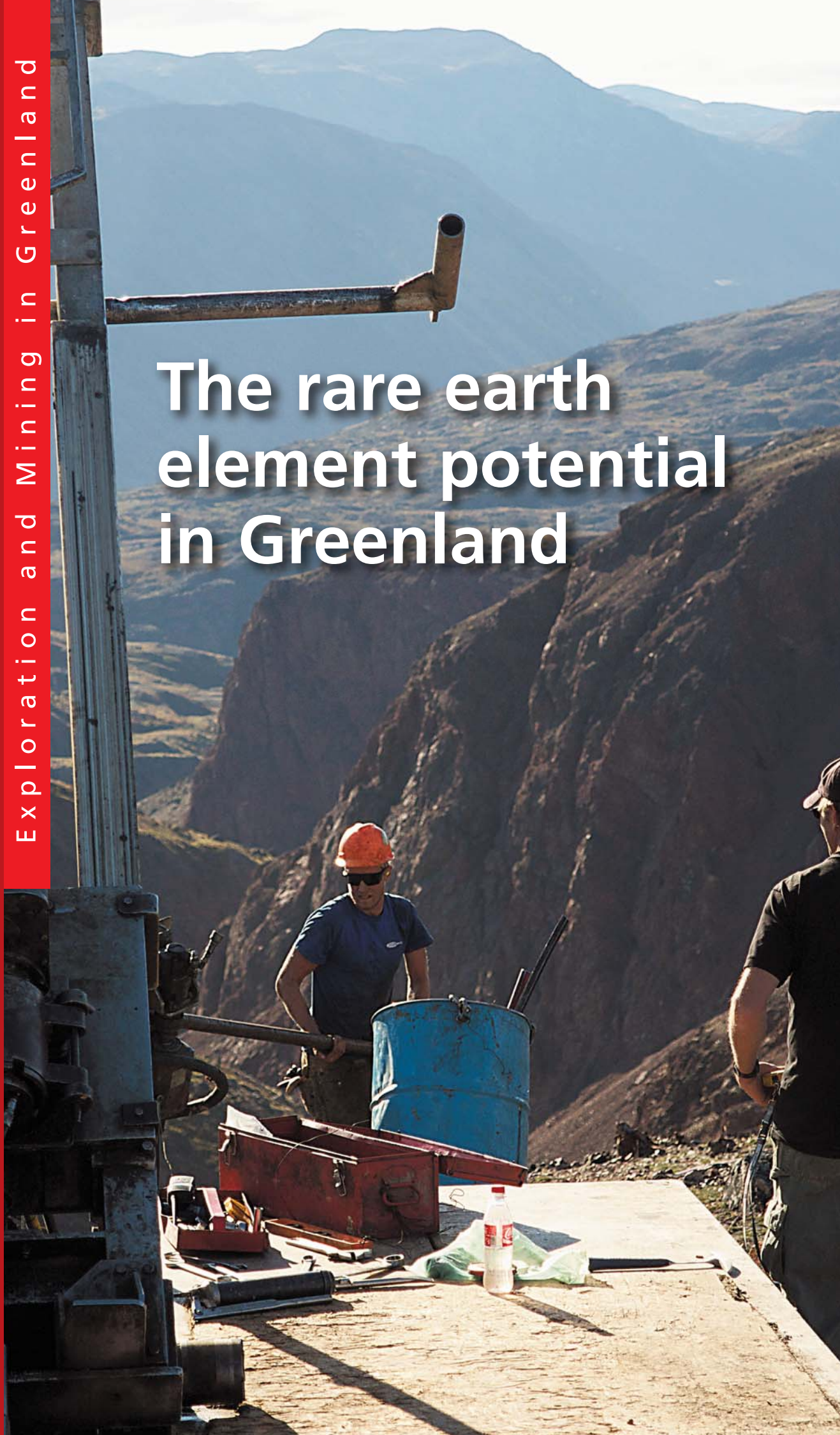
GEOLOGY AND ORE

Exploration and Mining in Greenland

The rare earth element potential in Greenland



The rare earth element potential in Greenland

Supply of rare earth elements (REE) is complex. REE deposits are geographically unevenly distributed and the content of individual REEs varies from deposit to deposit; some deposits only containing a few of the REEs in demand. Greenland is endowed with several large REE deposits, related to various geological settings. Several projects have reached advanced stages of exploration. Additionally, Greenland also holds geological terrains favourable for hosting undiscovered REE deposits, as concluded in a 2010 REE workshop.

Introduction

Demand for REE is growing rapidly due to innovation in the so-called 'green technologies', electronic devices, systems and petroleum refining catalysts. The global requirement for REEs in 2015 is estimated at approximately 150,000 t, equivalent to a 40,000 t growth over the decade; a substantial illegal production is not included (Machacek & Kalvig, 2016). In response to this rising global demand, Greenland has experienced a strong international interest over the past decade in search of new REE deposits. The fact that Greenland is endowed with geological environments favourable to hosting REE accumulation makes Greenland attractive to the REE exploration industry.

On this background the Geological Survey of Denmark and Greenland (GEUS) and the Ministry of Mineral Resources, (MMR), conducted a REE potential workshop in 2010 to provide the REE mineral exploration sector with the scientific background and necessary data to make qualified decisions. This magazine highlights some of the results from this workshop and updated information about REE potential in Greenland.

