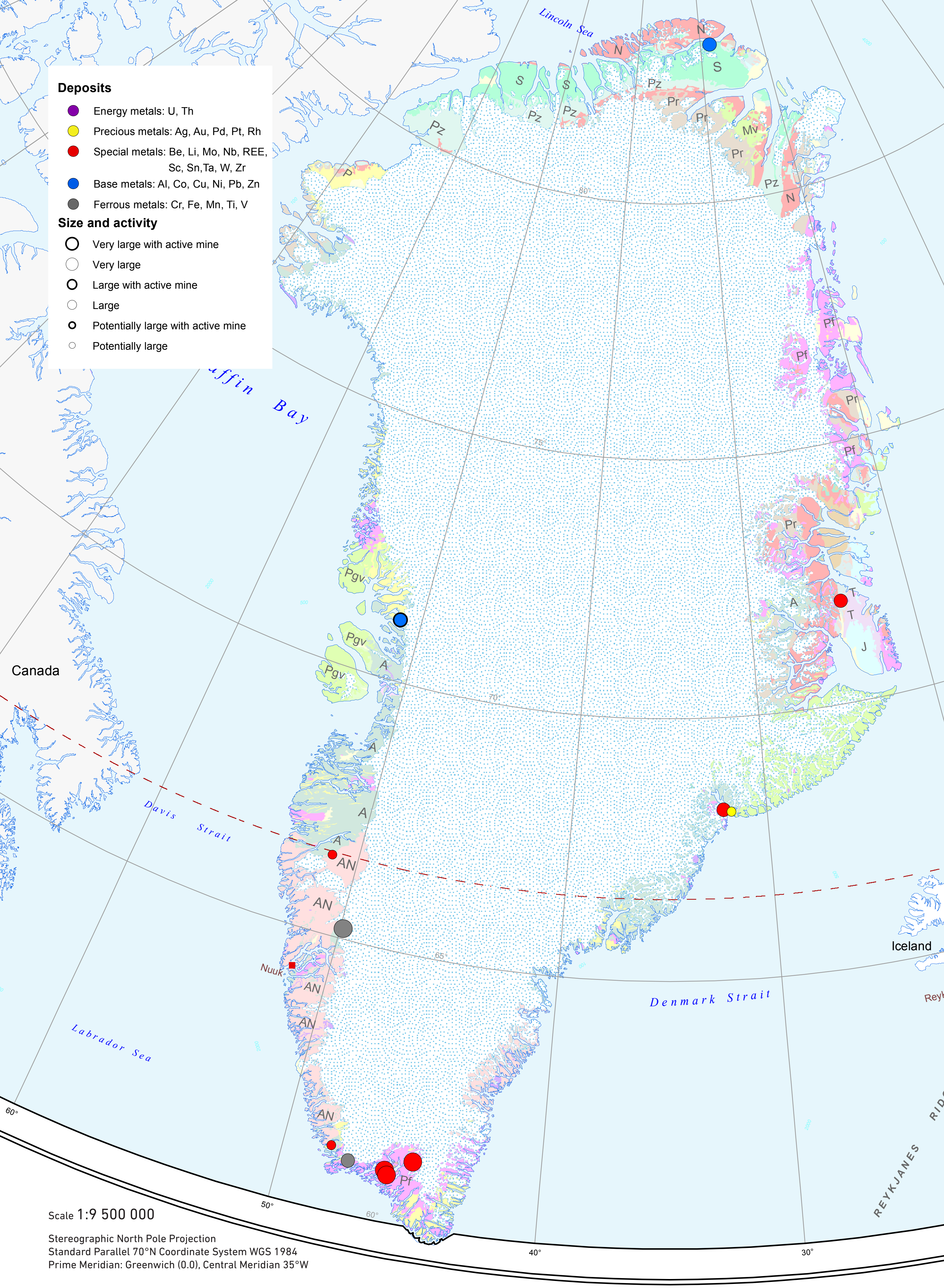

Deposits
Energy metals: U, Th
Precious metals: Ag, Au, Pd, Pt, Rh
Special metals: Be, Li, Mo, Nb, REE, Sc, Sn,Ta, W, Zr
Base metals: Al, Co, Cu, Ni, Pb, Zn
Ferrous metals: Cr, Fe, Mn, Ti, V
Size and activity
Very large with active mine
Very large
Large with active mine
Large
Potentially large with active mine
Potentially large
Lincoln Sea
Baffin Bay
Davis Strait
Labrador Sea
Denmark Strait
Canada
Iceland
Nuuk
REYKJANES
Scale 1:9 500 000
Stereographic North Pole Projection
Standard Parallel 70°N Coordinate System WGS 1984
Prime Meridian: Greenwich (0.0), Central Meridian 35°W

CHAPTER 3

GREENLAND

Authors: Jochen Kolb[1], Diogo Rosa[1], Kristine Thrane[1], Jakob K. Keiding[2]

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DESCRIPTION OF THE MAIN METALLOGENIC/KIMBERLITE PROVINCES

Jochen Kolb

The Archaean

Greenland is mainly underlain by Archaean rocks in particular along the western coast and the eastern coast north to approximately 70°N, where the Archaean forms the basement of the Caledonian orogen in the south turning into Palaeoproterozoic basement further north (Enclosed map; Bridgwater et al., 1978; Garde and Steenfelt, 1999; Connelly and Mengel, 2000; Friend and Nutman, 2001; Thrane, 2002; Friend and Nutman, 2005; Dawes, 2006; Nutman et al., 2008a; Nutman et al., 2008b; Kolb et al., 2013; Kolb, 2014). The Archaean generally consists of two major cratons, the North Atlantic craton in the south and the Rae craton in the northwest with a possible continuation to the northeast and east of Greenland, separated by the broadly west-northwest-trending Palaeoproterozoic Nagssugtoqidian orogen (Enclosed map; van Gool et al., 2002; Connelly et al., 2006; Nutman et al., 2008a; Nutman et al., 2008b; Kolb, 2014). The northern and southern margins of the Archaean cratons are characterized by Palaeoproterozoic orogens, the Inglefield and Ketilidian orogens, respectively (Nutman et al., 2008a; Steenfelt et al., 2016). The Archaean is characterized by granulite-gneiss terranes or similar terranes at amphibolite facies metamorphic grades that host orogenic gold and orthomagmatic deposits (Kolb et al., 2015). The few lower-grade metamorphic areas locally host banded iron formation (BIF), such as those in the Melville Bay area and the Isua greenstone belt with the Isua iron ore deposit, located approx. 150 km northeast of the capital, Nuuk (Enclosed map; Appel, 1991; Dawes, 2006). The Isua iron ore deposit is isolated and not part of a province. Prospective BIF was, however, mapped over 19 km strike in the Melville Bay area (Figure 1), including coarse-grained magnetite and haematite BIF. The Havik deposit was found most prospective and an inferred resource of 67 Mt at 31.4 wt. % Fe magnetite iron ore was defined (Red Rock Resources, 2016).

The Palaeoproterozoic

Archaean rocks in central West and North-West Greenland are overlain by the Palaeoproterozoic Karrat Group, and both units are deformed by Palaeoproterozoic Rinkian-Nagssugtoqidian orogens (Enclosed map; Henderson and Pulvertaft, 1967; Garde and Pulvertaft, 1976; Henderson and Pulvertaft, 1987; Grocott and Pulvertaft, 1990; van Gool et al., 2002; Connelly et al., 2006). The Karrat Group is an approximately 8.5 km thick metasedimentary sequence metamorphosed at greenschist to lower amphibolite facies conditions with local higher grades in contact aureoles. It is subdivided into three formations, namely the Mârmorilik, Qeqertarssuaq and Nûkavsak formations (Garde and Pulvertaft, 1976). The Qeqertarssuaq and Nûkavsak formations are dominated by metamorphosed siliciclastic rocks, with the Nûkavsak Formation consisting of >1950 Ma metagreywacke deposited from juvenile Palaeoproterozoic and Archaean basement sources (Henderson and Pulvertaft, 1967, 1987; Grocott and Pulvertaft, 1990; Kalsbeek et al., 1998). The Mârmorilik Formation hosts the Black Angel Zn-Pb deposit (Pedersen, 1980, 1981), and is composed of calcite and dolomite marble, fine-grained, locally graphite-bearing schist, quartzite and possible metamorphosed evaporite (Garde and Pulvertaft, 1976). The Black Angel Zn-Pb deposit is part of a Zn-Pb district with numerous massive to disseminated sulphide targets in the vicinity (Thomassen, 1991). Southwest of the Black Angel deposit, the Lower Mârmorilik Formation hosts mineralisation in east-southeast-trending fold hinges on the Ukkusissat peninsula, Appat island and Nuussuaq peninsula. The massive sulphide mineralisation on Ukkusissat peninsula is up to 8 m thick and 70 m long with 40 wt. % combined Zn+Pb and 72 ppm Ag (Thomassen, 1991). A massive sulphide mineralisation up to 1.5 m wide and consisting of pyrrhotite, sphalerite, galena and minor chalcopyrite is found 20 km north of the Black Angel deposit (Coppard et al., 1992). It is hosted in a 6-70 m thick marble horizon on top of Archaean orthogneiss. Massive sulphide ore occurs in lenses over 9 km strike with grades up to 41 wt. % Zn and 9.3 wt. % Pb over 1 m (Coppard et al., 1992). The various Zn-Pb sulphide ores in and around Black Angel as well as the mineralisation to the north, appear to be hosted by marble and controlled by fold structures, and thus form a Zn-Pb metallogenic province in central West Greenland. No other large metallogenic provinces are known from the Archaean and Palaeoproterozoic terranes.

The Mesoproterozoic to Cenozoic

South Greenland

The Mesoproterozoic Gardar intrusive suite in South Greenland formed in a period of continental rifting and alkaline magmatism lasting from ca. 1300 to 1140 Ma (Sørensen, 2006; Upton, 2013; Bartels et al., 2015). It consists of dyke swarms and 14 intrusive complexes with variable sizes from ~300 m up to 50 km in diameter (Upton and Emeleus, 1987). The alkaline and carbonatite magmas of the Gardar intrusive suite are enriched in Be, Li, F, Ga, P, Y, Zr, Nb, REE, Hf, Ta, U, Th, Fe, Ti, V and Zn. The degree of enrichment during magmatic differentiation, fractionation and hydrothermal alteration has determined their mineral potential (Steenfelt et al., 2016). This mainly rare metal province hosts some of the world's largest deposits of this kind, namely Kringlerne (Ta-Nb-REE-Zr), Kvanefjeld (U-REE-Zn) and Motzfeldt (Nb-Ta) (Enclosed map). The central province is located around the settlements of Narsaq and Narsarsuaq and trends northeast. It is approximately 30 km wide and 120 km long. Further intrusions are found approximately 80 km both west and east. The Gardar intrusive suite is divided into (1) early Gardar Province with dominantly west-trending dykes and minor plutons (1300-1220 Ma) and (2) late Gardar Province with west-southwest-trending dykes and plutons (1180-1140 Ma) (Sørensen, 2006; Upton, 2013; Bartels et al., 2015). The magmas of the dykes and intrusive complexes are mildly to strongly alkaline and formed a long range of rock types, such as alkali-basalt, trachyte, comendite, phonolite and alkali-gabbro, syenite, alkali granite, nepheline syenite and carbonatite (Upton et al., 2003). The melt source for the various rocks of the Gardar intrusive suite is interpreted to be located in metasomatised sub-continental lithospheric mantle (SCLM) above the garnet stability field (Goodenough et al., 2000; Marks et al., 2004; Upton, 2013; Bartels et al., 2015). Minor degrees of crustal contamination, magmatic differentiation by crystal fractionation and volatile transfer concentrated rare metals in the most evolved magmas and magmatic-hydrothermal fluids, but also formed magnetite or eudialyte cumulate. Most of the ores are hosted in the plutons themselves, with the exception of the Motzfeldt deposit where the magmatic-hydrothermal fluids altered the wall rocks and formed pyrochlore mineralisation.

