphides (pyrite), ferro-manganese minerals (chlorite), bacterial activity, migrated fluids from underlying hydrocarbon reservoirs. Sandstone deposits are commonly low- to medium grade. However, they make up more than 50 % of the world’s uranium.

### Table 2. Summary of consensus bids on the number of undiscovered uranium deposits in Greenland from the November 2016 assessment workshop held by GEUS and MMR.

<table>
<thead>
<tr>
<th>Tract No.</th>
<th>Tract name</th>
<th>Tract Area (km²)</th>
<th>Unconformity related deposits</th>
<th>Sandstone deposits</th>
<th>Intrusive deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>Eriksfjord Basin W</td>
<td>7,550</td>
<td>0 0 1 2 3 4 5 6 7 8</td>
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<td>U2</td>
<td>Central Eriksfjord Basin</td>
<td>1,265</td>
<td>1 1 3 5 7 10 2 4 6 8</td>
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<td>0.002508</td>
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<td>U3</td>
<td>Eriksfjord Basin E</td>
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<td>0 0 1 2 1 2</td>
<td>0.44</td>
<td>0.000341</td>
</tr>
<tr>
<td>U4</td>
<td>Møllebæk</td>
<td>277</td>
<td>0 0 0</td>
<td>0</td>
<td>0.11</td>
</tr>
<tr>
<td>U5</td>
<td>Arnap Nuna</td>
<td>106</td>
<td>0 0 0 1 2</td>
<td>0.11</td>
<td>0.000991</td>
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<tr>
<td>U7</td>
<td>Kornet Group</td>
<td>5,564</td>
<td>0 0 2 3 4</td>
<td>0.71</td>
<td>0.003285</td>
</tr>
<tr>
<td>U8-U10</td>
<td>Thule Basin</td>
<td>4,372</td>
<td>0 2 3 5 8</td>
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<td>0.004444</td>
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<tr>
<td>U11</td>
<td>Independence Fjord</td>
<td>7,470</td>
<td>0 1 2 4 6</td>
<td>1.21</td>
<td>0.006162</td>
</tr>
</tbody>
</table>

**Note:** N90, N50, N10, N05, N01 = Confidence levels; a measure of how reliable a statistical result is, expressed as a percentage that indicates the probability of the result being correct. A confidence level of 10% (N10) means that there is a probability of 10% that the result is reliable. Deposit density = the total number of deposits per km².
production. The largest producer is Kazakhstan, which has numerous sandstone deposits (e.g. Kanzhugan, Mohinum, Budennovskoye) all mixed by the in-situ acid-leaching method.

The known uranium occurrences in Greenland are either associated with igneous rocks (i.e. may be classified as intrusive type), or they result from epigenetic mineralisation of structural traps, and have previously been classified as vein type. This class, however, has been abandoned in the most recent IAEA classification, so that they were assigned to the intrusive type at the workshop.

Unconformity type:
Unconformity-related deposits are associated with and occur immediately below, above, or spanning an unconformable contact that separates Archaean to Palaeoproterozoic crystalline basement from overlying, redbed clastic sediments of Proterozoic age. In most cases, the basement rocks immediately below the unconformity are strongly hematited and clay altered, possibly the result of paleoaqueous and/or diagenetic/hydrothermal alteration. Deposits consist of pods, veins and semi-massive replacements mainly of pitchblende. Strong quartz dissolution is generally associated with them. The Proterozoic unconformity deposits are commonly very high grade. They include three sub-types of variable importance: 1) unconformity-contact deposits, 2) basement-hosted deposits and 3) stratiform structure-controlled deposits. They are preferentially located in two major districts, the Athabasca Basin (Canada) and the Pine Creek Orogen (Australia), all mixed by the in-situ acid-leaching method.

Western Central Domain, SVG 19
The Central Domain of the Palaeoproterozoic Kettillidian orogen of South Greenland covers the majority of the igneous components related to the orogen together with a few enclaves of supracrustal rocks. During the workshop, the Central Domain was divided into a western part, tract I9, and an eastern part, tract I10. Tract I9 (Fig. 8a) includes all known and potentially hidden intrusions of the Gardar Province except the Motzfeldt and Ilímaussaq intrusions, as they are covered in separate tracts described below (I2 and I11). The area covered by this tract is strongly enriched in uranium as described in the section on South Greenland (Fig. 4). The tract was considered to have a high potential for containing undiscovered deposits.

Ilímaussaq 111 and Motzfeldt 12
These intrusions are described in the section on Mesoproterozoic peralkaline intrusions in South Greenland. They were both considered to have a high potential for additional undiscovered deposits.

Southern Domain, SG 11
This tract (Fig. 8b) covers the Palaeoproterozoic supracrustal rocks described in the section on Palaeoproterozoic uranium mineralisation in South Greenland. Uranium mineralisations are present in the tract, which is generally under-explored and, therefore, considered to have a good potential for containing undiscovered deposits.

Assessment results
The tracts receiving the highest ranks in the assessment are commented below.

