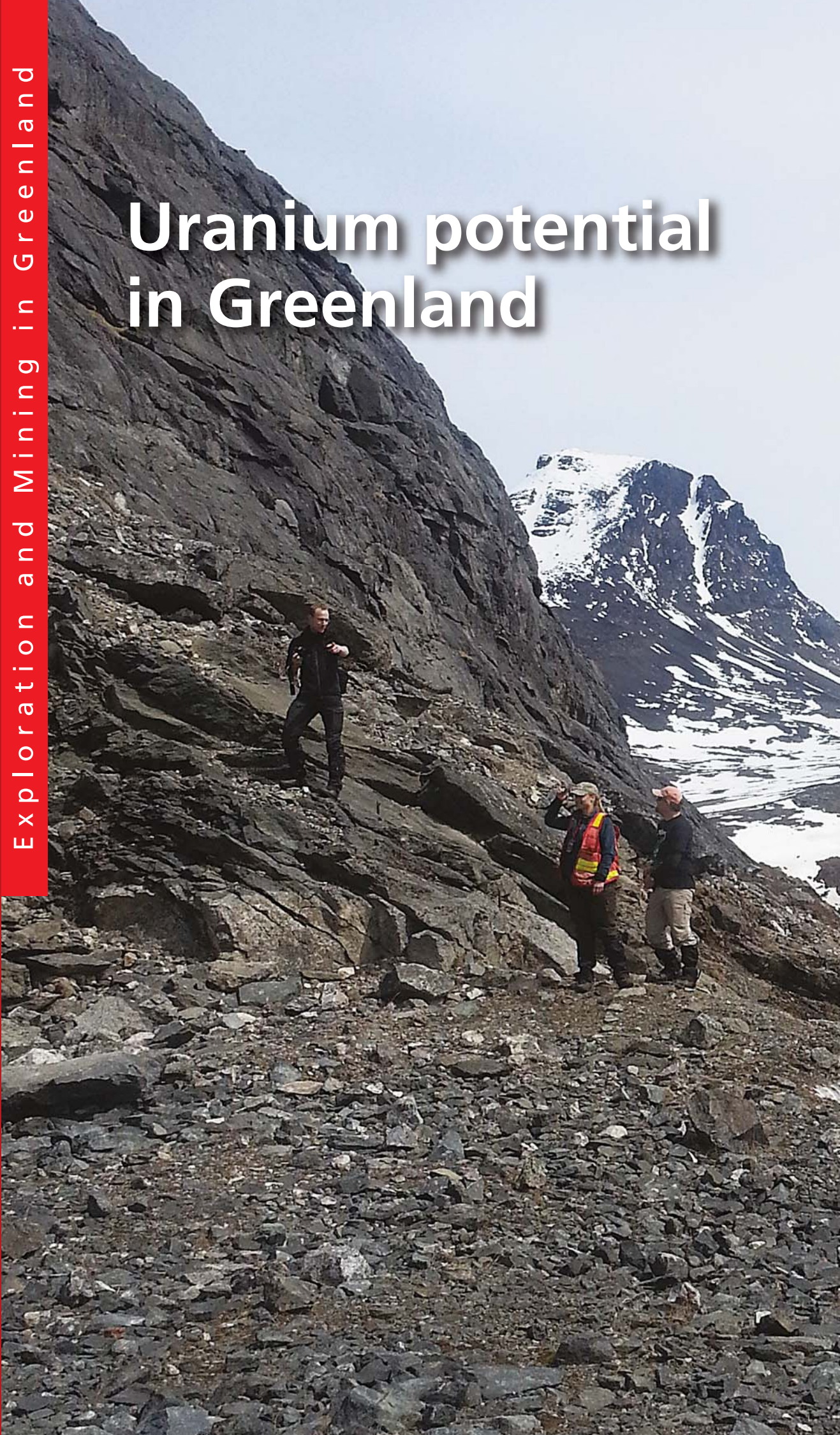




Uranium potential in Greenland



Uranium potential in Greenland



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 GWe 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 GWe in the low demand case and 683 GWe 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.