Southern West Greenland

Southern West Greenland has remained tectonically relatively stable since the Palaeoproterozoic and has only sporadic records of younger rock until Cretaceous-Palaeogene rifting formed sedimentary rocks and flood basalts around 70°N (Enclosed map). The Archaean and Palaeoproterozoic gneisses host, locally, carbonatite complexes and dyke swarms described as ultramafic lamprophyre and kimberlite (Larsen, 1991; Nielsen et al., 2009). This carbonatite-ultramafic lamprophyre province is located at the southern front of the Palaeoproterozoic Nagssugtoqidian Orogen (Enclosed map; Secher and Larsen, 1980; Scott, 1981; Nielsen et al., 2009). The ~90 km^2 and ca. 565 Ma Sarfartoq carbonatite complex forms a conical body with peripheral radial dykes and is situated approx. 50 km southwest of the Kangerlussuaq international airport (Enclosed map). This complex hosts a world class REE mineralisation, the Sarfartoq deposit (Druecker and Simpson, 2012). Dyke swarms of various ages are widely distributed in the Sisimiut-Sarfartoq-Maniitsoq region and locally host diamond, e.g. at Garnet Lake (Hutchison and Frei, 2009). They generally form ~1 m thick sheets or 1-2 m wide near-vertical dykes in approx. 50 km wide halos around the carbonatite. The geometry of the dykes and sheets is controlled by the foliation of the host gneiss: 1284-1209 Ma lamproite dykes in the Sisimiut area (Rb–Sr phlogopite ages) trend east to east-southeast, whereas the 604-555 Ma (Rb–Sr phlogopite and U–Pb perovskite/pyrochlore ages) dykes trend east-northeast in the Maniitsoq area and northward in the Sarfartoq area (Larsen and Rex, 1992; Secher et al., 2009).

Northern Greenland

In northern Greenland, the large Franklinian basin developed during the Neoproterozoic and Palaeozoic at the margin of Laurentia with a ~2000 km E-W extent into Canada (Enclosed map; Higgins et al., 1991). The Neoproterozoic-Palaeozoic rocks unconformably overlie Proterozoic sedimentary sequences (Higgins et al., 1991; Dawes, 2009). Sedimentation started in the Neoproterozoic and lasted until the Early Devonian, when the basin was inverted during the Ellesmerian orogeny (Higgins et al., 2000). The strata in the Franklinian basin are characterized by a distinct facies transition from ~3 km thick shallow-water platform carbonates in the south to ~8 km thick deep-water, mainly fine-grained siliciclastic trough sediments separated by the Navarana Fjord lineament in the north (Soper and Higgins, 1990; Higgins et al., 1991). In later stages of basin evolution, thermal subsidence controlled sedimentation in a starved basin until the Silurian (Soper and Higgins, 1987). Carbonate, carbonate conglomerate and black shale were deposited on the shelf slope, and cherty shale formed continuously in the trough until the end of the Ordovician (Higgins et al., 1991). Shelf carbonate formed until the Llandovery, followed by turbidite deposition from Wenlock to Early Devonian times (Soper and Higgins, 1990; Higgins et al., 1991). During this period, the platform-trough transition migrated southwards, which is explained by the onset of the Ellesmerian orogeny in the north (Soper and Higgins, 1990). The first indication of mineralisation in the region was reported in 1960 during a helicopter reconnaissance in Peary Land by the U.S. Geological Survey, who noted gossans ~20 km east of Citronen, which is a world-class Zn-Pb deposit documented more recently (van der Stijl and Mosher, 1998). Further sulphide mineralisation was found in 1969 during the Skidoo British Joint Services Expedition followed by mapping of the Geological Survey of Greenland in the years 1978-1980. Several Zn-Pb sulphide occurrences along the Navarana Fjord lineament may represent SEDEX occurrences similar to Citronen, defining a metallogenic Zn-Pb belt in northern Greenland (von Guttenberg and van der Stijl, 1993). These include the showings in Nares Land (Kap Wohlgemuth) and Nyboe Land (Hand Bugt and Repulse Havn) with up to 11 wt. % Zn and 2 wt. % Pb in grab samples (von Guttenberg and van der Stijl, 1993). Further Zn-Pb occurrences to the south are hosted in the shelf carbonates and probably represent MVT-style mineralisation that formed during Ellesmerian basin inversion (Rosa et al., 2013; Rosa et al., 2014).

East Greenland

East Greenland is, in its northern part, characterized by variably deformed and metamorphosed rocks that mainly formed between latest Palaeoproterozoic and Silurian times. Sedimentary rocks with local volcanic intercalations were deposited in continental to shallow marine basins along the eastern margin of Laurentia, and overlying the Archaean and Palaeoproterozoic basement (Enclosed map; Henriksen and Higgins, 2008). The Caledonian orogen resulted in the formation of regional-scale west-vergent nappe stacks and local granite intrusions (Leslie and Higgins, 2008). The Devonian marks the end of Caledonian deformation and the development of sedimentary basins in central East Greenland, before continental break-up and initiation of sea-floor spreading in the North Atlantic started in the Palaeogene. Post-Caledonian sedimentation up to the Cretaceous occurred in isolated north-trending basins that form graben structures. The sedimentary rocks locally host Cu-mineralisation and Caledonian granites formed a number of skarn or greisen occurrences (Harpøth et al., 1986).

The continental break-up and onset of Palaeogene sea-floor spreading closely related to a mantle plume was associated with major magmatism resulting in massive lava flows, intrusions, sills and dykes (White and McKenzie, 1989; Saunders et al., 1997). This large igneous province (LIP), the North Atlantic Igneous Province (NAIP), has been active since 63 Ma and extends for more than 3000 km from Baffin Island across

Greenland, Iceland and the Faeroe Islands to Scotland and Ireland. The Palaeogene in East Greenland stretches from 66°N to 75°N, a distance of more than 1300 km (Enclosed map). Thick volcanic sequences also exist off-shore on the eastern Greenland shelf (Brooks and Nielsen, 1982; Larsen et al., 1989; Pedersen et al., 1997). Evidence of the magmatism is also preserved as dyke swarms, sill complexes, gabbroic intrusions and alkaline and granite intrusions. The 63-13 Ma NAIP in eastern Greenland was formed by episodic magmatism (Tegner et al., 1998; Tegner et al., 2008; Larsen et al., 2014). The three main magmatic stages are: (1) ca. 62-57 Ma picritic and tholeiitic volcanism (Lower Basalts) over a wide area, possibly triggered by plume activity; (2) ca. 56-55 Ma tholeiitic volcanism forming flood basalts (Plateau Basalts) and intrusions related to continental rifting; and (3) ca. 53-47 Ma gabbro and syenite intrusions and transitional alkaline volcanism in a late post-breakup phase. Sporadic younger magmatism is locally recorded at Kialineq at ca. 35 Ma, Malmbjerg at ca. 26 Ma and finally by the small volumes of the ca. 13 Ma-old Vindtoppen Formation basalt. More than 60 intrusions are found along the eastern Greenland margin, with 28 in the Kangerlussuaq Fjord area alone. The mafic to ultramafic intrusions host orthomagmatic PGE-Au mineralisation, the largest deposit known being in the Skaergaard intrusion (Holwell et al., 2012a; Nielsen et al., 2015). The felsic intrusions include both undersaturated and oversaturated syenite and monzogranite, and host Mo-porphyry ores as well as peripheral Au-rich veins and Zn-Pb vein mineralisation, e.g. at Malmbjerg and Flammefjeld (Schassberger and Galey, 1975; Geyti and Thomassen, 1984). Volumetrically minor alkaline intrusions form the Gardiner Complex, at the head of the Kangerlussuaq Fjord, and carbonatites of the Sulugssut Complex (Brooks, 2011). The Kangerlussuaq basin and the Kangerlussuaq Fjord form the best endowed area, with orthomagmatic PGE-Au, Mo-porphyry and Au-Ag vein deposits (Skaergaard, Flammefjeld, Kap Edward Holm, macrodykes) and is interpreted as the locus of the mantle plume (Enclosed map; Brooks, 1973; Schassberger and Galey, 1975; Brooks and Nielsen, 1982; Geyti and Thomassen, 1984; White and McKenzie, 1989; Arnason and Bird, 2000; Thomassen and Krebs, 2001; Holwell et al., 2012a; Nielsen et al., 2015). The Kangerlussuaq Fjord is interpreted to represent the failed arm of a triple junction with break-up and rift-related magmatism concentrated in two arms forming the present Greenlandic coast line (Brooks, 1973).

HISTORY OF MINING

Jochen Kolb

Greenland has a long tradition of mining and mineral exploration starting with the colonisation in the 18th century with a first culmination marked by the discovery and subsequent mining of a cryolite ($Na_3[AlF_6]$) deposit near Ivittuut in South Greenland. Cryolite was used first as an aluminium ore and then as flux in the electrolytic processing of aluminium from bauxite ore. The Ivigtut cryolite mine was mined for over 130 years from 1854 until 1987 and represents one of the few economic mining successes in Greenland so far (Pauly and Bailey, 1999). The mine was the only one of its kind in the world until natural cryolite was replaced by synthetic cryolite in the 1960s. The company that operated the Ivigtut cryolite mine, Kryolitselskabet Øresund A/S, started the first systematic exploration program in the 1950s with helicopter prospecting flights mainly along the west coast, selecting targets for mapping and further exploration. At the same time, Nordisk Mineselskab A/S started mineral exploration programs in eastern Greenland based on finds from earlier expeditions, i.e. the small Blyklippen Zn-Pb deposit that was mined between 1956 and 1962 (Harpøth et al., 1986). Other early, small mining operations include the Josva copper mine (1904-1915) and the Amitsoq graphite mine (1915-1924) in

South Greenland, and the Qullissat coal mine (1924-1972) on Disko Island in central West Greenland. The discovery of the world-class Zn-Pb Black Angel deposit is the second important event in Greenland's mining history. The deposit was successfully mined between 1973 and 1990 in a spectacular operation, where ore and the miners were transported between the adit at an elevation of 600 m above sea level and the opposite side of a fjord by a cable car. Several exploration companies became active in the wake of the successful mining operations, identifying several mineral exploration targets mainly by prospecting. Mineral exploration, geophysical and geological investigations have been supported through the partly state-owned exploration company Nunaoil A/S with the split-off NunaMinerals A/S and the geological surveys (Geological Survey of Greenland and later Geological Survey of Denmark and Greenland). This resulted in the discovery of gold and olivine deposits, which led to establishment of the Nalunaq gold mine (2003-2013) in South Greenland and the Seqi olivine mine (2005-2010) north of Nuuk, respectively. With the termination of gold production in Nalunaq in 2013 and the final closure of the mine in 2014, mining activity came to halt in Greenland for the first time in 160 years. Status January 2016, approximately 55 exclusive exploration and 6 exploitation licenses are active, covering approximately 10 % of Greenland's ice-free area (Government of Greenland, 2016). Exploration activity focuses on the Proterozoic of South Greenland (REE, Fe-Ti, Au, U), the Archaean between Fiskenæsset and Sisimiut in western Greenland (Cr, Ni, PGE, Ti-V, REE, gemstones), the Archaean and Palaeoproterozoic in north-western Greenland (Zn, Fe, Au, Cu) and the Caledonian Orogen of eastern Greenland (Cu, W). Exploitation licenses have been granted for the Nalunaq gold deposit, the Black Angel zinc-lead deposit, the Malmbjerg molybdenum-porphyry deposit, the Isua iron ore deposit, the Aappaluttoq ruby deposit and the White Mountain calcium feldspar deposit. Mining of corundum gemstone from the Aappaluttoq ruby deposit commenced in December 2015. Reviews of the economic geology of Greenland are given in Ball (1922), Nielsen (1973, 1976), Henriksen et al. (2009) and Kolb et al. (2015); Kolb et al. (in review).

ISUA IRON ORE DEPOSIT

Jochen Kolb

The Isua iron ore deposit was discovered in 1965 by Kryolitselskabet Øresund A/S during an aeromagnetic survey 150 km northwest of Nuuk (Nielsen, 1973). It was studied in detail with drilling and the definition of a resource of magnetite ore until 1974, but was considered only marginally economic. Exploration was resumed in 1995, when RTZ Mining and Exploration Ltd. started investigating haematite ore targets underneath the Inland Ice (Figure 1, Enclosed map; Coppard and Harris, 1996). Recent resource estimates on re-examined magnetite ore, calculated by London Mining in 2014, gave figures of 1107 Mt grading 32.6 % Fe. General Nice Development Limited took over the license for the Isua iron ore deposit in 2015.