Since 2007, exploration campaigns targeting REE have been conducted in Greenland, part of a global trend of about 200 exploration projects. Given that the volume of the REE-market is limited and the economic drivers are related to Nd, Dy, Pr, and Sm, a large number of exploration projects, dominated by LREE, have been put on hold. This is the case as well in Greenland, and the active projects are the large tonnage, low grade deposits related to the alkaline intrusions in South Greenland.

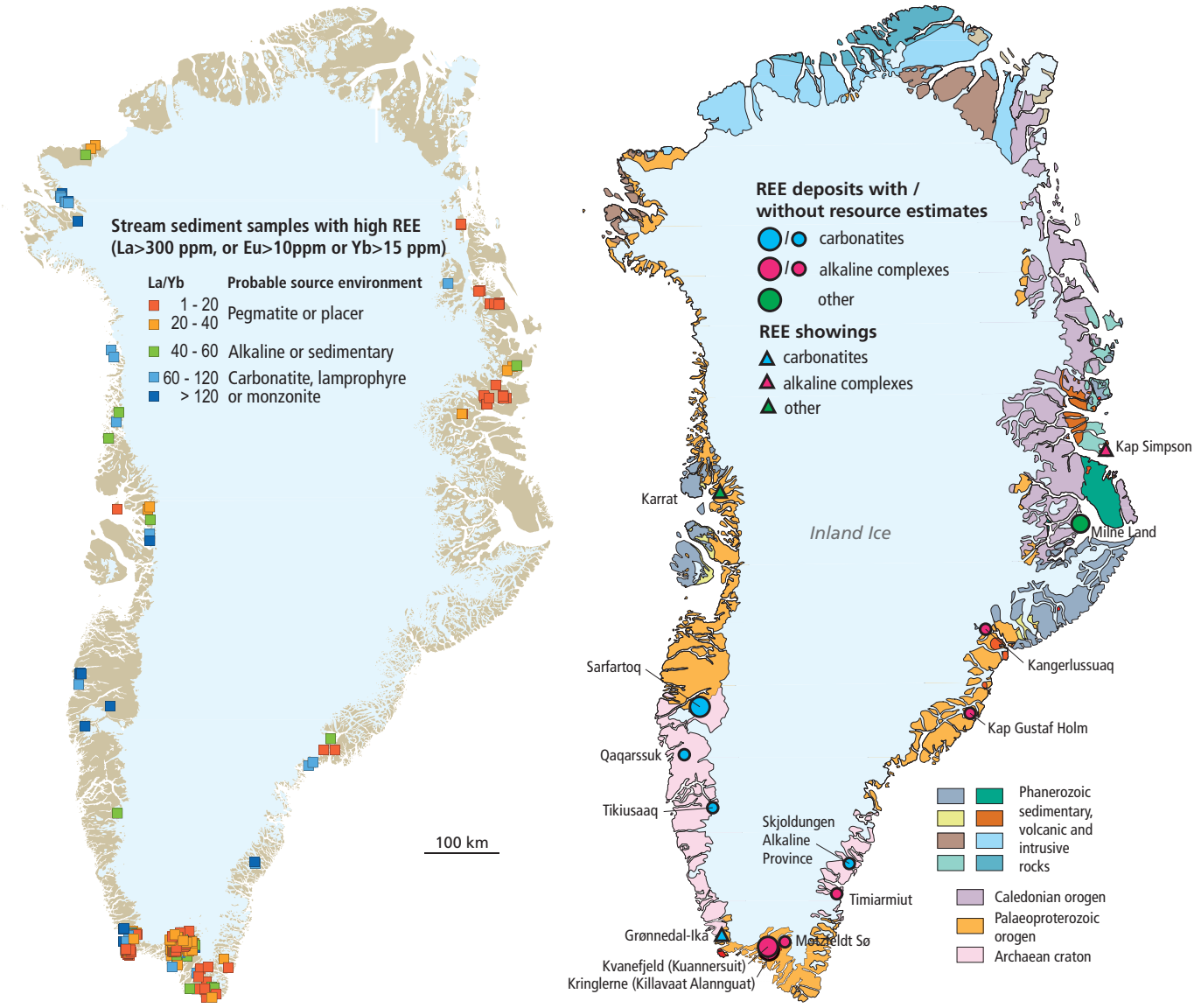
Highlights from the REE potential assessment workshop

A total of thirty-five areas were assessed by an expert panel during the REE workshop.

Information compiled on known REE deposits and geological provinces in Greenland, as well as compilations of geochemical stream sediment data were treated in conjunction with models for REE deposits in order to assess the potential for REE deposits in Greenland.

An overview of the REE distribution based on geochemical information from available stream sediment data is demonstrated by the compilation map of stream sediments (see figure in page 3).

View of the Kringlerne (Killavaat Alannguat) multi-element deposit with the characteristic mountain Redekammen in the background. Photo: Ministry of Mineral Resources.



Left figure: Plot of REE-anomalous stream sediment samples in Greenland reflecting the presence of known and unknown REE mineralisation or very REE-enriched rocks. Symbol colour scale illustrates the variation in La/Yb ratio of the anomalies. Since fractionation among light and heavy REE shows considerable and characteristic variation among diverse REE-rich lithologies, and since these characteristics are reflected in the stream sediments, the La/Yb ratio can be used to indicate the probable source lithology of a stream sediment anomaly. Right figure: Simplified geological map with selected known REE deposits and showings.

The REE workshop assessed the following REE-prone geological environments:

- **Carbonatite magmatism**
  REE accumulations are observed associated with carbonatite complexes. In Greenland the accumulation is often related to late hydrothermal activity, where pathways in shear zones and joints play an important role.