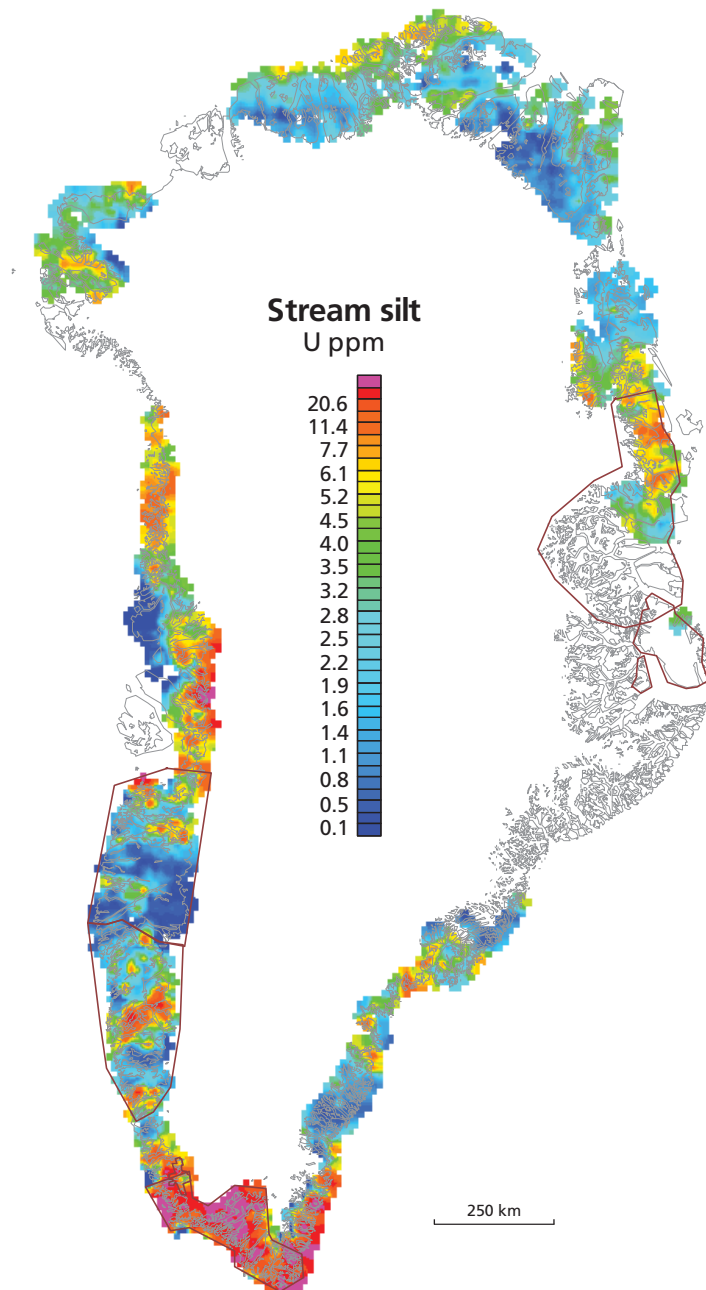


Figure 1. Variations in uranium concentration over Greenland as reflected in the <0.1 mm grain-size fraction of systematically collected stream sediment samples. South Greenland stands out as the most uranium-enriched province in Greenland, where the best uranium prospects are also located. Areas surveyed by airborne gamma-spectrometry are outlined. From Steenfelt (2014).

Area	Name	Mineralisation setting	Mineralisation age	Host rock age	Host rock lithology	Mineralogy	Grade U %	Tonnage	Category
West Greenland	Sarfartoq	fracture	Neoproterozoic	Neoproterozoic	carbonatite and fenite	pyrochlore	0.5-1	low	Nb-Ta-REE prospect
West Greenland	Nuuk region	magmatic	Neoproterozoic	Neoproterozoic	pegmatite	uraninite	0.5-2	low	showing
West Greenland	Nuuk region	fracture	Neoproterozoic	Archaean	amphibolite	uraninite	0.5-1	low	showing
South Greenland	Nunatak	strata-bound	Palaeoproterozoic	Palaeoproterozoic	metasediment raft in granite	uraninite	0.5-1	low	showing
South Greenland	Ilorsuit	fracture	Palaeoproterozoic	Palaeoproterozoic	metasediment	uraninite	1-3	low	prospect
South Greenland	Kvanefjeld	magmatic	Mesoproterozoic	Mesoproterozoic	agpaitic syenite	steenstrupine	0.03-0.08	high	JORC reserve
South Greenland	Sørensen and Zone 3	magmatic	Mesoproterozoic	Mesoproterozoic	agpaitic syenite	steenstrupine	0.03-0.08	high	estimated additional resource
South Greenland	Motzfeldt Sø	magmatic-hydrothermal	Mesoproterozoic	Mesoproterozoic	agpaitic syenite	pyrochlore	0.005-0.05	moderate	Nb-Ta-REE prospect
South Greenland	Central Domain, several localities	fault zone fracture	Mesoproterozoic	Palaeoproterozoic	granite	uraninite	1-2	moderate	One prospect many showings
South Greenland	Tasermit	intrusive	Palaeoproterozoic	Palaeoproterozoic	pegmatite	uraninite	0.5-1	low	showing
East Greenland	Randbøldal	fault zone fracture	Post-Devonian	Devonian	rhyolite	carburan	0.3-0.5	low	showing
East Greenland	Hochwacht	fault zone fracture	Post-Devonian	Devonian	rhyolite	β-uranophane	0.5-1	low	showing
East Greenland	Arkosedal	fault zone fracture	Post-Devonian	Silurian	fluorite vein in granite	uraninite	0.1-0.5	low	showing

Table 1. Significant uranium occurrences in Greenland (Fig. 2). Three types are encountered: large, low-grade magmatic deposits, small syn- to epigenetic pyrochlore mineralisation related to alkaline syenite and carbonatite and small, high-grade (>0.5 % U) epigenetic uraninite mineralisation hosted in fracture zones.

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 exploration over most of South Greenland from 1979 to 1984 comprised helicopter-borne gamma-spectrometry and systematic stream sediment and stream-water geochemistry, and that returned so high uranium concentrations that large parts of South Greenland were defined as a geochemical as well as metallogenetic uranium province.

Uranium occurrences

Uranium exploration in Greenland has identified large low-grade uranium deposits hosted by alkaline igneous complexes as well as a number of high-grade uraninite occurrences hosted in fractures and pegmatites. Known uranium occurrences are all situated in areas outlined as uranium enriched by reconnaissance scale airborne gamma-spectrometric and drainage geochemical surveys (Fig. 2).

Significant uranium occurrences discovered 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 uraninite 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 granodiorite and granite as well as large volumes of supracrustal rocks of sedimentary and volcanic origin that are moderately to strongly folded, thrustured and partially melted. The Ilua plutonic suite (1755–1730 Ma) represents the last intrusive event in the orogeny.