The deposit is hosted in an oxide-facies banded iron-formation (BIF) in the eastern part of the Isua greenstone belt in the northern ca. 3700 Ma terrane of the Isua greenstone belt (Nutman and Friend, 2009). The BIF crops out as a sheet, 1.5 km long, 200 m thick and dipping east-southeast at 60-70°. it is located along the hinge of a large-scale antiform close to the Inland Ice and increases in thickness to 450 m with depth (Figures 1 and 2). The lower section is formed by iron-rich garnet-chlorite biotite schist and the upper section by a laminated quartz-carbonate-magnetite-iron silicate rock with 20-30 wt. % Fe (Keto, 1970). The BIF is laterally zoned with magnetite-rich rocks in the centre grading to more silicate-rich rocks in

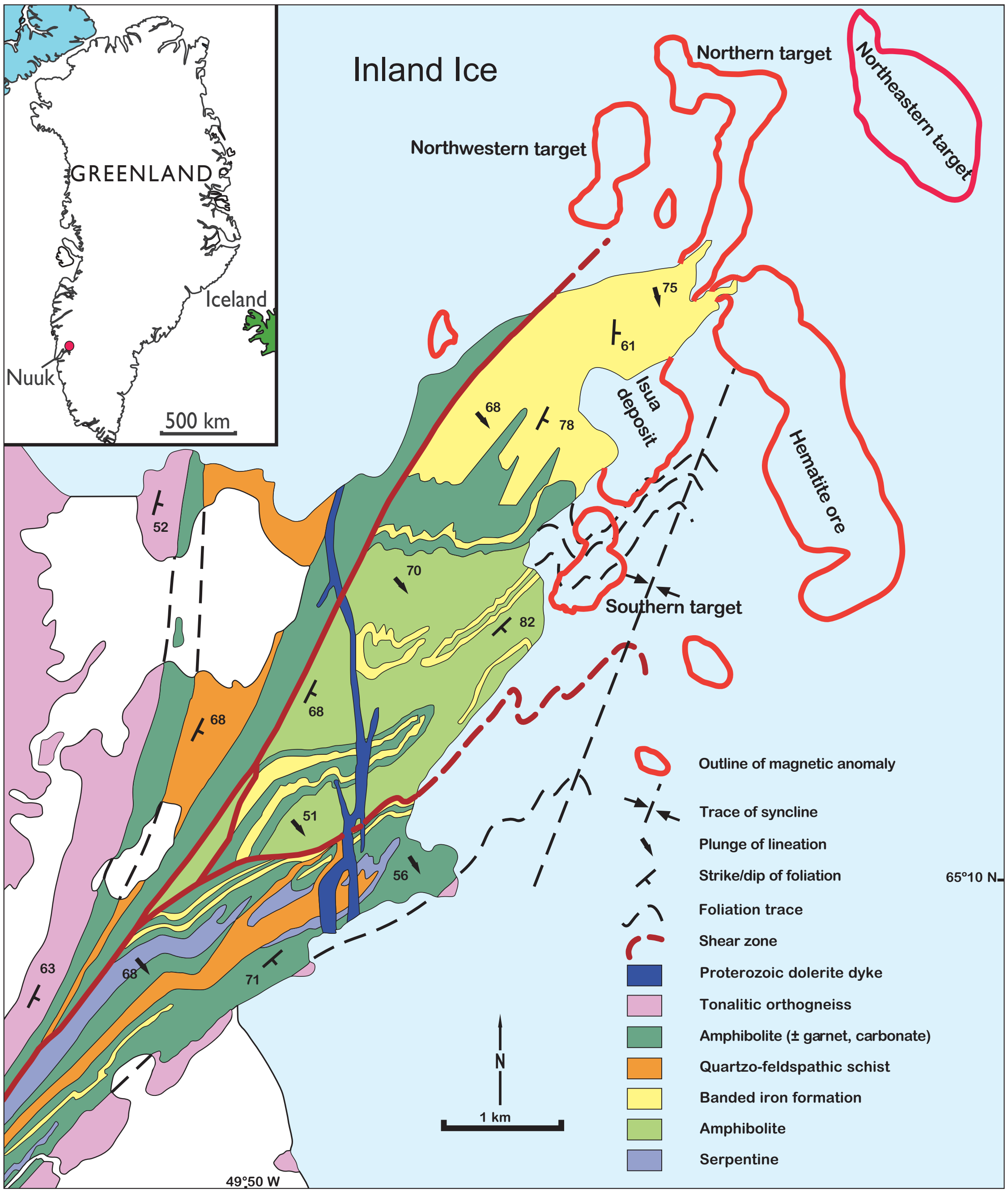


Figure 1. Geological map of the northeastern area of the Isua greenstone belt (unpublished map by J. Myers). The thick BIF representing the magnetite iron ore is located close to the Inland Ice in an anticline. Further BIF-targets identified from aero-magnetic survey and drill campaigns underneath the Inland Ice are outlined schematically.

the periphery. The quartz- and magnetite-rich bands are 0.5-100 mm thick (Nielsen, 1973; Appel, 1980; Frei et al., 1999). The quartz-rich bands consist additionally of minor chlorite, calcite, tremolite and grunerite, whereas the magnetite-rich bands contain minor pyrite, tremolite, quartz, chalcopyrite and pyrrhotite (Keto, 1970). The banding is folded and an axial planar foliation defined by amphibole and magnetite is developed at high angles to the banding (Frei et al., 1999). Magnetite is replaced by haematite (martitisation) in areas of strong folding. Locally, 10 cm wide L-type mylonite includes cigar-shaped composite aggregates of magnetite, actinolite and quartz, and 10-15 cm wide magnetite-quartz brecciae with a magnetite matrix (Appel, 1980). Quartz-calcite-chlorite veins crosscut the banding (Keto, 1970).

Only loose boulders of haematite ore are found in ice-free areas, which have haematite- and quartz (-magnetite) bands or deformed haematite bands in a yellow jasper matrix (Appel, 1980). The haematite BIF is additionally composed of sericite, quartz and minor relic magnetite and contains ~60 wt. % Fe and ~14 wt. % Si (Coppard and Harris, 1996). In drill cores, the haematite BIF has drusy structures that are filled by quartz

Figure 2. Photograph of the Isua BIF outcrop close to the Inland Ice during a core drilling campaign (C. Østergaard).

and is crosscut by quartz-jasper veins. The drilled occurrence of haematite BIF has a lower fault contact at 678 m and is underlain by magnetite BIF (Coppard and Harris, 1996).

The mineralisation formed as an Algoma-type BIF at 3691 ± 22 Ma due to hydrothermal fluids percolating through mid-ocean ridge-type rocks (Frei et al., 1999). Quartz-magnetite-grunerite-stilpnomelane or quartz-magnetite-actinolite-grunerite-ferrosalite assemblages indicate amphibolite facies metamorphism (Frei et al., 1999). Discordant veins with ~5 mm hydrothermal alteration zones formed during the amphibolite facies metamorphism at 3630 ± 70 Ma (Nielsen, 1973; Frei et al., 1999). Magnetite is locally replaced by fine-grained haematite, indicating alteration of the magnetite BIF (Nielsen, 1973; Appel, 1980). The haematite ore probably represents an upgraded ore formed by oxidation of the magnetite BIF during hydrothermal or supergene alteration.

BLACK ANGEL ZINC-LEAD DEPOSIT

Diogo Rosa

The Black Angel deposit, at Maarmorilik, comprises ten distinct ore bodies; Angel, Cover, Tributary, I and I South, Banana, Deep Ice, V16 and Nunngarut 1 and 2 (Figure 3; Enclosed map). These totalled 13.6 Mt, with grades of 12.3 % Zn, 4.0 % Pb and 29 ppm Ag (Thomassen, 1991), of which 11.2 Mt were mined between 1973 and 1990. Upon closure of the mine, approximately 2.4 Mt of ore remained in pillars, which have been planned to be exploited. The massive sphalerite-galena-pyrite ore is hosted by calcitic and dolomitic marble (Figure 3), with intercalations of anhydrite-bearing marble and pelitic schist, of the Mârmorilik Formation of the Palaeoproterozoic Karrat Group. The Karrat Group corresponds to a metasedimentary sequence which unconformably covers the Archaean basement in northern West Greenland (Henderson and Pulvertaft, 1987). Towards the south, the Karrat Group consists mostly of the carbonate-dominated Mârmorilik Formation. Towards the north, the Karrat Group includes the lower, mainly siliciclastic (quartzitic), Qeqertarssuaq Formation, and the upper, turbiditic Nûkasvsak Formation, which contains occasional pyrrhotite-chert-graphite horizons. Amphibolites present between the two latter formations have been interpreted to represent a volcanic package, referred to as the Kangigdleq basic volcanics by Allen and Harris (1980).

The genesis of the ores, whether sedimentary-exhalative or a later stage Mississippi Valley-type, remains uncertain (Thomassen, 1991) because of poor age constraints and the effects of deformation, as well as the 1881±20 Ma amphibolites-facies metamorphism (Taylor and Kalsbeek, 1990). These processes during the evolution of the Rinkian mobile belt, caused the original sulphide sheets, which were originally 0.5 to 8 m thick, to be deformed into 0.5-35 m thick, flat-lying sheets along a 3 km long and up to 600 m wide zone (Pedersen, 1980, 1981).

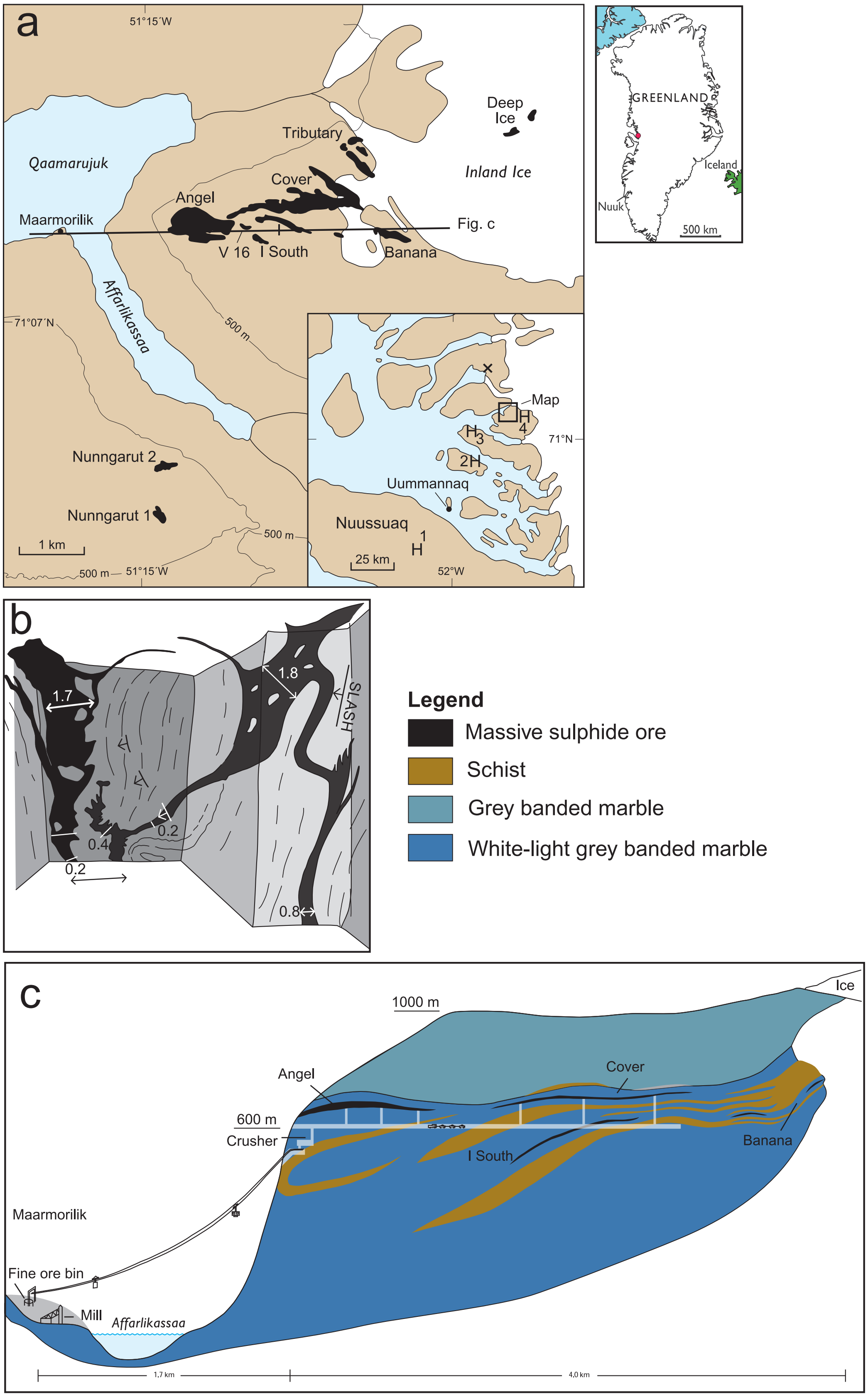


Figure 3. (a) Schematic map showing the Black Angel Zn-Pb deposit and its various ore bodies. The inset shows Zn-Pb mineralisation in the district. (b) Sketch of the ore body and marble host rock showing the intense ductile deformation defining the deposit geometry. (c) Schematic cross section through the Black Angel mine (modified after: Thomassen, 1991).