- **Alkaline intrusions**
  REE accumulations are typical during igneous processes in layered intrusions of strongly differentiated magmas with or without hydrothermal overprints.

- **Pegmatite settings**
  In simple pegmatites related to granites, the minerals allanite and monazite are commonly enriched in light REEs, whereas a whole range of uncommon REE minerals occurs in alkaline pegmatites.

- **IOCG mineralising systems**
  REE accumulations are typical in mineralising systems with low Ti - contents and where there are extensive Na and K - alterations, combined with increased contents of Co, Ag, U, Cu and P in coeval magmatism.

- **Paleoplacer environments**
  Placer deposits are a result of secondary accumulation of heavy minerals, often REE bearing minerals like monazite and xenotime.

The individual alkaline intrusion and carbonatite magmatism tracts assessed during the workshop are shown on page 7.

The potential areas outlined in the southern, eastern and southwestern part of Greenland are due to the presence of the Gardar intrusives, carbonatites and alkaline intrusions. In North Greenland, however, only a few areas were defined, due to the extensive carbonate platform

Tract name	Location	Deposit model	Geological settings	Resource estimates and grade*	Score
A1	Kvanefjeld (all deposits, incl. Sørensen, Zone 3)	Alkaline	Known deposit. High level of information. Extensive drilling has been conducted on the deposit. Contains uranium above background level.	1,010 Mt @ 1.1% TREO (including 0.0399% THREO), 0.0266% U_3O_8, 0.2397% Zn	50
A2	Kringlerne	Alkaline	Known deposit. High level of information. Extensive drilling has been conducted on the deposit. Low uranium content below or equal to background level.	4,700 Mt @ 1.8% ZrO_2, 0.2% Nb_2O_5, 0.2% Ta_2O_5 0.5% LREO, 0.15% HREO.	50
C3.1	Sarfartoq	Carbonatite	Known carbonatite showing. Kimberlites & terraine boundary in the area = active pathways.	14 Mt @ 1.53% TREO.	41
O3	Karrat	Other	The REE prospect has been drilled, which classifies it as an undiscovered deposit. Lamprophyric dykes are found in the area = active pathways. The deposition model is not yet fully understood – more work required.	26 Mt @ 1.36% TREO + Y.	35
C3.2	Qaqertaasaq	Carbonatite	Known carbonatite. Lamprophyres are found in the area = active pathways.	Unknown.	32
A3	Motzfeldt Sø	Alkaline	Known REE prospect. Micro syenites (which host the REEs) not much investigated. Limited drilling – only Ta, Nb and U targets drilled. More work is needed to evaluate the REE potential.	Historical data, non compliant: 600 Mt @120 ppm Ta + 130 Mt @ 0.4 - 1.0% Nb_2O_5.	31
A3.1	Qassiarsuk	Alkaline	Dyke with aegirine as prime mineral. The dyke is up to 4 m thick and can be followed for several kilometres. High Th content.	Unknown. Showings of REE known - up to 1%.	22
C4	Tikiusaaq	Carbonatite	Known carbonatite. Lamprophyres and possible terraine boundary in the area = active pathways.	Unknown.	21
A11.1	Kap Simpson	Alkaline	Alkali syenite complex. Malmbjerg type alteration (high temp) seen via hyperspectral mapping. Several sources of mineralised rocks sampled from glaciers.	Unknown. Rock samples enriched in REEs (3%) & Nb (3.2%).	19
C8.1	Overall tract around the Grønnedal-Ika carbonatite.	Carbonatite	Known carbonatite. Lamprophyres and aillikites are found in the area. Greisen alteration at Ivittuut. Radioactive dykes (Ce-enriched) are present in the area – radiating from the Grønnedal-Ika carbonatite.	Unknown.	19

Table 1. List of the 9 alkaline intrusions and carbonatite magmatism REE occurrences with the highest scores from the workshop assessment. Maximum score is 50.Tract name refers to the areas shown on maps on page 7.
** Deposit size and grade numbers are based on company announcements and available online data as of December 2017. For specific and updated information please refer to the company websites of the individual deposits.*

and sedimentary basins hiding possible REE deposits.

A list of the ten REE occurrences with the highest assessment score from the workshop assessment is given in Table 1.