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

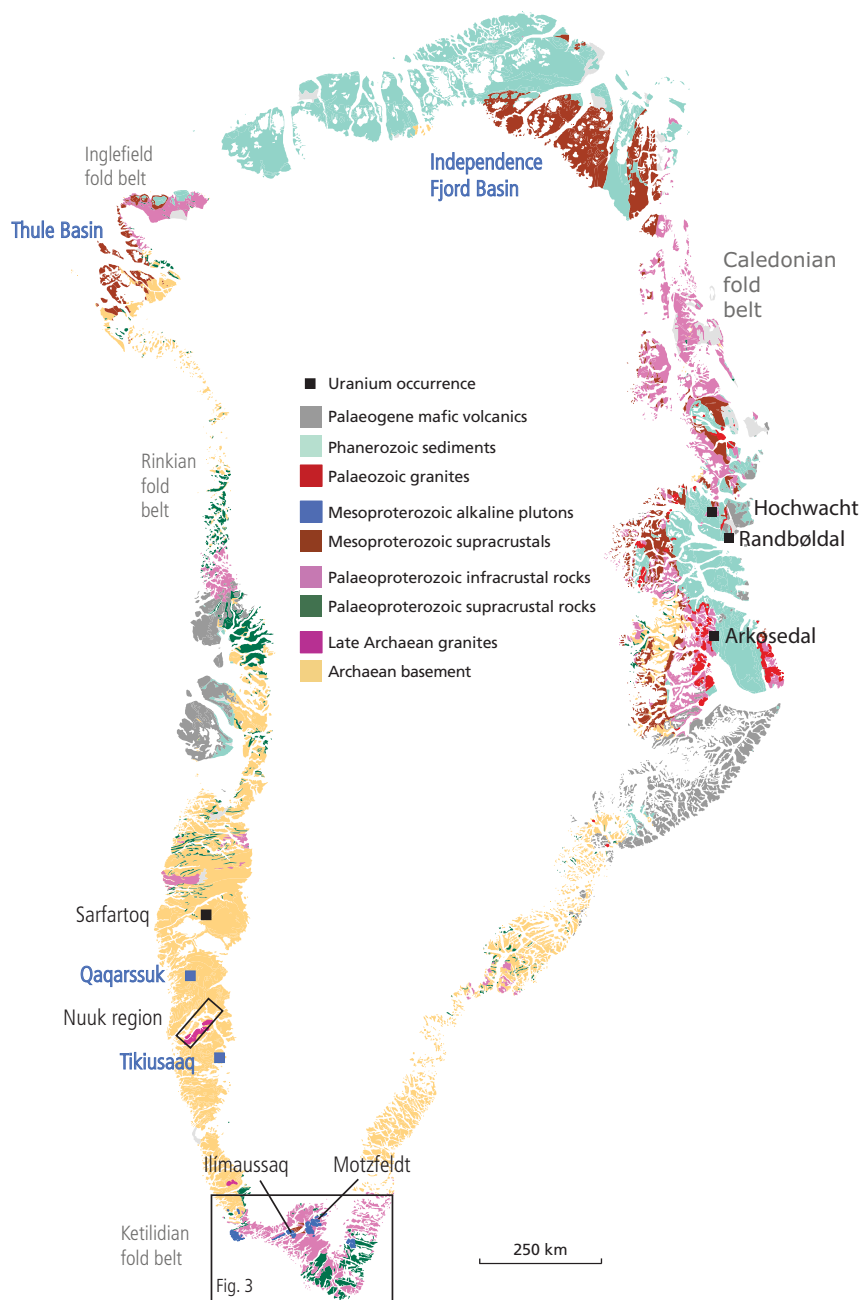


Figure 2. Main lithostratigraphic units in Greenland with location of known uranium occurrences (see Table 1). Black squares for localities with uranium concentrations above 0.5 % in rock samples. Blue text for lithological units with uranium potential. See Fig. 3 for details on South Greenland. Source: Steinfelt (2014).

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 Ilua 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 reflects 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 Tasermit (Table 1, Fig. 4).

Mesoproterozoic fault-zone related uranium mineralisation

Large parts of the Julianehåb 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 Julianehåb igneous complex.

Uranium vein mineralisation occurs in ENE–WSW-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 chalcocopyrite, whereas