ISORTOQ IRON-TITANIUM-VANADIUM DEPOSIT

Kristine Thrane

The Isortoq deposit occurs in a troctolite dyke which intrudes the Julianehåb igneous complex in the Qaqortoq District of South Greenland, approximately 70 km west of Narsaq. The dyke extends over 16.3 km, and is one of the many Mid-Proterozoic mafic dykes in the area (Bridgwater and Coe, 1970). The deposit is referred to as the Isortoq Project and is licensed to West Melville Metals Inc. In 2012, the company carried out a ground geophysical survey and drilled 11 holes, producing a total of 2,684 m of core. The drilling program was carried out along strike for approximately 1 km of the mineralised body, and showed that its width ranges from 100 to 200 m and its vertical thickness from 100 to 300 m. In 2013, West Melville Metals Inc. announced an initial National Instrument (NI) 43-101 compliant resource estimate of 70.3 Mt grading 38.1 wt. % FeO (29.6 wt. % Fe), 10.9 wt. % TiO_2 and 0.144 wt. % V_2O_5 applying a 15 wt. % Fe cut-off.

Bench-scale beneficiation tests carried out in 2014 produced average concentrate grades of 50.2 wt. % Fe (71.8 wt. % Fe_2O_3); 20.9 wt. % TiO_2 and 0.34 wt. % V_2O_5 with acceptably low levels of penalty elements, such as S, P, Si, Al (West Melville Metals Inc., 2016).

MOTZFELDT NIOBIUM-TANTALUM-ZIRCONIUM-RARE EARTH ELEMENT DEPOSIT

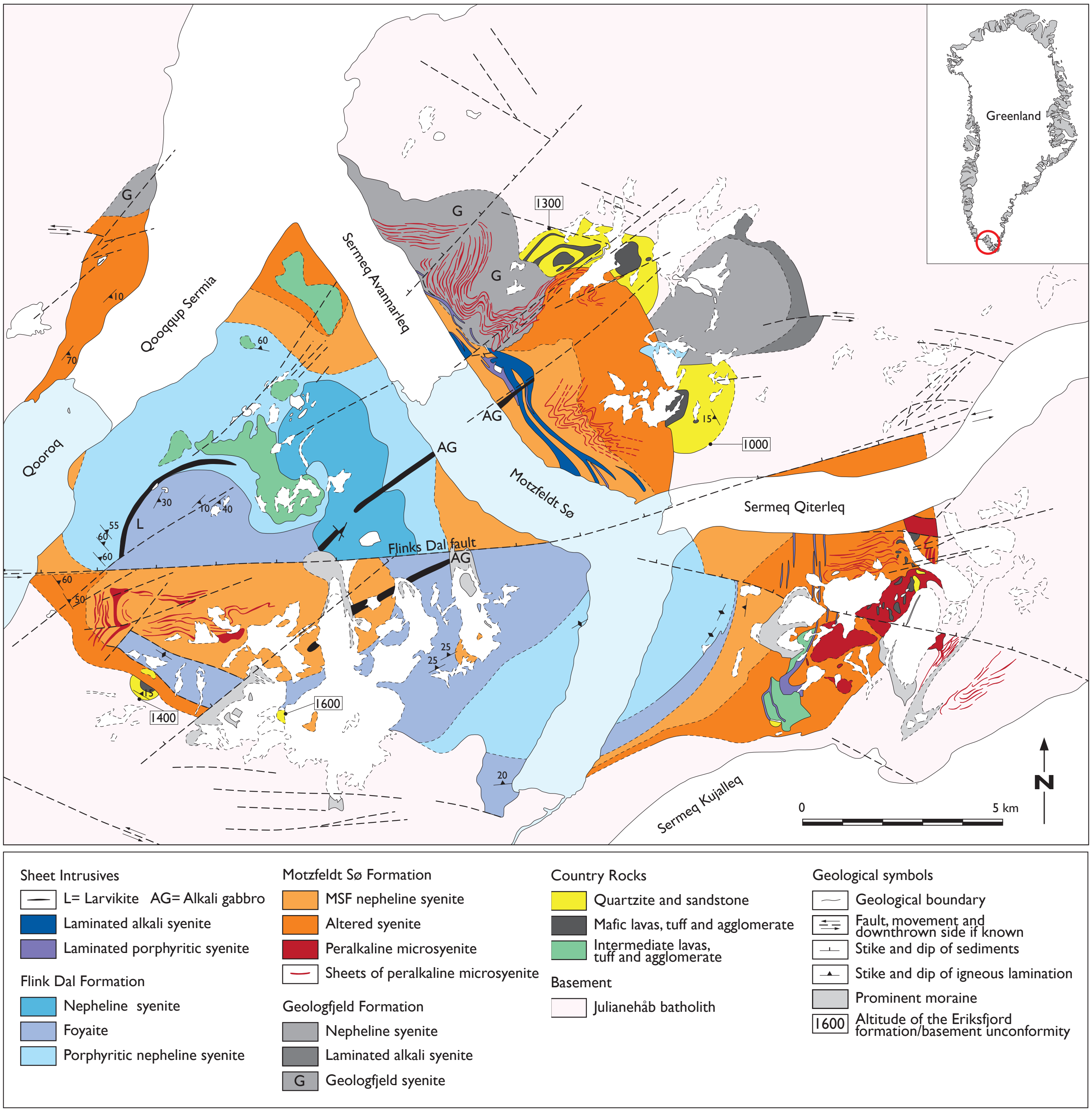
Kristine Thrane

An extensive Nb-Ta-U-Th-Zr-REE mineralisation was discovered in the centre of the Motzfeldt intrusion during the reconnaissance surveys of the Syduran project (Bridgwater and Coe, 1970). The Motzfeldt intrusion is part of the Mesoproterozoic Igaliko alkaline intrusive complex in the Gardar Province (Figure 4, Enclosed map). It consists of multiple units of syenite and nepheline syenite that intruded the Proterozoic Julianehåb intrusive complex and the unconformably overlying supracrustal rocks, the Eriksfjord Formation. The Motzfeldt intrusion covers an area of approximately 150 km^2. McCreath et al. (2012) dated the intrusion at 1273 ± 6 Ma, by concordant U-Pb zircon ages. The central part of the Motzfeldt intrusion, called Motzfeldt Centre, is divided into the Geologfjeld, Motzfeldt Sø and Flinks Dal Formation, where each part is divided into several subdivisions (Figure 4). At least two sets of faults cut the intrusion; the older generation of faults strikes SW-NE and those of the younger generation strike E-W. The coarser syenitic rocks are intruded by sills or sheets of peralkaline microsyenite in the north and north-eastern part of the Motzfeldt Centre.

The Nb-Ta-U-Th-Zr-REE mineralisation is hosted by the altered syenites and microsyenites of the Motzfeldt Sø Formation. The metals are mainly hosted in pyrochlore (Nb, Ta, U, REE), thorite (Th), zircon (Zr), bastnaesite (REE, Th) and monazite (REE) (Thomassen, 1988, 1989; Lewis et al., 2012). The pyrochlore is concentrated into a 200-300 m wide zone along the outer margin of the intrusion. The micro-syenite contains up to 2000 ppm U and up to 1 wt. % Th. Metasomatic processes enriched U in zones extending over several 100 m. The width of most of the zones lies in the range of several to >100 metres. The pyrochlore contains 3-9 wt. % UO_2 and up to 0.25 wt. % ThO_2 (Tukiainen, 1986). Significant Ta-Nb-enriched zones are also related to minor pegmatite and diorite dykes and high-grade REE intersections are related to pegmatites.

Regency Mines Plc. currently holds the license for the area. The resource estimate by the former licence holder, RAM resources Ltd, is 340 Mt ore grading 0.26 wt. % TREO, 0.19 wt. % Nb_2O_3, 0.012 wt. % Ta_2O_3 and 0.46 wt. % ZrO_2.

Figure 4. Geological map of Motzfeldt intrusion (modified after: Tukiainen et al., 1984). The great numbers of dykes, predominantly alkali trachytes of the late-Gardar dyke swarm are omitted for the sake of clarity.



IVIGTUT CRYOLITE DEPOSIT

Kristine Thrane

The Ivigtût intrusion is one of the most evolved complexes in the Gardar Province, but it is the only one that intruded Archaean basement. A Rb-Sr isochron yields an age of 1248 ± 25 Ma for the granite (Thomassen, 1989). The granite stock is 300 m in diameter and expands with increasing depth. The unique cryolite (Na_3AlF_6) body in the intrusion was mined from 1854 to 1987 (Figure 5). In addition, an occurrence of uranium was discovered by Kryolitselskabet Øresund A/S when carrying out radiometric investigations around the cryolite mine. The main U occurrence is associated with columbite in the marginal areas of the cryolite body. The main cryolite body is now exhausted, and the mine abandoned; the majority of the remaining tailings stored adjacent to the mine site have also been processed. A halo of radioactivity around the Ivigtût intrusion has been recognized and investigated; it contains 50-100 ppm U in the highly altered granites. The U/Th ratio is approximately 1:4 (Pauly, 1960).

Rimbal Pty. Ltd. currently holds the license for the area, exploring for ultra-pure quartz beneath the former cryolite body.

Figure 5. Abandoned mine site at Ivigtût.

KVANEFJELD URANIUM-RARE EARTH ELEMENT-ZINC DEPOSIT

Kristine Thrane

The 150 km² Mesoproterozoic Ilímaussaq alkaline complex hosts the REE-U-Th-Zn-F deposit referred to as Kvanefjeld (Figure 6, Enclosed map). The complex is unique and world famous for its wealth of rare minerals, several of which are only found at Kvanefjeld. It has been studied intensely since the beginning of the 19th century for both scientific and economic reasons (see Sørensen, 2001) for an overview. Ilímaussaq is c. 1160 Ma old (Lewis et al., 2012) and one of the youngest

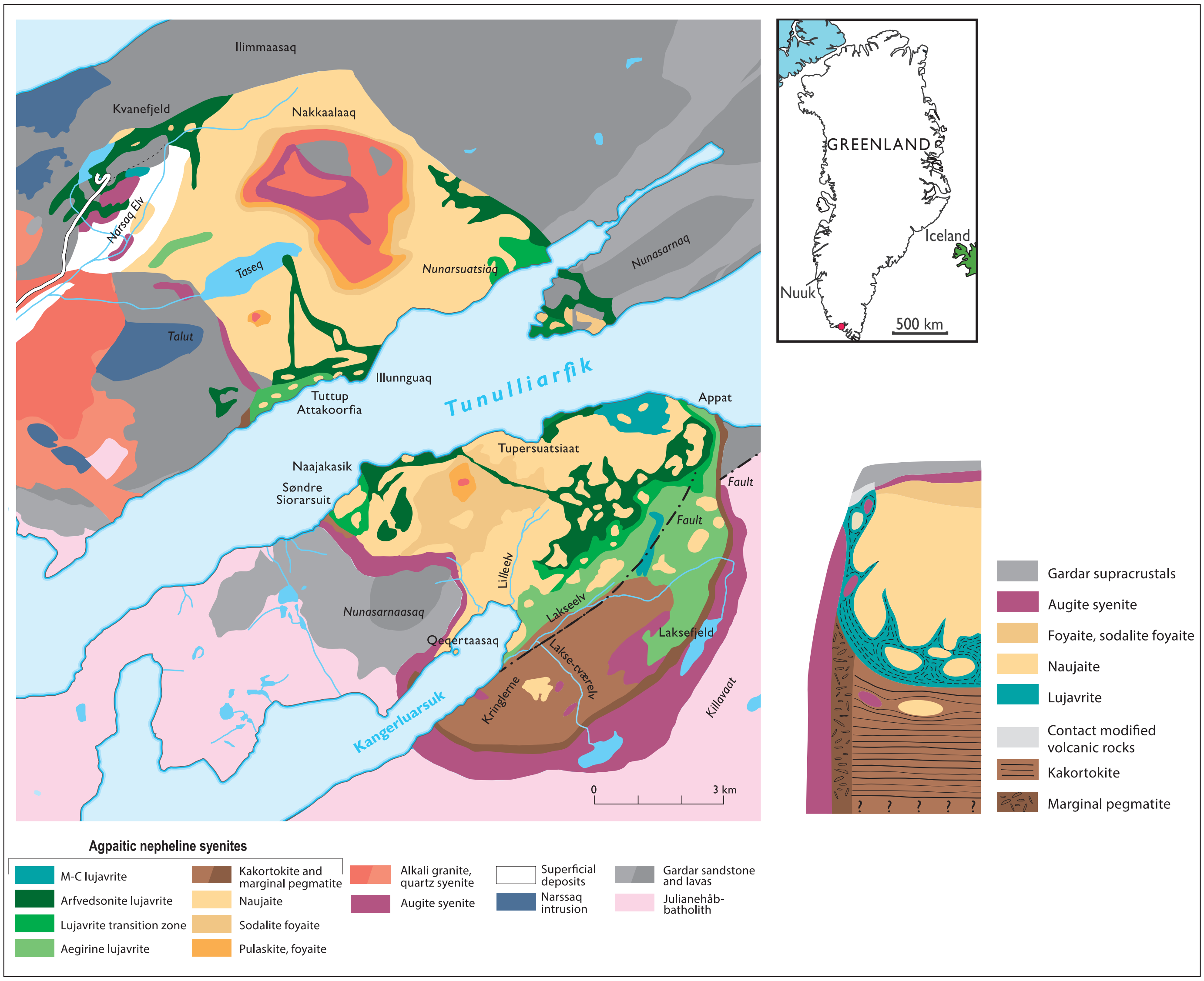


Figure 6. Geological map of the Ilímaussaq intrusion and a schematic cross-section (modified after Upton, 2013).
The REE deposits hosted by lujavrite indicated.