Known REE deposits

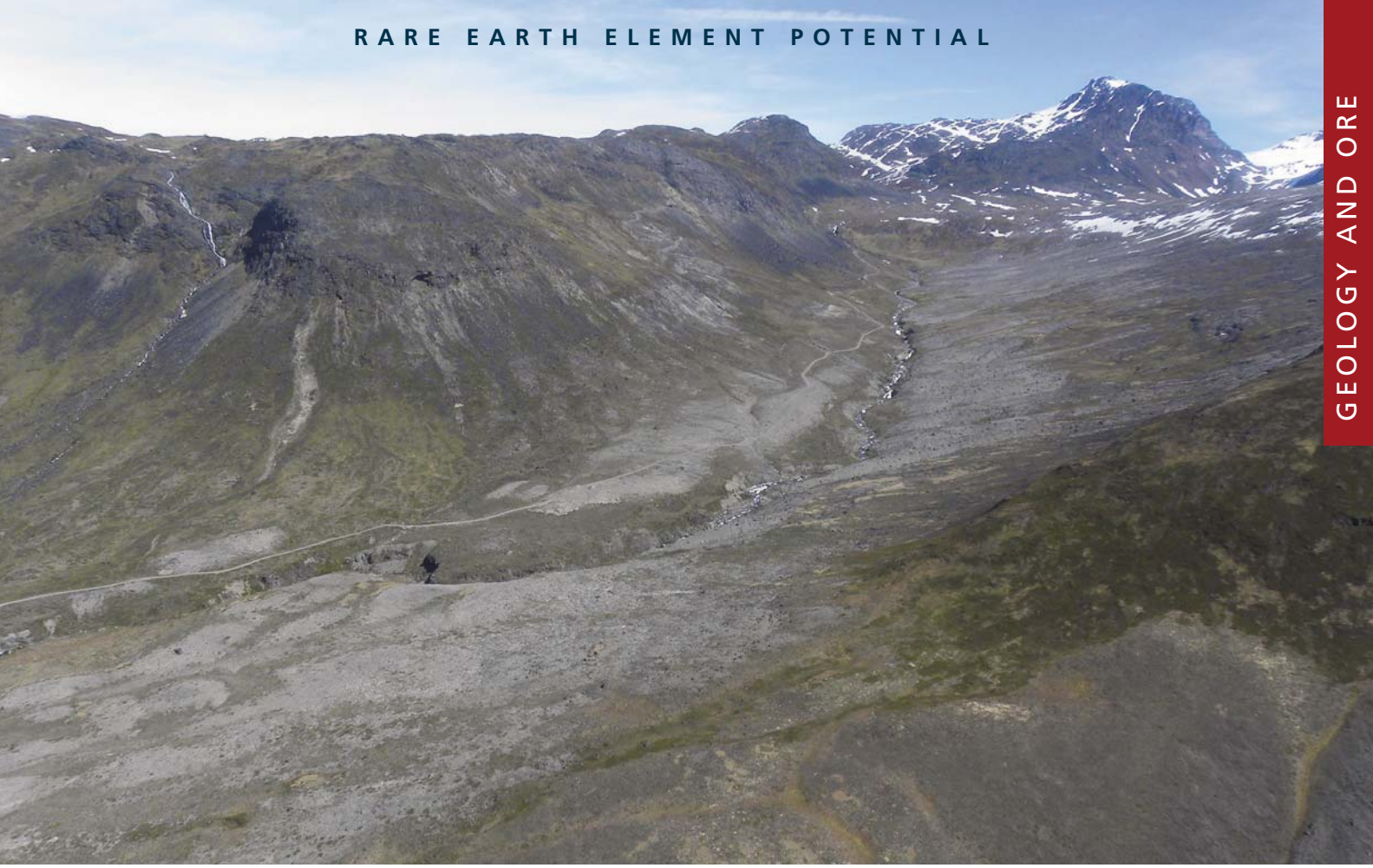
Eight REE deposits have been discovered to date in Greenland, of which two may well be amongst the ten largest REE deposits in the world. The geological settings for these REE deposits vary, and the ages cover a wide span. A brief introduction to these known deposits follows.

The Gardar Province hosts three large REE deposits: Kvanefjeld (Kuannersuit), Kringlerne (Killavaat Alannguat) and Motzfeldt Sø

The Mesoproterozoic Gardar Province in South Greenland is a cratonic rift province consisting of sandstones, and a variety of volcanic and plutonic igneous rocks. The plutonic rocks are alkaline to peralkaline, and are hosted within the Ilímaussaq Intrusion (1160 Ma). The Ilímaussaq intrusion is largely emplaced by block subsidence and formed by three pulses, of which the third formed a layered series of nepheline syenites. The Ilímaussaq Intrusion is generally enriched in the elements U, Th, Nb, Ta, Be, Zr, Li, F, Zn and REE, and hosts two REE deposits, Kringlerne (dominated by the kakortokite bottom cumulates) and Kvanefjeld (Kuannersuit) (dominated by lujavrites). The Gardar Province also includes the Igaliko Nepheline Syenite Complex, hosting the Motzfeldt Sø REE deposit.

Kvanefjeld (Kuannersuit)

The Kvanefjeld (Kuannersuit) multi-element deposits, located a few kilometers north of Narsaq, South Greenland, are an accumulation of various igneous rocks and supracrustals from the roof of the Ilímaussaq



View of the Narsaq Valley, Kvanefjeld (Kuannersuit) and gravel road to the former test mine. Photo: Greenland Minerals and Energy A/S.

Intrusion. Additionally, rocks from the early phases of the alkaline intrusion are also included, forming blocks and sheets within the later agpaitic magma. The bulk of the REE (as well as U and Th) is associated with the lujavrite rocks hosting disseminated steenstrupine, which is the primary mineral host of REEs, U and Th. The deposits also contain Zn, occurring mainly as disseminated sphalerite in the lujavrite, and fluorine hosted in the mineral villiaumite (NaF). The Kvanefjeld (Kuannersuit) deposits have previously been explored for the potential of U and Th.

Greenland Minerals and Energy A/S has reported the following resource estimate figures (Kvanefjeld deposit only, based on 150 ppm U_3O_8 cut-off, June 2016 quarterly report):

- Total JORC resource of 673 Mt, grading 1.09% TREO, 248 ppm U_3O_8; and 0.227% Zn
- Indicated JORC resources of 308 Mt, grading 1.11% TREO, 253 ppm U_3O_8, and 0.290% Zn
- Measured JORC resources of 143 Mt, grading 1.21% TREO, 303 ppm U_3O_8, and 0.237% Zn
- Contained measured metal inventory for the Kvanefjeld (Kuannersuit) deposit of 1.72 Mt TREO, including 0.20 Mt HREO as well as 95.2 M lbs U_3O_8 and 0.34 Mt Zn

The company is presently working through the requirements for the EIA.