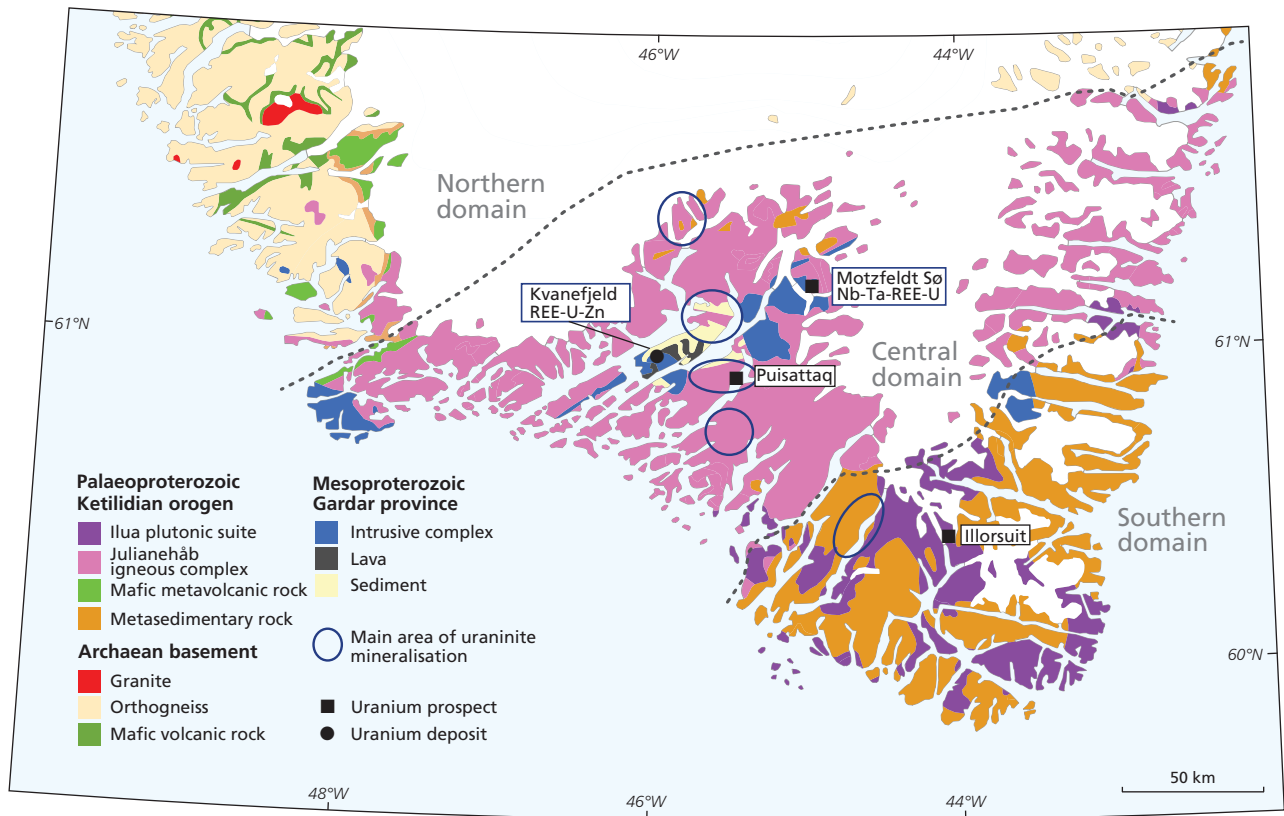


Figure 3. Main lithostratigraphic units within South Greenland together with known uranium occurrences. Uranium mineralisations are documented by rock samples (see Fig. 4); prospects have been investigated in detail. From the workshop presentation by A. Steenfelt.

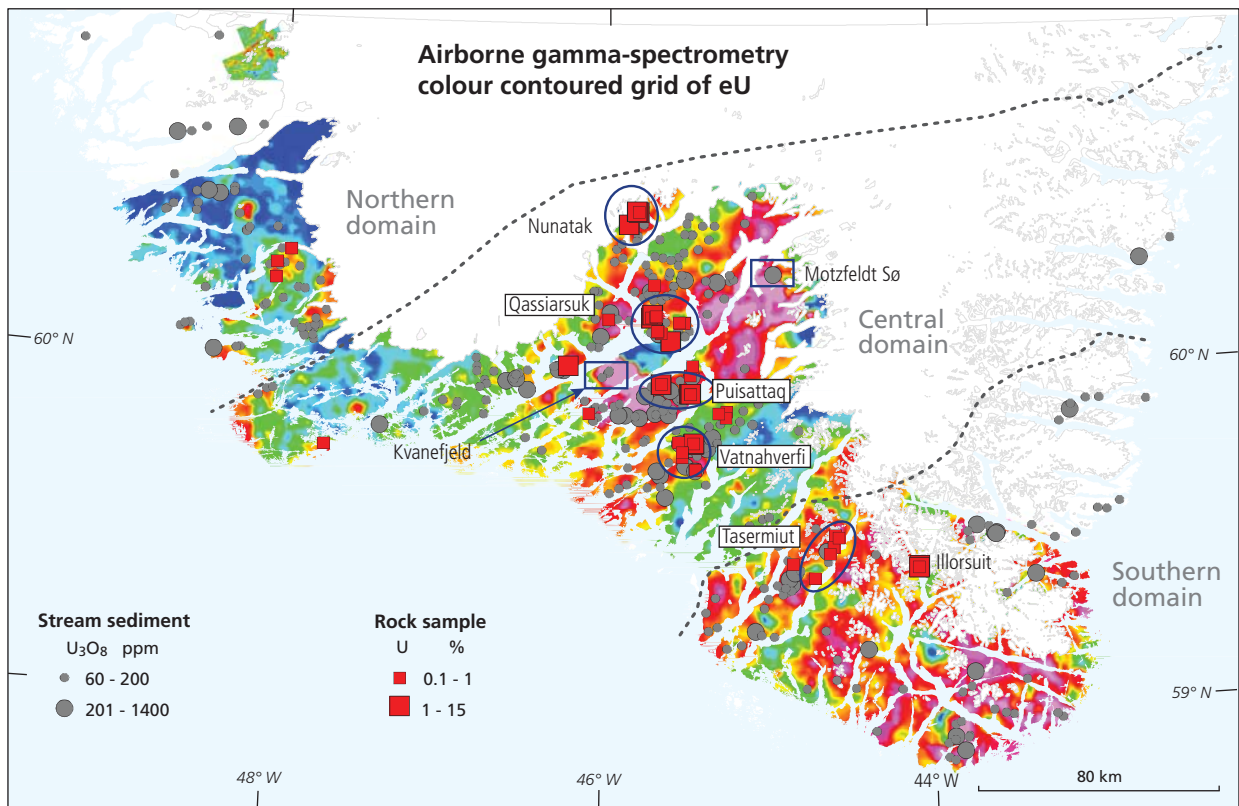


Figure 4. Summary of results of uranium exploration 1979–1984 in South Greenland. Elevated to high uranium contents of stream sediment and rock samples displayed on top of gridded data for equivalent uranium (eU) recorded during helicopter-borne gamma-spectrometry. From the workshop presentation by A. Steenfelt.

gangue minerals commonly include calcite, quartz and fluorite. Isotopic data indicate an age of about 1180 Ma for pitchblende. The most studied occurrences, Qassiarsuk, Puisattaq 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, naujaite, kakortokite and aegirine lujavrite. The last phase, arfvedsonite lujavrite with agpaite to hyper-agpaite composition, features very high concentrations of Li, Be, F, Zn, Y, Zr, Hf, Nb, Ta, REE, Th, and U and is the basis for the Kvanefjeld 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