Highest ranked tracts for undiscovered intrusive-type uranium deposits in Greenland were the Mesoproterozoic Ilímaussaq and Motzfeldt peralkaline igneous intrusions, which already have known reserves and occurrences, respectively (Tracts I2, I11). In addition, both the Central Domain and the Southern Domain of South Greenland were ranked as having a high potential for containing undiscovered intrusive deposits (I9 and I11).

The highest ranked tracts defined for unconformity-type deposits comprise the two Mesoproterozoic basin formations in Greenland that rest unconformably on Palaeoproterozoic or Archaean basement, namely the Eriksfjord Formation in South Greenland (U1, U2) and the Thule Supergroup (U15) in North Greenland.

Some of the most productive uranium deposits worldwide occur in the basement below or at the unconformable base of Mesoproterozoic continental sandstones (Athabasca Basin, Canada). No unconformity-related uranium occurrences have been found in Greenland, even though Greenland has large Mesoproterozoic sedimentary deposits lying unconformably on Palaeoproterozoic or Archaean basement. Hence, a potential for unconformity-related uranium deposits exists in Greenland.

Central Eriksfjord Basin U2 and U1
Remnants of the Mesoproterozoic Eriksfjord Formation are now mostly preserved in down-faulted graben structures in the EN-WSW trending central zone of the Central Domain, where the formation rests unconformably on the Julianehåb gneisses complex (Fig. 3). Isolated occurrences of lavas and sandstone outside the central zone are taken as evidence that the sediments and lavas once covered a much larger area.

The preserved section of the Eriksfjord Formation is just over 3000 m in thickness and comprises six members of alternating continental sediments and lavas. The sediments are sandstones, conglomerates and arkoses laid down mostly in a fluvial environment and with aeolian deposits occurring more commonly in the upper part of the formation. The volcanic rocks comprise basaits, hawaiites, and carbonatic lavas and pyroclastic rocks in the lower members, whereas upper members are more alkaline and also include trachybasalts, trachyandesites, trachytes and phonolites. It has been assumed that the provenance of the sandstone was the immediately surrounding granites of the younger parts of the Julianehåb igneous complex. However, the detrital
The zircon population from the lower sandstone units at Qassiarsuk is dominated by Archaean and Palaeoproterozoic ages similar to those recorded in the Northern Domain with a minor contribution of ages relatable to the younger part of the Julianehåb igneous complex. Many sandstone and mudstone beds are oxidised with characteristic reduction spots (Fig. 9).

The Eriksfjord Formation is deposited in a uranium-rich environment and some of the known uraninite fracture-hosted occurrences in the Julianehåb igneous complex have been suggested to be unconformity-related. Accordingly, the potential for undiscovered uranium deposits was highly ranked.

Tract U2 is defined as the area where the Eriksfjord Formation is present today (Fig. 8A). However, since the Eriksfjord Formation originally covered a much larger area, a potential unconformity deposit could still be hidden in the surrounding basement. Tract U1 represents a doughnut-shaped area, surrounding but not including U2.

The Eriksfjord Formation is deposited in a uranium-rich environment and some of the known uraninite fracture-hosted occurrences in the Julianehåb igneous complex have been suggested to be unconformity-related. Accordingly, the potential for undiscovered uranium deposits was highly ranked.

The Thule Basin consists of an unmetamorphosed sedimentary-volcanic succession that is at least 6 km thick and was deposited during middle Mesoproterozoic – late Neoproterozoic times. The Thule Basin is an intracratonic fracture basin characterised by block faulting and basin sagging formed during an extensional tectonic regime. The sediments were deposited in a series of half-grabens on top of a basement of Archaean gneiss and Palaeoproterozoic supracrustal rocks. Alteration of the crystalline rocks, intense reddish-brown banding and strong reduction patterns have been recorded particularly in basal strata close to the Precambrian basement, both in the central basin and in basin margins, suggesting that the unconformity acted as a passageway for the reducing solutions.

The unconformity at the base of the Thule Supergroup, as well as the basement below, represents such a favourable structural setting for unconformity-type uranium mineralisation that the potential for undiscovered deposits was ranked as relatively high. However, contrary to the situation in the Eriksfjord Formation, no anomalies have been recorded in stream sediment and scintillometer surveys over the Thule Supergroup, and no indications for uranium enrichment in the surrounding basement rocks have been recorded. Nevertheless, the tract was considered to have a good potential for containing undiscovered deposits.

Concluding remarks
The uranium potential in Greenland is considered relatively high with one very
large deposit already being advanced toward production (pending application and approval). Existing evidence from aeroradiometric and drainage surveys combined with field investigations points to South Greenland as the most prospective region for additional hidden or unrecognized intrusive-type uranium occurrences. Favorable geological settings for unconformity-related uranium mineralization are identified, suggesting a potential for such deposits.

References
Davies, P.R. 2006: Explanatory notes to the Geological map of Greenland and Greenland Map Series 2, 97 pp. – map.

Figure 9. Eriksfjord sandstone with signs of reducing conditions.