Kringlerne (Killavaat Alannguat)

The multi-element deposit at Kringlerne (Killavaat Alannguat) is hosted in the lower cumulates of the layered agpaitic nepheline syenites, referred to as kakortokite, and is situated near the townships of Narsaq and Qaqortoq in South Greenland. The kakortokite cumulates form a total of 29 cyclic, and regular

The characteristic layering of the karkortokite at the Kringlerne (Killavaat Alannguat) multi-element deposit. Note the campsite in the lower left part of the image as scale. Photo: TANBREEZ Mining Greenland A/S.

Drill core logging at the Motzfeldt Sø camp in 2011. Photo: Ram Resources Ltd.

layers, with a total thicknes of about 200 m, made by units composed of black syenite (arfvedsonite-dominated), reddish syenite (eudialyte-dominated) and whitish syenite (feldspar-dominated) rocks. The mineral eudialyte (Greek for 'easily dissolved') is enriched in Ta-Nb-REE-Zr-Y, which is the main exploration target of the licensee, Tanbreez Mining Greenland A/S The kakortokites have been investigated for de-cades, focusing in particular on Zr, Y, Nb, and REE.

The current, non compliant, inferred resource estimate is of more than 4700 Mt of eudialyte ore with an average grade of 1.8% ZrO_2, 0.2% Nb_2O_5, 0.5% LREE and 0.15% HREE.

Motzfeldt Sø

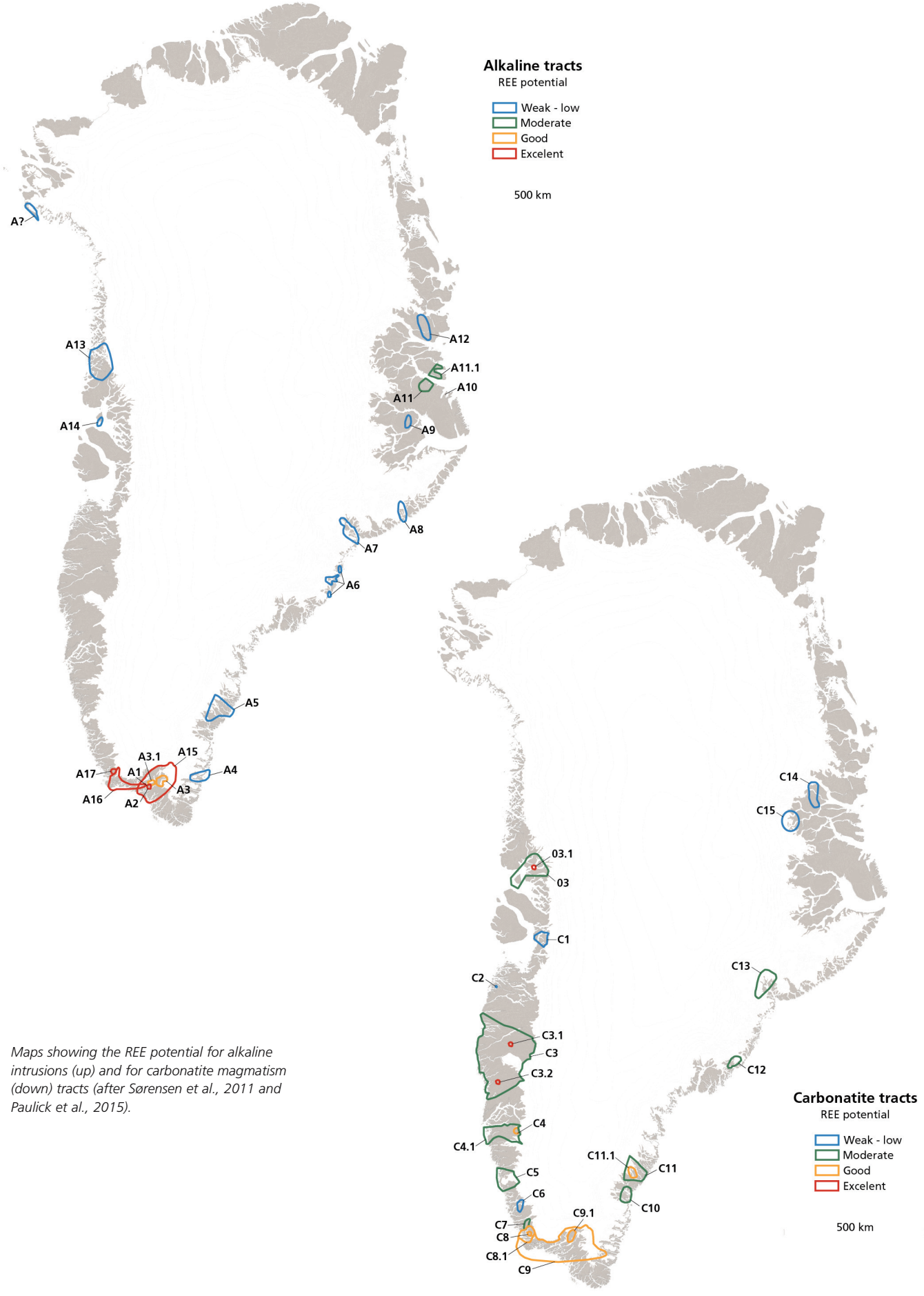
The Motzfeldt Sø REE deposit is part of the Motzfeldt Centre, which in turn is part of the Igaliko Nepheline Syenite Complex. Pyrochlore accumulations in the Motzfeldt Sø syenite show significant grades of Ta. The estimated resource based on investigations carried out by GEUS in the 1980s is 600 Mt grading 120 ppm Ta. High grade zones carry up to 426 ppm Ta. Additionally, a Nb resource of at least 130 Mt grading 0.4-1.0% Nb_20_5 is known. The deposit is regarded as a 'low grade-large tonnage' type of resource.