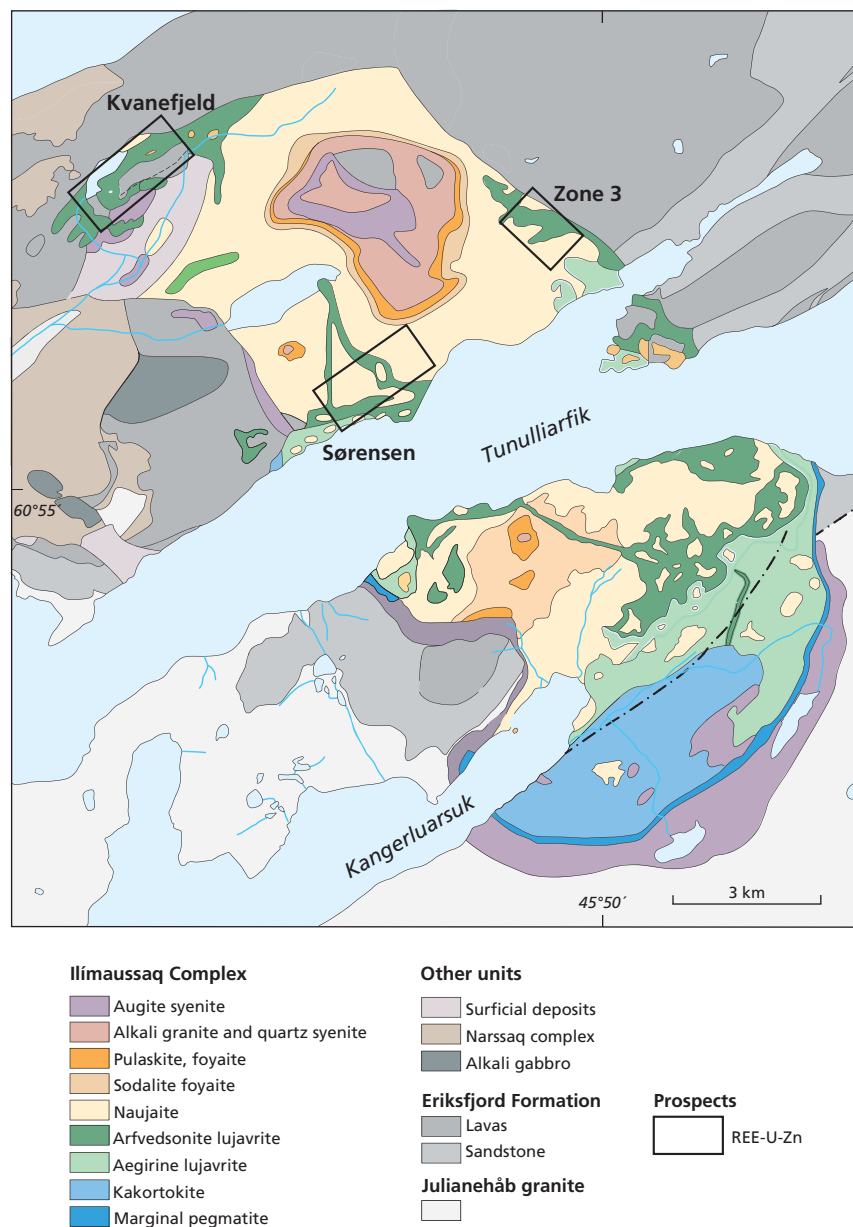


Figure 5. Geological map of the Mesoproterozoic Ilímaussaq intrusive complex with location of prospective areas of REE-U-Zn-F mineralisation assessed by Greenland Minerals and Energy Ltd. Modified from Steinfeld *et al.* (2016).

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

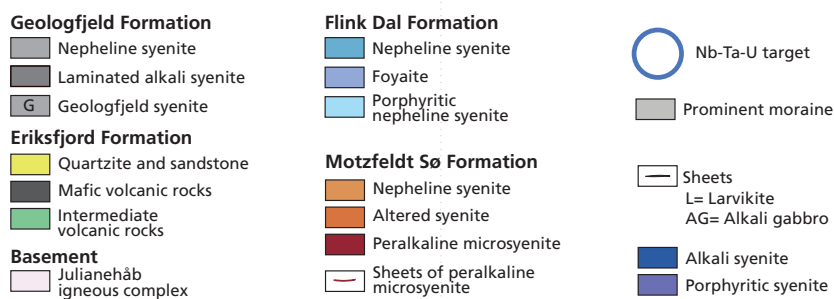
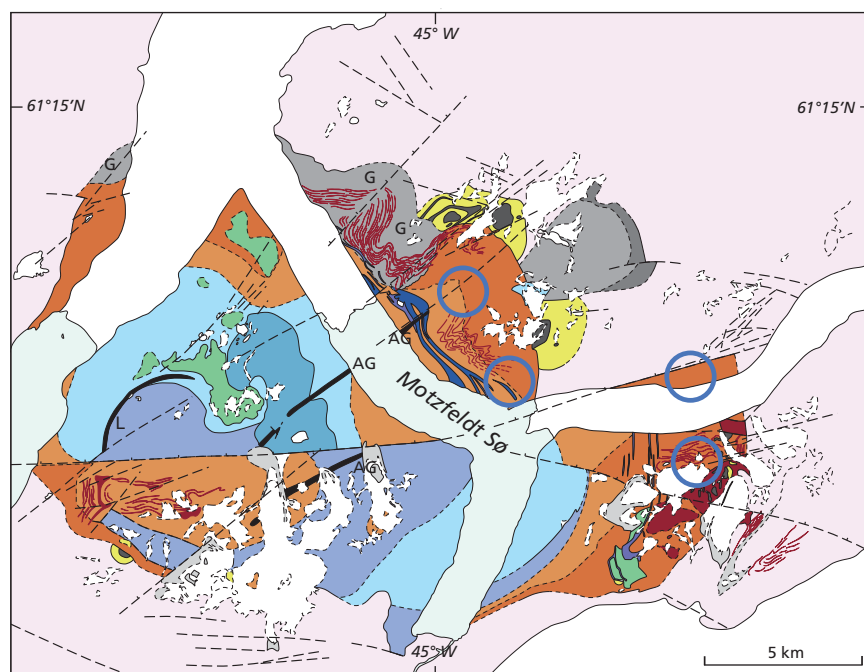


Figure 6. Geological map of the Motzfeldt Complex with the location of investigated pyrochlore mineralisation. Based on Thomassen (1989) and Steenfelt et al. (2016).