intrusions of the Gardar igneous province. It intruded the Palaeoproterozoic Julianehåb igneous complex and the unconformably overlying Mesoproterozoic Eriksfjord formation comprising sandstone and basalt. The complex is composed of a series of nepheline syenites and is the type locality for agpaitic rocks. Kvanefjeld represents the intermediate series of the Ilímaussaq intrusion, sandwiched between the roof and floor series, and is composed of hyper-agpaitic lujavrite and naujarite. The lujavrite represents the residual liquid after the crystallization of the highly differentiated alkali- and volatile-rich magma with high concentrations of incompatible elements (Bohse et al., 1974). Kvanefjeld has an average U_3O_8 concentration of 273 ppm and approximately 3 times the amount of Th. In addition, it has an average TREO concentration of 1.06 wt. % (402 ppm HREO) and 0.22 wt. % Zn. The REE, U and Th are predominantly hosted by the complex phosphate-silicate mineral steenstrupine, containing 0.2-1.5 wt. % U and 0.2-7.4 wt. % Th.

Kvanefjeld was explored for uranium between 1956 and 1984. Geological mapping and radiometric surveys were carried out, 12,455 metres of core were drilled and a 1 km long adit was constructed.

Since 2007, Greenland Minerals and Energy Ltd. has conducted REE-exploration activities in the Kvanefjeld area, including drilling of an additional 57,710 m of core. Greenland Minerals and Energy Ltd. reports (2016) that the overall resource inventory for Kvanefjeld (150 ppm U_3O_8 cut-off) is 673 Mt of ore containing 167,000 t U_3O_8 and 7.34 Mt TREO, including 0.247 Mt HREO, and 1.36 Mt Zn. An application for an exploitation licence is expected to be submitted early in 2016. Planned annual production is 3 Mt ore, equal to 23,000 t TREO, 500 t U_3O_8 and 6,000 t Zn. Additional resources exist in Zone Sørensen and Zone 3.

KRINGLERNE TANTALUM-NIOBIUM-RARE EARTH ELEMENT-ZIRCONIUM DEPOSIT

Kristine Thrane

The Kringlerne multi-element deposit is hosted in the basal cumulates, the kakortokites, of the Ilímaussaq alkaline complex (Figure 6, Enclosed map). The kakortokites crop out in the southern part of the Ilímaussaq complex, and consist of 29 exposed cyclic units with a total thickness of about 200 m (Bohse et al., 1971). Each individual unit is made up by 3 density-stratified layers: a dark arfvedsonite dominated kakortokite layer, a reddish eudialyte dominated kakortokite layer, and a grey/white nepheline-feldspar dominated kakortokite layer (Figure 7). Eudialyte, the main economic mineral, is enriched in REE-Zr-Nb-Ta. Rimbal Pty Ltd., the current license-holder reports an inferred resource to be at least 4,300 Mt, grading 0.65 wt. % TREO, 0.2 wt. % Nb_2O_3 and 1.8 wt. % Zr_2O_5 equalling 28 Mt TREO (Rimbal Pty Ltd., 2016). An application for an exploitation licence has been submitted and is currently under review. The proposed mining project involves an open-pit mine near the fjord, hauling ore to a nearby beneficiation plant, where three products will be produced by magnetic mineral separation: (i) eudialyte concentrate (REE, Nb, Zr); (ii) feldspar concentrate; and (iii) arfvedsonite concentrate, all to be shipped for further processing or use outside Greenland. Planned annual production is 500,000 t ore, equal to 3,250 t TREO (equivalent to 400 t Nd_2O_3 and ca. 90 t Dy_2O_3) and 9,000 t Zr_2O_5.

Figure 7. Layered kakortokite sequence exposed at Kringlerne. View is seen from the Kangerluarsuk Fjord, in westerly direction. The high ranges in the background are the 1100 m high Killavaat (Redekammen), consisting of Julianehåb granite (K. Secher).

SARFARTOQ RARE EARTH ELEMENT-NIOBIUM DEPOSIT

Jochen Kolb

The ca. 565 Ma old Sarfartoq carbonatite complex contains 14 Mt ore grading 1.5 wt. % total rare earth oxides (TREO) with a cut-off at 0.8 wt. % TREO (Druecker and Simpson, 2012). It has been explored since 2009 by Hudson Resources, and 25,400 m of core have been drilled and 273 km of geophysical surveys have been flown. Mineral exploration in the 1980's and 1990's by Hecla Mining and New Millennium Resources NL concentrated on a small high-grade Nb resource near the core of the complex. The resources to a depth of 90 m are estimated at 64,301 t at 3.89 wt. % Nb corresponding to 5.56 wt. % Nb_2O_5 at a cut-off grade of 1.0 wt. % Nb (Woodbury, 2003; Stendal et al., 2005).

The carbonatite complex consists of concentric intrusions of rauhaugite and beforsite in the up to 4 km wide and 5 km long intrusion centre forming a conical body with an axis, which plunges steeply to the northwest (Figures 8 and 9, Enclosed map). This centre is surrounded by a fenite zone several hundred metres wide and a marginal zone, which is several kilometres wide. The rauhaugite in the intrusion centre consists of dolomite, apatite, biotite, magnetite, richterite-arfvedsonite solid solution and minor zircon, ilmenite, pyrochlore and pyrite (Secher and Larsen, 1980). The concentric intrusions are 0.5-20 m wide, strongly foliated and layered, and host abundant wall-rock xenoliths. The layering is defined by local magnetite and beforsite bands in larger intrusions. The dyke- and sheet-like intrusions are separated by narrow bands of fenitised wall rock, which also forms the xenoliths (Figure 9c). The structures vary from foliated

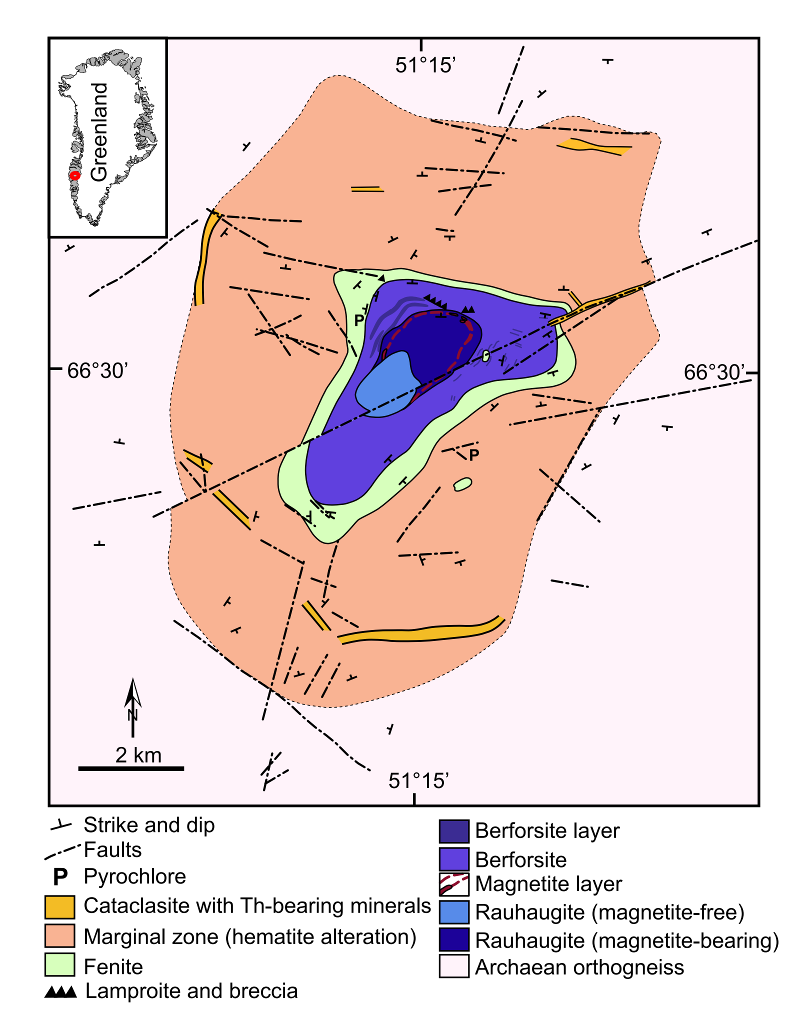
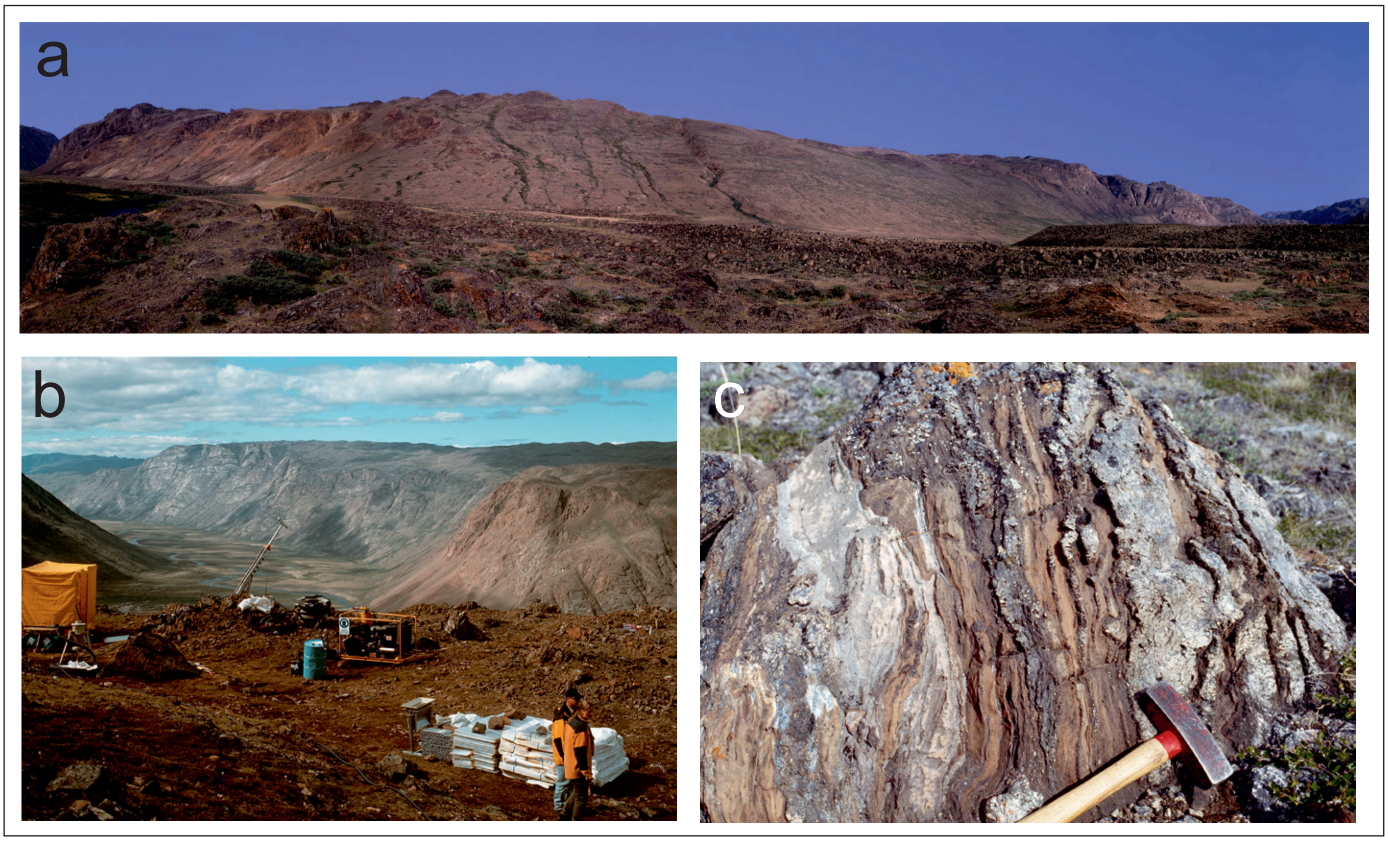


Figure 8. Geological map of the Sarfartoq carbonatite complex, showing the conical intrusion centre, the narrow fenite rim and the kilometre-wide marginal zone (modified after: Secher and Larsen, 1980).