Regency Mines Plc holds a 555 km^2 license covering the vast majority of the Motzfeldt Nd-Ta-REE-deposit. The license area was investigated by Ram Resources, and most activities were undertaken in the 2010 field season. This work indicates that the known Ta-Nb mineralisation is only weakly correlated with the REE mineralisation. In the central part of the intrusion, where the richest Ta-Nb mineralisation is found, the lithology is predominantly altered syenite, with minor pegmatite and diorite dykes. However, high grade REE intersections are concentrated in the pegmatite intrusives at depth, but are also found scattered throughout the drill holes, gradually decreasing in grade towards the east.

Sarfartoq

The 564 Ma Sarfartoq Carbonatite Complex is well exposed, situated on the transition zone between the Archaean craton and the Palaeoproterozoic Nagssugtoqidian Orogen. The host rocks are granodioritic gneisses.The complex was discovered by the Geological Survey of Greenland (predecessor of GEUS) in 1976 on the basis of a regional airborne radiometric survey and later fieldwork. Subsequently, the complex has been the target of various exploration campaigns focusing on diamonds, P, Nb and REE.

The central core zone of the complex is surrounded by a series of ring-like layers or dykes, containing innumerable intrusive carbonate breccia veins. Substantial fenitisation occurs around the core. Mineralisation of



Maps showing the REE potential for alkaline intrusions (up) and for carbonatite magmatism (down) tracts (after Sørensen et al., 2011 and Paulick et al., 2015).

Nb and REE has been recorded from separate zones in the outer fenitised zone. The REE minerals are correlated with Th and are mainly bastnasite, synchysite and monazite.

In 2010 Hudson Resources reported an NI 43-101 compliant resources estimate result over the ST1 site in the northern part of the complex: 14 Mt inferred resource averaging 1.53% TREO at a cut-off grade of 0.8% TREO. The REE distribution is 45% Ce, 20% La, 25% Nd, 6% Pr, 2% Sm, and approximately 2% Gd, Dy and Y.