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 Julianeåb granitoids and the unconformably overlying Mesoproterozoic Eriksfjord 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 % UO_2 . The microsyenite contains 100–500 ppm uranium.

West Greenland Archaean pegmatites and shear zones in the Nuuk region.

An aeroradiometric survey in 1976 outlined the Nuuk region (Fig. 2) as an area with many anomalies and general eleva-

ted background for uranium (and thorium). Stream-sediment and stream-water geochemistry confirmed uranium enrichment, and ground investigations identified many localities with U-bearing minerals like allanite and euxenite hosted by Neoproterozoic pegmatites. Uraninite was identified in some of the pegmatite occurrences and was also located in adjacent amphibolite. The uranium occurrences in the Nuuk region are situated within a zone of repeated shearing and hydrothermal alteration including gold mineralisation. It is likely that the uranium mineralisation is at least partly hydrothermal.

Carbonatite complexes

The Neoproterozoic Sarfartoq carbonatite has uraniferous pyrochlore mineralisation in three settings: 1) pyrochlore occurs in the outer core in 0.5–1 m wide rauhaugite sheets (average 15 ppm, up to 400 ppm U), 2) disseminated pyrochlore occurs in late before site dykes (20–40 cm wide, 30 m long, average 10 ppm, up to 140 ppm U) within the marginal zone of the complex and 3) pyrochlore veining and brecciation occur in shear zones. One location with 1–5 m wide monomineralic veins has up to 1 % U.

Two Jurassic carbonatite complexes, the Qaqarssuk and Tikiusaaq complexes, also have local enrichments in uraniferous minerals, but no high concentrations or large amounts of uranium have been encountered so far.

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 Arkosedal, 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 com-

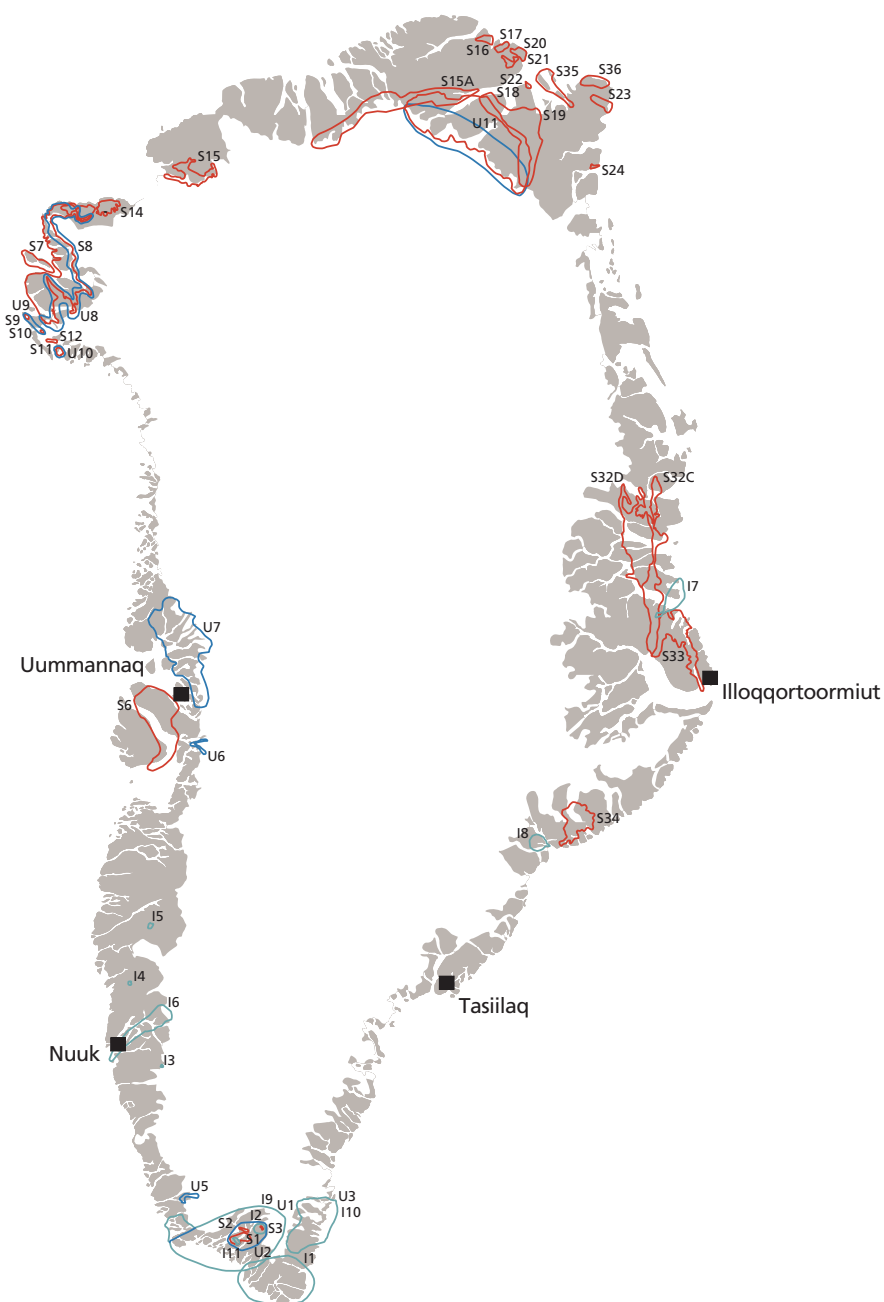


Figure 7. Tracts assessed for undiscovered intrusive, sandstone and unconformity-type uranium deposits during the GEUS–MMR workshop, November 2016.