Figure 9. (a) Panorama view of the Sarfartoq carbonatite in reddish colours. The altered wall rock orthogneiss is seen with grey colours at the right and left margin (J. Lautrup). (b) View of drill rig and the carbonatite in the cliff wall. In the distance the wall rock shows shallow-dipping bands of orthogneiss and amphibolite. The plateau is at an elevation of approximately 800 m above sea level. (c) Rauhaugite intrusion with bands of fenite from the intrusion centre (L.M. Larsen).



to folded and brecciated, indicating a dynamic setting for emplacement of the carbonatite. The fenites are aegirine-bearing orthogneiss and altered mafic rocks with abundant pyrochlore, and generally contain alkali feldspar, aegirine, biotite, amphibole and minor calcite and pyrochlore (Secher and Larsen, 1980).

The marginal zone is characterized by haematite alteration and 50-200 m wide cataclastic fault zones that have a broadly radial geometry (Secher and Larsen, 1980). Monomineralic pyrochlore veins, 1-5 m wide also form a radial geometry surrounding the central conical intrusion. The marginal zone also hosts radial beforsite dykes, 5-100 cm wide and concentric breccia zones with carbonatite matrix. The beforsite consists of the same assemblage as the rauhaugite with additional K-feldspar, chlorite, quartz, baryte, pyrite, haematite and rutile (Figure 8; Secher and Larsen, 1980). Late hydrothermal carbonate and calcite-fluorite veins cross-cut the carbonatite complex.

The REE mineralisation is hosted by the beforsite (ferrocarbonatite) dykes in the periphery of the complex and was identified by a radiometric Th-anomaly during exploration (Secher and Larsen, 1980; Druecker and Simpson, 2012). In the beforsite, the REE mineralisation is mainly located in bastnaesite, monazite, synchysite ($CaCe(CO_3)_2F$) and zhonghuacerite ($Ba_2Ce_{0.6}La_{0.3}Nd_{0.1}(CO_3)_3F$) (Druecker and Simpson, 2012). The REE-bearing carbonates are enriched in Ce, La, Nd, Pr and Eu, yielding ore that is dominated by the light REE (Secher and Larsen, 1980; Druecker and Simpson, 2012).

The Sarfartoq carbonatite complex formed in two major stages: (1) intrusion of a central conical body; and (2) intrusion of concentric and radial beforsite dykes in the periphery (Secher and Larsen, 1980). The mineralisation formed in the late stages of carbonatite magmatism by subsolidus REE-enrichment in hydrothermal fluids associated with the peripheral dykes (Secher and Larsen, 1980).

CITRONEN ZINC-LEAD DEPOSIT

Diogo Rosa

Citronen is a large sedimentary-exhalative deposit located in Peary Land, in northern Greenland (Figure 10; Enclosed map), with reported total resources (measured + indicated + inferred), at 2.0 wt.% Zn cut off, of 132 Mt @ 4.0 wt.% Zn and 0.4 wt.% Pb (Ironbark Zinc Limited, 2012). This yet unmined deposit is composed of five major mounds, located within three main mineralised horizons (Figure 10). Each stratabound sulphide mound has dimensions reaching a length of 1500 m, a width of 600 m, and a thickness of 25 m, with individual sulphide beds being 0.3 to 2.0 m thick and interlayered with thin (≤10 cm) beds of mudstone (Kragh et al., 1997). The mounds consist of massive and bedded pyrite, with variable amounts of sphalerite and galena, and are hosted by mudstone, shale and debris flows of the Ordovician Amundsen Land Group (van der Stijl and Mosher, 1998). This group was deposited in a sediment-starved trough or elongate basin, separated from the shallow-water carbonate platform to the south by a prominent paleo-escarpment, the Navarana Fjord escarpment (Higgins et al., 1991; van der Stijl and Mosher, 1998). It has been suggested that the local basin bottom waters shifted from oxic to anoxic and locally sulphidic. This was caused by the emplacement of debris-flow conglomerates that sealed off the basin from oxic seawater, and due to the venting of reduced hydrothermal fluids, which allowed for the preservation of sulphides on the sea floor (Slack et al., 2015). Subsequent deformation is expressed by open to recumbent folds and local thrust faults, related to the Late Devonian to early Carboniferous Ellesmerian orogeny (van der Stijl and Mosher, 1998).

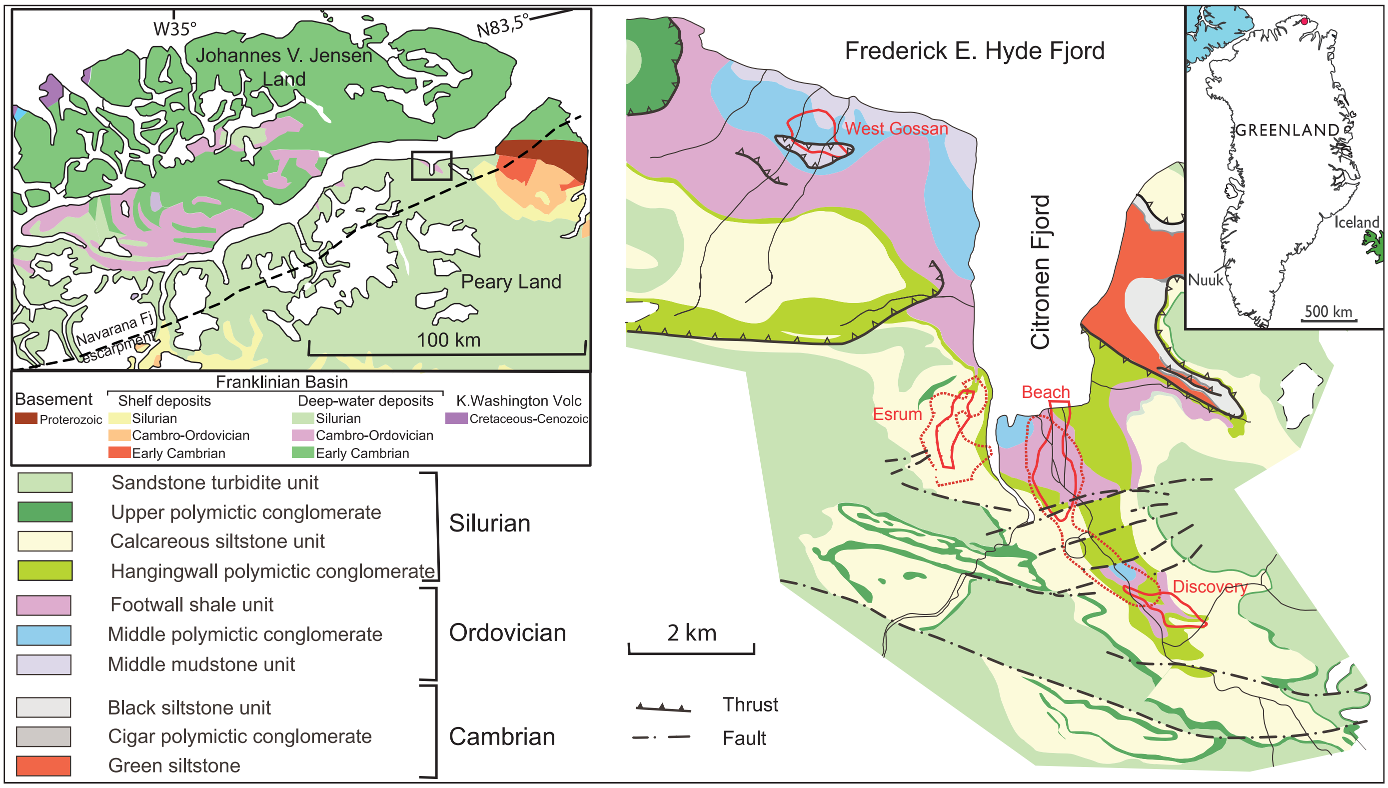


Figure 10. Geology of Citronen Fjord area (modified after: van der Stijl and Mosher, 1998), showing surface projections of mineralised zones (solid and dashed red lines are levels 1+2 and 3, respectively). Inset shows regional geology of North Greenland (modified after: Escher and Pulvertaft, 1995) with small box outlining deposit area.

SKAERGAARD PLATINUM GROUP ELEMENTS-GOLD DEPOSIT

Jakob K. Keiding

The layered mafic Skaergaard intrusion, located at the at the mouth of the Kangerlussuaq fjord in East Greenland (Figure 11, Enclosed map), hosts a major stratabound PGE-Au mineralisation with a total resource of 202 Mt at 0.88 g/t Au, 1.33 g/t Pd and 0.11 g/t Pt (Platina Resources Ltd., 2013). In addition to the precious metals, the deposit is rich in oxides and could be of interest for multi-element extraction of Ti, V and Fe. The deposit was discovered by Platinova Resources Ltd. in 1987 and has subsequently been explored by Skaergaard Minerals Corp. and Platina Resources Ltd. The three companies have drilled 68 diamond boreholes in total, corresponding to more than 35 km.

The intrusion is world famous for its spectacular layering and has served as a natural laboratory for studying magma chamber processes and differentiation of basaltic liquids. Extensive descriptions and reviews on the intrusion are given by Wager and Brown (1968); McBirney (1996); Irvine et al. (1998). The Skaergaard intrusion was emplaced at 56.0 Ma (Wotzlaw et al., 2012) into a fault-bounded space at the unconformity between the Precambrian basement and the overlying Eocene flood basalts. The intrusion is part of the major Eocene magmatic episode associated with the early continental break-up during the opening of the North Atlantic. The intrusion, which measures approximately 7 x 11 km (Figure 11), crystallised under closed-system conditions from ferrobasalt magma and developed through a continuous crystallisation sequence from olivine gabbro to ferrodiorite. It is divided into three zones originally defined by Wager and Deer, (1939): the Layered Series (LS), the Upper Border Series (UBS), and the Marginal Border Series (MBS), which crystallised on the floor, roof and walls of the chamber, respectively (Figure 12a). The interface at which the downward crystallising UBS met the upward crystallising LS is known as the Sandwich Horizon (SH). Each of the three series are further subdivided into Lower-, Middle-, and Upper Zone and subzones based on phase layering (Figure 12a, e.g. Wager and Brown, 1968; Irvine et al., 1998). Extreme fractional crystallisation is reflected in the cryptic variation resulting in pure iron end-members for olivine and Ca-rich pyroxene, and the progressive change in plagioclase, without reversals, from An70 at the margins to An25 at the centre of the intrusion (McBirney, 1996).