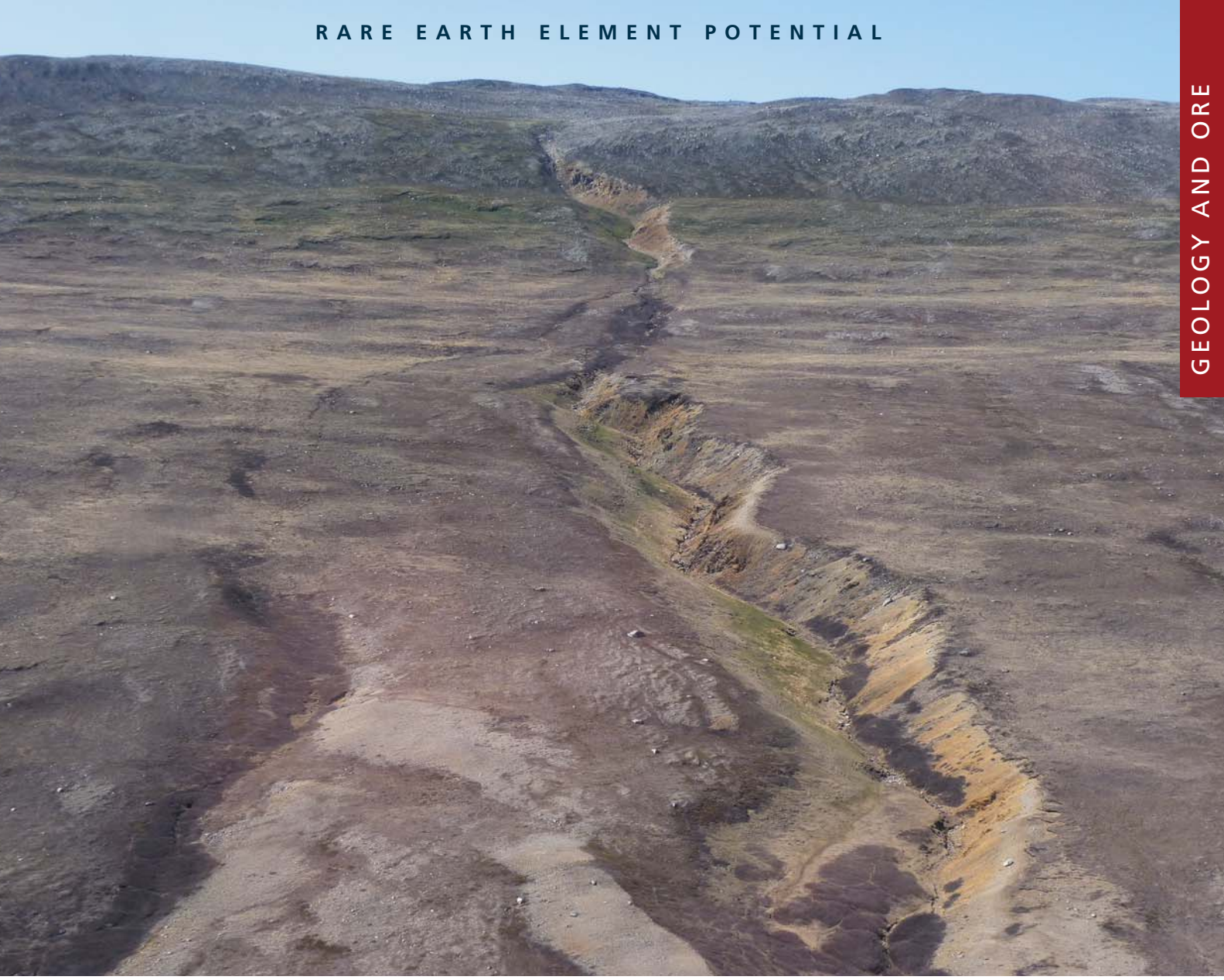
Qaqarssuk

The 165 Ma Qaqarssuk Carbonatite Complex, situated 60 km east of Maniitsoq, West Greenland, intruded the Archaean gneiss complex, along with kimberlite dykes and alkaline intrusions. The composition of the carbonatite varies from sövite to rauhaugite.

In 2010, NunaMinerals A/S carried out REE exploration within the carbonatite. The main potential appears to lie in the

View towards the well-exposed outcrop at the ST1 site, part of the Sarfartoq Carbonatite Complex. The slope is c. 200 m high.

Outcrop of vertical to subvertical, early stage carbonatite sheets of the Qaqarssuk Carbonatite Complex. Photo: NunaMinerals A/S.



Aerial view of the Tikiusaaq carbonatite complex with carbonatite sheets and fenites (yellowish areas) exposed in north walls of the gully. The extent of the gully is c. 1-1.5 km. Photo: NunaMinerals A/S.

core of the complex, concealed in carbonate veins, and NunaMinerals A/S reported the average grade for a 1.5 km^2 area as 2.4% TREO, mainly hosted in ancylite (Sr-REE-carbonate); the mineralisation is LREE dominated with 50% Ce, 27% La, 16% Nd, and 5% Pr. The REE-mineralised veins are generally less than one metre thick.

Tikiusaaq

The Tikiusaaq carbonatite, discovered by GEUS in 2005 by using regional stream sediment data, regional airborne geophysical data and field work, consists of massive dolomite-calcite carbonatite sheets intruded along a ductile shear zone at approximately 158 Ma. The carbonatite is later intruded by carbonate-rich ultramafic silicate dykes. NunaMinerals A/S initiated exploration of the Tikiusaaq carbonatite in 2010, and focussed on the aeromagnetically defined 'carbonatite core'. REEs are typically enriched in the latest phases of carbonatite magmatism, and the main REE mineral is ancylite (Sr-REE carbonate). REE-enriched carbonatite surface samples containing up to 9.6% TREO (predominantly LREE), have been found in an area of anomalous Th counts. The REE concentration is 47% Ce, 33% La, 12% Nd, 4% Pr and 4% other REEs. High phosphate grades (up to 8.5% P_2O_5) were returned from surface samples within the magnetic core of the carbonatite.

Radiometric and magnetic data indicate a separate carbonatite body about 750 m long and 100 m wide, and the extension of the carbonatite dykes continuing to a depth of at least 500 m.

The Niaqornakassak and Umiammakku Nunaa REE deposits

The Niaqornakassak (NIAQ) REE deposit in central West Greenland was discovered by Avannaa Resources Ltd. in 2007. An extension of the deposit was discovered on the Umiammakku Nunaa (UMIA) peninsula, 7 km along strike from the NIAQ site in 2009. The two deposits are jointly named 'Karrat'.

Work conducted by Avannaa Resources Ltd. on the NIAQ and UMIA deposits in 2010 included diamond drilling and collecting 13 mini-bulk samples. The REE accumulation is hosted in an amphibolite unit of the Palaeoproterozoic Karrat Group. The strike length of NIAQ is 1.5 km, but open at both ends. The tabular NIAQ ore body has been found at a maximum elevation of 56 m above sea level

and down to 168 m below sea level; the thickness varies between approximately 10 m and 33 m. The NIAQ bulk samples indicate an average of TREO of 1.36%, of which the average HREO content is approximately 13%. Preliminary non-compliant resource estimates of the NIAQ body are 26 Mt. The REE are mainly hosted by bastnasite, monazite and allanite related to hydrothermal activities within the mineralised sequences. Very limited work has been undertaken on the UMIA body. Based on three drill holes, the TREO of the UMIA deposit is in the range of 0.08 - 0.12%.

Milne Land REE deposit

The Mesozoic Milne Land paleoplacer was discovered by Nordisk Mineselskab A/S, in 1968 in connection with a heavy minerals concentrate sampling programme and an airborne radiometric survey. The placer is in the basal part of the Charcot Bugt Formation, and the most anomalous locality, "Hill 800" in Bays Fjelde, is around 500 m in diameter and 40-50 m thick. The heavy minerals are hosted by a 20 m thick basal sandstone. The potential resources REE,Ti and Th are mainly hosted in monazite.

In 1990, Coffs Harbour Rutile extracted a 15 t selective bulk samples from 5 pits in the "Hill 800" area, and about 10 t were investigated metallurgically. Recoveries from a pilot scale study led to the conclusion that it is feasible to extract commercial products of monazite, zircon and garnet, but not of anatase due to its fine-grained and complex nature. Coffs Harbour Rutile estimated the resource for "Hill 800" at 3.7 Mt with 1.1% zircon, 0.5% monazite, 2.6% anatase, 3.1% garnet and 0.03% xenotime. CGRG currently holds the licence for this placer deposit.