positions, 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. Rössing and Husab, Namibia) and 2) intrusive plutonic deposits related to magmatic differentiation and subdivided into three classes: quartz monzonite, peralkaline 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-magnesian 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 worlds uranium

Tract No.	Tract name	Tract Area (km ²)	Consensus bids on number of undiscovered uranium deposits at different confidence levels					Number of unknown deposits	Deposit density
			N90	N50	N10	N05	N01		
Unconformity related deposits									
U1	Larger Eriksfjord Basin W	7,550	0	1	3	5	7	1.51	0.000200
U2	Central Eriksfjord Basin	1,265	1	3	5	7	10	3.17	0.002508
U3	Eriksfjord Basin E	1,274	0	0	1	2	4	0.44	0.000341
U5	Midternæs	271	0	0	0	1	2	0.11	0.000387
U6	Anap Nuna	106	0	0	0	1	2	0.11	0.000991
U7	Karrat Group	5,584	0	0	2	3	4	0.71	0.000126
U8-U10	Thule Basin	4,372	0	2	3	5	8	1.94	0.000444
U11	Independence Fjord	7,470	0	1	2	4	6	1.21	0.000162
Sandstone deposits									
S1-3	Eriksfjord Basin	167	0	0	0	1	2	0.11	0.000629
S6	Nuussuaq Basin	289	0	0	1	2	4	0.44	0.001505
S7-12	Thule Basin	2,398	0	0	0	1	4	0.17	0.000069
S13-15	Franklinian shelf	2,574	0	0	0	2	3	0.18	0.000070
S16-18	Independence Fjord Group	7,987	0	0	0	0	1	0.03	0.000004
S19	Hagen Group	1,790	0	0	0	1	3	0.14	0.000075
S20	Dunken & Parish Bj. Fm	505	0	0	0	1	1	0.08	0.000149
S21	Ladegårdsåen Fm	131	0	0	0	1	2	0.11	0.000802
S22	Kap Rigsdagen	29	0	0	0	0	1	0.03	0.001034
S23	Kilen	117	0	0	0	1	2	0.11	0.000897
S24	Sortebakker Fm	39	0	0	1	1	2	0.33	0.008462
S32D	Dev. East Greenland Basin	3,225	0	0	2	2	3	0.63	0.000195
S32C	Carb. East Greenland Basin	1,620	0	0	2	3	5	0.74	0.000454
S33	Jameson Land	2,838	0	0	0	1	2	0.11	0.000037
S34	Kangerdlugssuaq Group	486	0	0	0	1	2	0.11	0.000216
S35	Princess Islands	534	0	0	0	1	2	0.11	0.000197
Intrusive deposits									
I1	Southern domain, SG	5,401	0	2	3	4	6	1.84	0.000340
I2	Motzfeldt	282	1	2	3	4	5	2.04	0.007227
I3	Tikusaaq	50	0	0	0	0	2	0.06	0.001200
I4	Qaqarssuk	10	0	0	0	1	3	0.14	0.013500
I5	Sarfartoq	200	0	0	1	2	3	0.41	0.002025
I6	Nuuk region	1,482	0	0	1	3	4	0.48	0.000324
I7	Werner bj., Kap Simpson & Kap Parry	712	0	0	0	1	2	0.11	0.000147
I8	Kangerlussuaq intrusion	182	0	0	0	0	1	0.03	0.000165
I9	Central Domain SVG	8,815	0	2	2	4	5	1.58	0.000179
I10	Central Domain SEG	1,274	0	0	2	3	4	0.71	0.000553
I11	Ilmaussaq	78	2	3	4	5	7	3.00	0.076936

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

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.

production. The largest producer is Kazakhstan, which has numerous sandstone deposits (e.g. Kanzhugan, Moinkum, Budenovskoye) all mined 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 hematized and clay altered, possibly the result of palaeoweathering 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), supplying c. 20 % of the global uranium market.

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 I1).

Western Central Domain, SVG I9

The Central Domain of the Palaeoproterozoic Ketilidian 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 I11 and Motzfeldt I2

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 I1

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.

None of the tracts considered as possible hosts for **sandstone-type deposits** attained high ranks at the workshop and the potential for such kind of uranium deposits seems very low in Greenland.

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 (U8-10) 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 ENE–WSW-trending central zone of the Central Domain, where the formation rests unconformably on the Julianehåb igneous 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 basalts, hawaiites, and carbonatitic 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