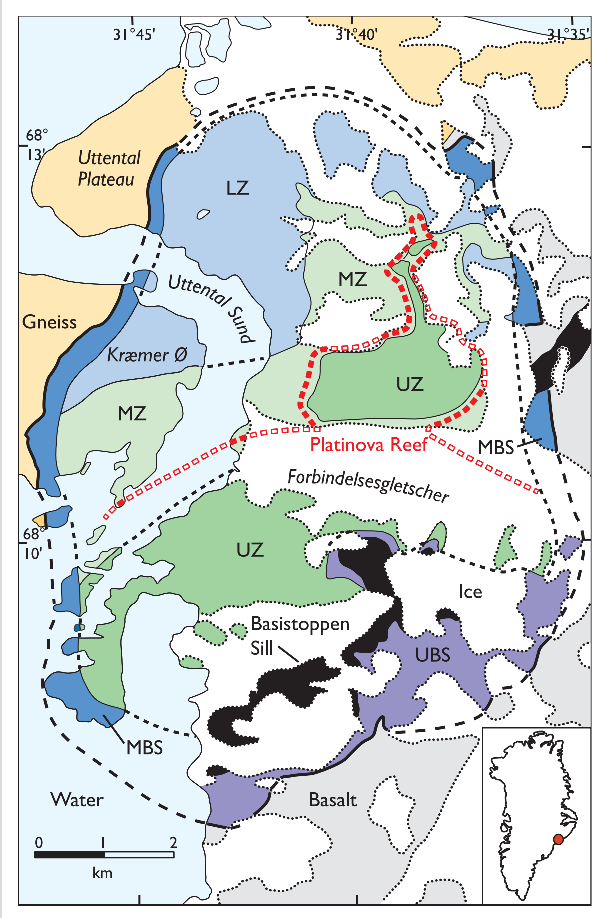


Figure 11. Simplified geological map of the Skaergaard intrusion (modified after: McBirney, 1996). The location of the Platinova Reef is shown in red. LZ, Lower Zone; MZ, Middle Zone; UZ, Upper Zone; SH, Sandwich Horizon; MBS, Marginal Border Series; UBS, Upper Border Series.

The upper part of the Middle Zone of the Layered Series hosts a large PGE and gold mineralisation known as the Platinova Reef (Figures 11 and 12; Bird et al., 1991) with maximum grades of 220 ppb Pt, 5.1 ppm Pd and 20 ppm Au (Bird et al., 1991; Andersen et al., 1998). The reef is hosted in the Triple Group which is a 100 m thick macro-rhythmic unit of three characteristic leucocratic layers (L1-L3) that are easily identified in drill cores as well as in the field (Figure 13). A buff-coloured, thinner and less distinct layer 20 m below L1 has been accepted as a member of the Triple Group and it is referred to as L0 and defines the base of the reef (Nielsen et al., 2015). The mineralisation, which has a total thickness of c. 50 m, is perfectly concordant with the L-layers and is defined by five main Pd-rich layers and one Au-rich layer. It consists of a stack of compositionally zoned, saucer-shaped layers of decreasing diameter, separated from each other by a layer of non-mineralised ferro-diorite of constant width (Figure 12b). The sulphides are entirely dominated by bornite, digenite and chalcocite while the precious metals are alloys of palladium, gold and copper, with skaergaardite (PdCu), nielsenite ($PdCu_3$), zviagintsevite (Pd_3Pb) and tetra-auricupride (AuCu) being the most common minerals (Bird et al., 1991; Andersen et al., 1998; Nielsen et al., 2005).

The Platinova reef is an example of a rare type of PGE deposit, typified by a Pd-Au-Cu-dominant, Ni-Pt-S poor ore mineralogy. It is generally accepted to be an orthomagmatic deposit with little post-solidification remobilisation, but the nature of the mineralisation process remains contentious (Bird et al., 1991; Andersen et al., 1998; Nielsen et al., 2005; Andersen, 2006; Holwell and Keays, 2014; Holwell et al., 2015; Nielsen et al., 2015). The current knowledge favours a multistage model of sulphide PGE-scavenging followed by sulphide dissolution and noble metal upgrading in the later stages of crystallization with separation of Fe- and Si-rich immiscible liquids playing a key role for redistribution of the precious metals (Nielsen et al., 2015).

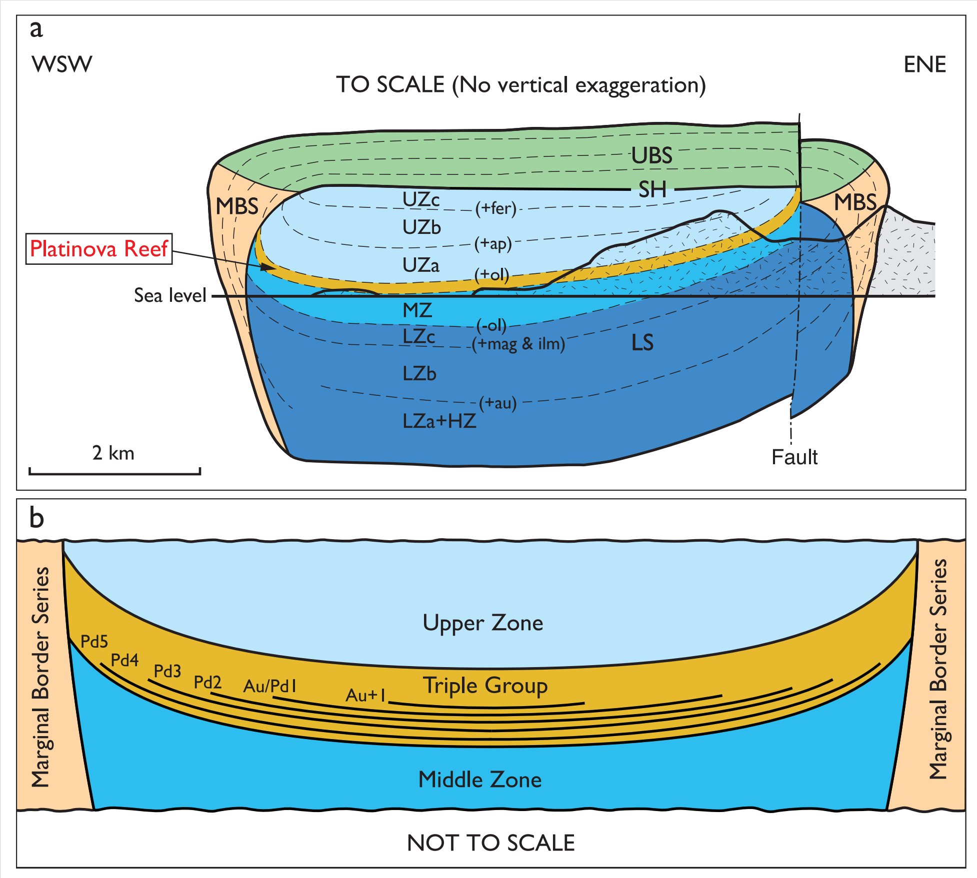
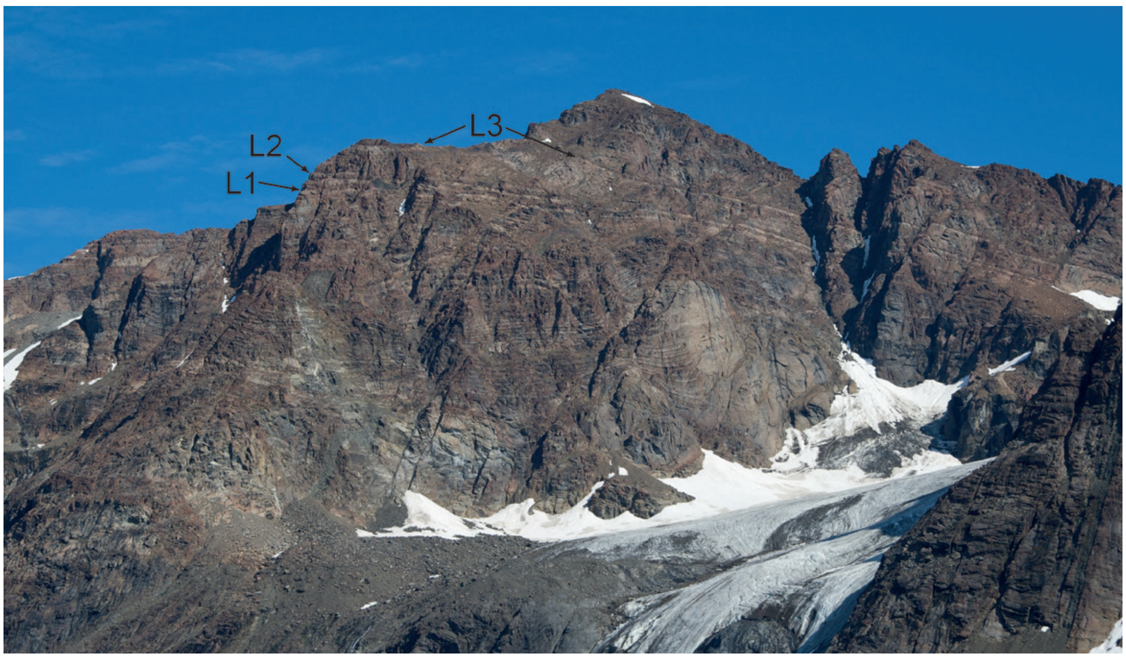


Figure 12. (a) Two-dimensional WSW-ENE schematic cross-section of the Skaergaard intrusion showing the tree main series of the intrusion. LS: Layered Series (crystallising from the floor and upward); UBS: Upper Border Series (crystallising top down) and MBS: Marginal Border Series (crystallising inwards from the walls). The LS and UBS meet at the Sandwich Horizon (SH). HZ-LZ (a, b, c), MZ and UZ (a, b, c) denote the Hidden, Lower, Middle, and Upper Zones (and subzones, respectively) of the LS and is based on appearance and disappearance of cumulus minerals indicated by plus and minus signs on the figure. Equivalent zones and subzones exist for the UBS and MBS. The Platinova Reef is within the LS located in the top of the Middle Zone (MZ). Mineral abbreviations: ap, apatite; au, augite; fer, ferrobustamite; ilm, ilmenite; mag, magnetite; ol, olivine. (b) The saucer shaped model of the Platinova Reef mineralisation showing the individual PGE and Au layers (modified after: Nielsen et al., 2015).

Figure 13. Photograph of the Triple Group, hosting the PGE-Au mineralisation in the Platinova Reef of the Skaergaard intrusion. The three characteristic leucogabbro macro-rhythmic layers (L1-L3) are highlighted. The thickness of the Triple Group is approximately 100 m (C. Tegner).



FLAMMEFJELD MOLYBDENUM DEPOSIT

Jakob K. Keiding

Flammefjeld (Flame Mountain) takes its name from the prominent gossan on a top of a 938 m high mountain (Figure 14), which attracted the attention of exploration geologists from Nordisk Mineselskab A/S during reconnaissance in 1970. Subsequent work indicated that it hosts a prominent Climax-type Mo porphyry mineralisation, although no drilling has been carried out to date (Geyti and Thomassen, 1983, 1984). Assays of mineralised boulders range from 0.04 to 0.45 wt. % Mo with an average of 0.17 wt. % Mo (Della Valle et al., 2010). This 39.6 Ma subvolcanic complex is situated at Amdrup Fjord in East Greenland (Enclosed map) at the south-western periphery of the Kangerlussuaq intrusion (Geyti and Thomassen, 1984; Brooks et al., 2004).

The Flammefjeld igneous complex has an oval shape of 500 m x 800 m and consists of volcanic brecciae and younger quartz-feldspar porphyries and aplites (Geyti and Thomassen, 1984). The complex is dominated by a large intrusive breccia pipe hosted in syenite, which again contains several different breccia types reflecting different levels of intrusion. These brecciae include a basal aplite intrusion breccia with metre-scale angular to subrounded fragments, intermediate breccia dykes with fine-grained quartz-K-feldspar matrix, and an upper igneous breccia containing metre-sized fragments ranging from basaltic to granitic composition (Geyti and Thomassen, 1984). The quartz-feldspar porphyries occur both as an intrusive body, confined to the intrusion breccia as concentric inward-dipping ring dykes in the periphery of the complex, and as fragments in the breccia.