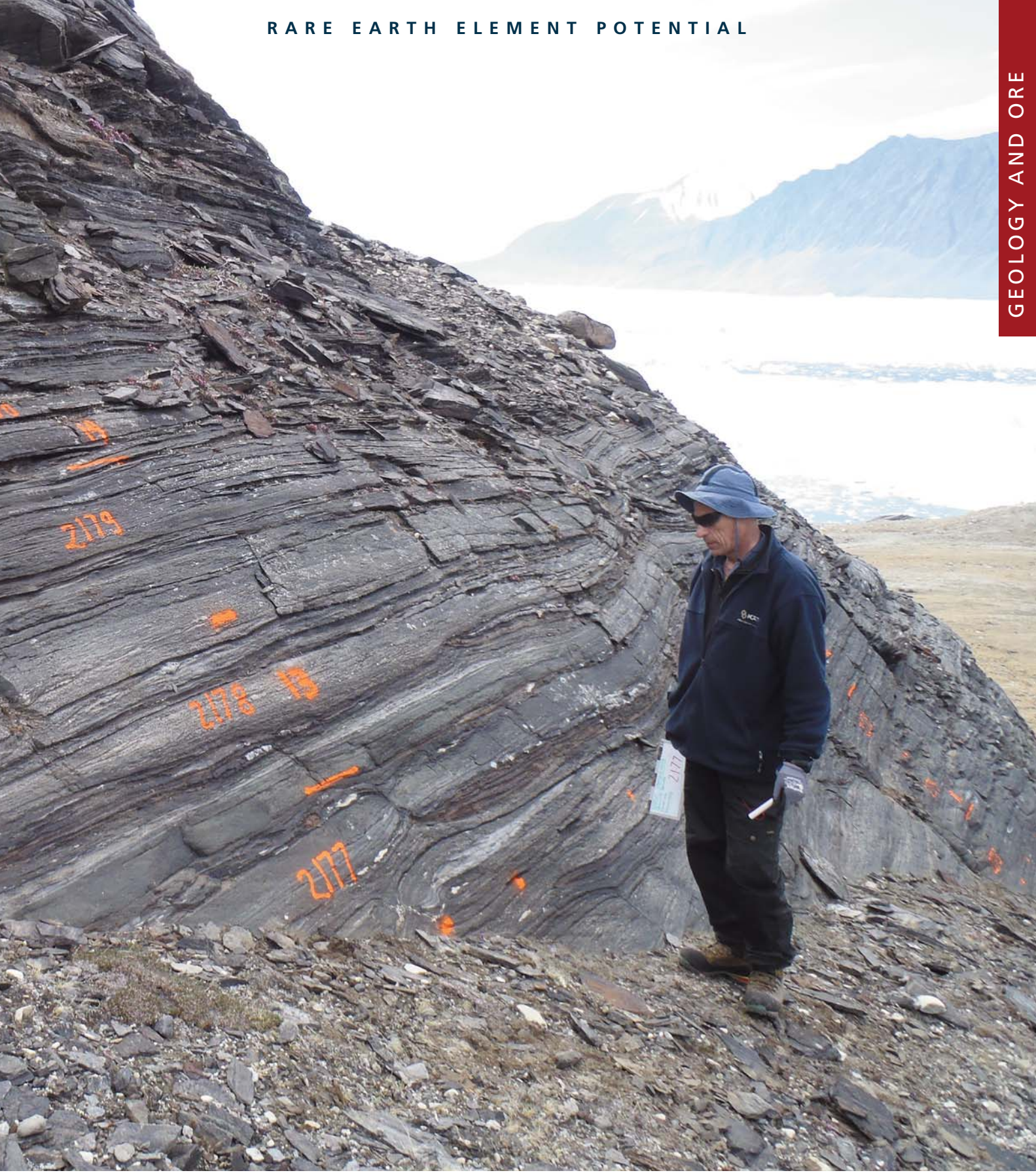
Conclusions

Based on the conclusions of the workshop and some follow up work, South Greenland is believed to have the largest potential for hosting new REE deposits, aside from of the known deposits at Kvanefjeld (Kuannersuit) and Kringlerne (Killavaat Alannguat). More promising areas are found around the Grønnedal-Ika carbonatite.

West Greenland is highly prospective for carbonatite-related REE deposits. Some of the known deposits are Sarfartoq, Qaqarssuk and Tikiusaaq, where the last was only discovered in 2006.

In the more remote and less investigated areas of Greenland, the Kap Simpson alkaline intrusion in central East Greenland and the Skjoldungen Alkaline Province in South East Greenland are believed to have a good potential for hosting new REE deposits.

Several of the known deposits are already covered by exploration licences,



Geological mapping and sampling of the NIAQ REE deposit in 2010.
Photo: Avannaa Resources Ltd.

where extensive exploration and drilling has been carried out to move the projects towards exploitation. Greenland has thus responded to the increased global demand and has a possibility to become a major exporter of REE.

View of the NIAQ and UMIA REE deposits. The distance between the two deposits is 7 km. Photo: Avannaa Resources Ltd.

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Usage of the term rare earth element (REE) in this magazine is restricted to 16 elements including Y, La, and the lanthanides.

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

G E U S

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
Front cover photograph: Hudson Resources Inc. drilling for REEs at its ST19 target which is part of the Sarfartoq carbonatite complex. Photo: Hudson Resources Inc.

Authors
Lars Lund Sørensen,
Per Kalvig & Diogo Rosa, GEUS

Editors
Lars Lund Sørensen &
Karsten Secher, GEUS

Graphic Production
Carsten E. Thuesen and
Annabeth Andersen, GEUS

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