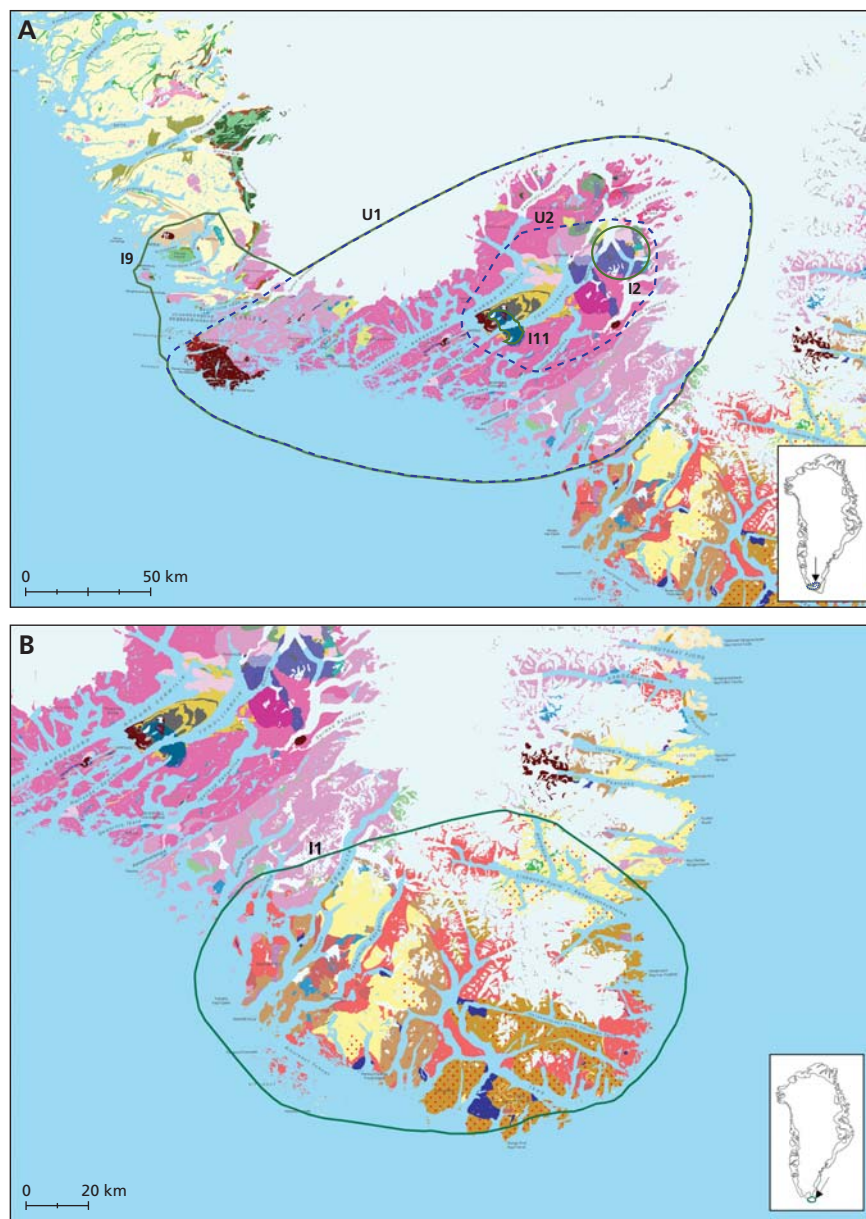


Figure 8A. Tract map of the Western Central Domain in South Greenland, for highly ranked tracts of both intrusive-type deposits (Tracts I2, I9 and I11) and unconformity-type deposits (U1, U2).
Figure 8B. Tract map of the Southern Domain in South Greenland (Tract I1).

zircon population from the lower sandstone units at Qassarsuk is dominated by Archaean and Palaeoproterozoic ages similar to those recorded in the Northern Domain with a minor contribution of ages related 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.

Thule Basin U8-U10

The Thule Supergroup (Fig. 2) 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



Figure 9. Eriksfjord sandstone with signs of reducing conditions.

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 unrecognised intrusive-type uranium occurrences. Favourable geological settings for unconformity-related uranium mineralisation are identified, suggesting a potential for such deposits.

References

- Bruneton, P., Cuney, M., Dahlkamp, F. & Zaluski, G. 2014:** IAEA geological classification of uranium deposits. In: International Symposium on "Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental issues", URAM 2014, IAEA-CN- 216, 12–13.
- Dawes, P.R. 2006:** Explanatory notes to the Geological map of Greenland, 1:500 000, Thule, Sheet 5. Geological Survey of Denmark and Greenland Map Series 2, 97 pp. + map.
- Keulen, N., Thrane, K., Stensgaard B.M. & Kalvig, P. 2014:** An evaluation of the potential for uranium deposits in Greenland. Center for minerals and materials report, 2014/1.

OECD/NEA-IAEA, Uranium 2014: Resources, production and demand (Red Book). A joint report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency. OECD Paris.

Steenfelt, A. 2014: Uranium data for Greenland registered by GEUS: data acquisition, coverage and spatial uranium variation. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2014/28, 51 pp.

Steenfelt, A., Kolb, J. & Thrane, K. 2016: Metallogeny of South Greenland: a review of geological evolution, mineral occurrences and geochemical exploration data. *Ore Geology Reviews* 77, 194–245.

Thrane, K., Keulen, N. & Kalvig, P.: Uranium potential in Greenland. Reporting on the 8th Greenland Mineral Resource Assessment Workshop. Danmarks og Grønlands Geologiske Undersøgelse Rapport.

Sørensen, H., Bailey, J.C. & Rose-Hansen, J. 2011: The emplacement and crystallization of the U–Th–REE-rich agpaitic and hyperagpaitic lujavrites at Kvanefjeld, Ilímaussaḡ alkaline complex, South Greenland. *Bulletin of the Geological Society of Denmark* 59, 69–92.

Thomassen, B. 1989: Evaluation of the niobium-tantalum potential of the Motzfeldt Centre, South Greenland. *Rapport Grønlands Geologiske Undersøgelse* 145, 66–73.



The Ministry of Mineral Resources (MMR)
Government of Greenland
Postbox 930
Imaneq 1A, 201
3900 Nuuk
Greenland

Tel: (+299) 34 68 00
Fax: (+299) 32 43 02
E-mail: mmr@nanoq.gl
Internet: www.govmin.gl
www.naalakkersuisut.gl
www.greenmin.gl



GEUS

Geological Survey of Denmark
and Greenland (GEUS)
Øster Voldgade 10
DK-1350 Copenhagen K
Denmark

Tel: (+45) 38 14 20 00
E-mail: geus@geus.dk
Internet: www.geus.dk

Front cover photograph

Geologists studying the Kvanefjeld deposit of the Ilímaussaḡ peralkaline intrusion, South Greenland.

Authors

Kristine Thrane & Agnete Steenfelt,
GEUS

Editor

Kristine Thrane, GEUS

Graphic Production

Annabeth Andersen, GEUS

Printed

January 2018 © GEUS

Printers

Rosendahls A/S

ISSN

1602-818x (print)
2246-3372 (online)