The mineralised body is not exposed but has been identified within the breccia pipe in blocks up to

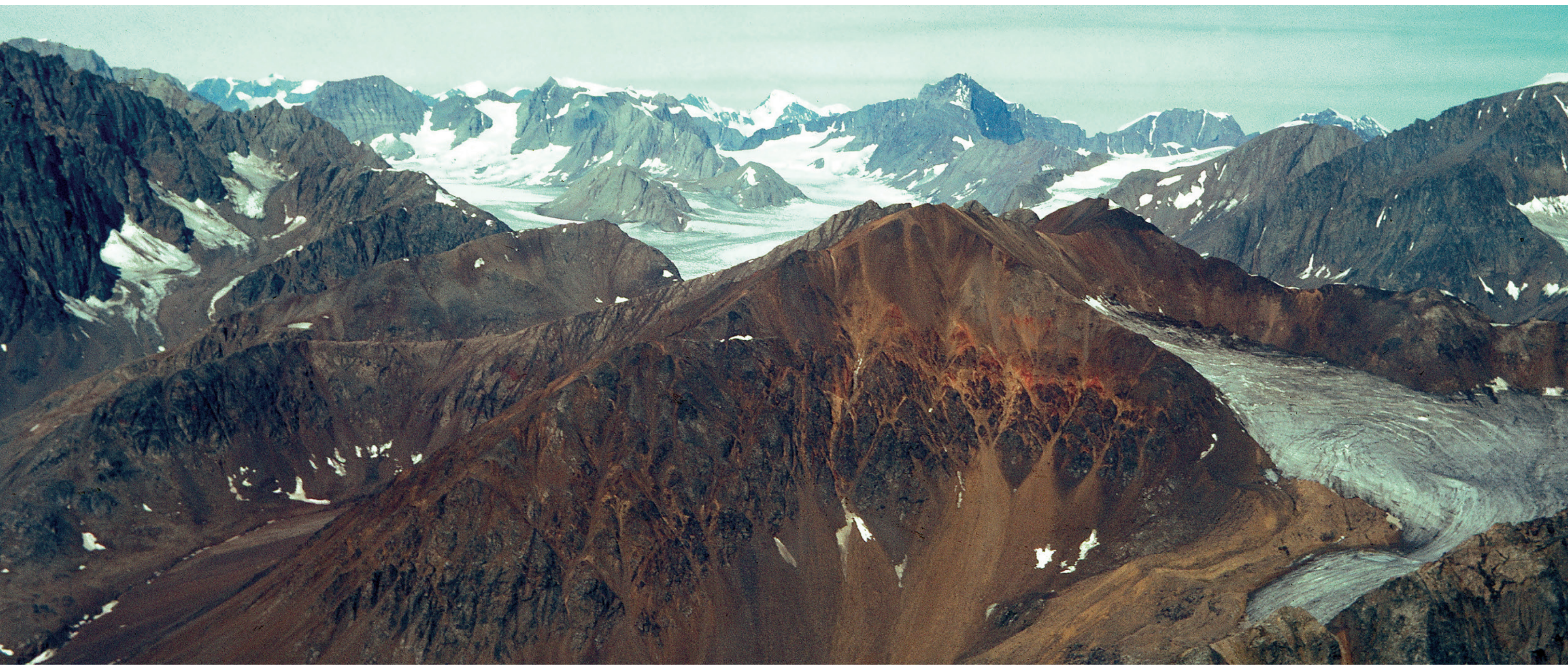


Figure 14. Arial photograph from SE of the Flammefjeld complex showing vivid yellow and red oxidation colours (B. Thomassen). The peak is at 938 m above sea level. The large alkaline Kangerlussuaq intrusion is seen in the background.

1 m in size that are assumed to have been torn off from a deeper porphyry system. Molybdenite is mostly found in felsic pipe brecciae where it forms typical stockwork molybdenite mineralisations. Usually, the molybdenite occurs in a dense network of veinlets associated with quartz, pyrite and minor chalcopyrite (Geyti and Thomassen, 1984). Alteration is pervasive in the Flammefjeld subvolcanic complex, and includes quartz-sericite, pyritic and argillic types. Potassic alteration is limited and restricted to biotite. A conceptual model was presented by Geyti and Thomassen (1983) who envisaged an inverted-saucer shaped ore-body with a grade of up to 0.5 wt. % MoS_2, a diameter of 800 m, a thickness of 200 m and which is believed to be located at about 500 m below the present exposures.

Epithermal gold- and silver-bearing quartz-carbonate veins of low-sulphidation type occur within a distance of 5 km from the Flammefjeld igneous complex with which they are associated (Geyti and Thomassen, 1984; Thomassen and Krebs, 2001; Holwell et al., 2012b). In total about 40 veins have been discovered of which most are <1 m wide and generally trending WNW-ESE. The two widest veins are the Yellow Zone and Tågegangen with widths of up to 30 m and strike extent of several hundred metres (Thomassen and Krebs, 2001). The mineralisation can, according to Thomassen and Krebs (2001), be grouped into three types: (1) pyrite-Au bearing veins; (2) galena-sphalerite-pyrite veins with Ag; and (3) polymetallic chalcopyrite-tetrahedrite-tennantite-pyrite ± sphalerite ± galena veins with Au and Ag. Float samples from the veins returned maximum 38.4 g/t Au and in-situ grab samples up to 7.5 g/t Au and 1583 g/t Ag, 7.7 wt. % Cu, 10.1 wt. % Pb and 12.2 wt. % Zn. The mineralisation also has elevated Mn, As, Sb, Mo and Bi.

MALMBJERG MOLYBDENUM DEPOSIT

Jakob K. Keiding

The Malmbjerg porphyry-molybdenum deposit is located in the Werner Bjerg complex; East Greenland (Bearth, 1959; Schassberger and Galey, 1975; Harpøth et al., 1986). It was discovered in 1954 during systematic mapping by the Danish East Greenland Expeditions and from 1958 to present more than 30 km have been drilled and adits totalling 1329 m have been excavated. With a measured and indicated resource of 329 Mt grading 0.10 wt. % Mo (KGHM, 2015), Malmberg ranks as one of the world's largest molybdenum deposits. Although access is difficult, it promises to be of exploitable value and inception of mining operation at Malmbjerg was close at the time of the world economic crisis in 2008. However, there is now renewed interest in the deposit. An exploitation license was issued for the deposit in 2009 and Malmbjerg is now (2015) licensed to KGHM.

The Malmbjerg deposit is hosted in a 25.7 Ma composite alkali granite stock that was intruded into Carboniferous to lower Permian sediments (Figure 15; Brooks et al., 2004). The dominant lithology is perthitic granite with a quartz-feldspar porphyry roof phase (Figure 16). It was intruded by heterogeneous porphyritic aplite and porphyritic granites (Harpøth et al., 1986). Volumetrically minor dykes of basaltic, trachytic and lamprophyric composition later intruded the complex.

Three types of mineralisation are associated with Malmbjerg: (1) stockwork molybdenite mineralisation; (2) Mo-W-bearing greisen veins; and (3) a base metal mineralisation. The stockwork molybdenite mineralisation is predominately hosted by the perthitic granite and the quartz-feldspar porphyry roof zone and forms an inverted bowl-like structure of approximately 700 x 700 x 150 m (Figure 16). The molybdenite

Figure 15. Photograph of the Malmbjerg deposit, located between Schuchert Gletscher (left) and Arcturus Gletscher (right) showing the light-coloured granite cupola stock intruding into darker Carboniferous to Permian sandstones. The reddish colour of the granite is due to hydrothermal alteration that also extends out into the sedimentary host rocks (B. Thomassen). The peak is approximately 1500 m above sea level.

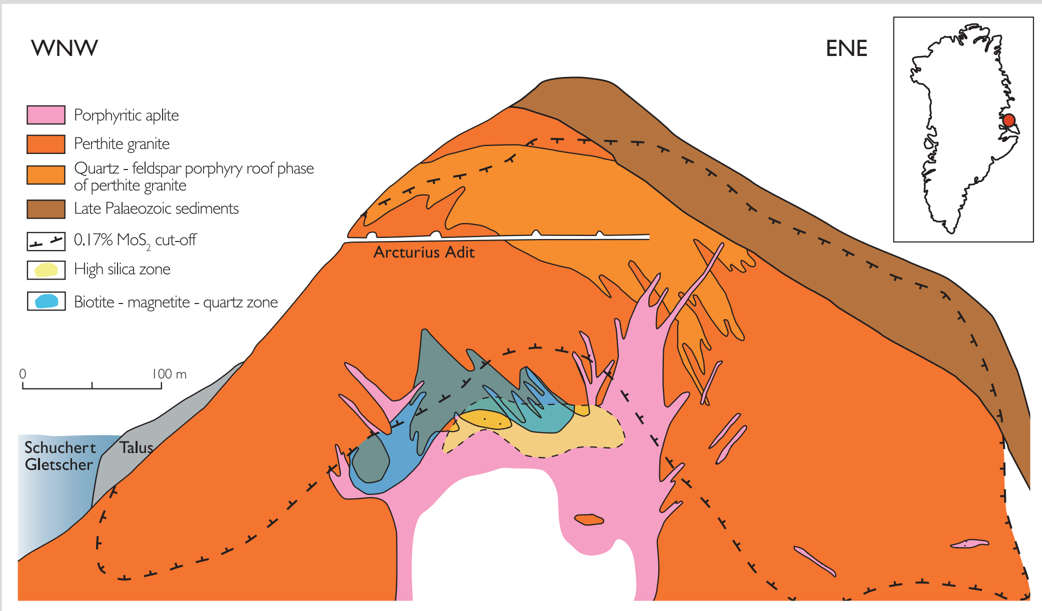


Figure 16. Schematic illustration of the Malmbjerg deposit showing the various intrusions and the geometry of mineralisation and hydrothermal alteration zones in the roof zone of the porphyritic aplite (modified after: Harpøth et al., 1986).

occurs in veinlets ranging in thickness from < 1 mm to 5 cm. The veinlets form a stockwork of mutually offsetting veins and consist mostly of biotite, molybdenite, quartz, fluorite, magnetite and minor siderite (Harpøth et al., 1986). The greisen mineralisation is found as up to 1 m wide flat-lying veins both in the granite stock and in the surrounding contact-metamorphosed sediments; they locally make up more than 10 % of the volume in the porphyritic aplite where they are most abundant. The veins have a mineralogy of quartz, molybdenite, wolframite, topaz and fluorite but locally also include beryl, cassiterite, siderite, pyrite, sphalerite, chalcopyrite, bismuth and bismuthinite (Harpøth et al., 1986). The base-metal mineralisation, which cuts both the stockwork and the greisen mineralisations, is hosted by sub-vertical 30 cm thick argillised fractures. It occurs mostly distally and is minor. The base metal mineralisation consists of quartz, biotite, sphalerite, chalcopyrite, galena, pyrite and siderite or dolomite, ankerite, fluorite, sphalerite and pyrite (Harpøth et al., 1986). Silicification and hydrothermal alteration is extensive both above and below the stockwork mineralisation (Figures 15 and 16) and locally completely overprints the original rock fabrics (Schassberger and Galey, 1975).

REFERENCES

Allen, C.R. and Harris, C.J., 1980. Karrat Group reconnaissance programme, Marmorilik area, West Greenland, Cominco Ltd. & Greenex A/S, Vancouver Number of 114 pp.

Andersen, J.C.Ø., 2006. Postmagmatic sulphur loss in the Skaergaard Intrusion: Implications for the formation of the Platinova Reef. Lithos, 92(1-2): 198-221.

Andersen, J.C.Ø., Rasmussen, H., Nielsen, T.F.D. and Rønsbo, J., 1998. The Triple Group and the Platinova gold and palladium reefs in the Skaergaard Intrusion; stratigraphic and petrologic relations. Economic Geology, 93: 488-509.

Appel, P.W.U., 1980. On the early archaean isua iron-formation, West Greenland. Precambrian Research, 11(1): 73-87.

Appel, P.W.U., 1991. The Isua iron ore deposit at Isukasia, West Greenland. Open File Series Grønlands Geologiske Undersøgelse, 91/3: 31.

Arnason, J.G. and Bird, D.K., 2000. A gold- and platinum-mineralized layer in gabbros of the Kap Edvard Holm Complex: field, petrologic and geochemical relations. Economic Geology, 95: 945-970.

Ball, H.S., 1922. The mineral resources of Greenland. Meddelelser om Grønland, 63: 1-60.

Bartels, A., Nielsen, T.F.D., Lee, S.R., Upton, B.G.J. and Thomsen, T.B., 2015. Petrological and geochemical characteristics of mid-Proterozoic dyke swarms in the Gardar Igneous Province, South Greenland: evidence for a major sub-continental lithospheric mantle component in the generation of magmatism. Mineralogical Magazine, in review.

Bearth, P., 1959. On the alkali massif of the Werner Bjerge in East Greenland. Meddelelser om Grønland 153: 63 pp.

Bird, D.K., Brooks, C.K., Gannicott, R.A. and Turner, P.A., 1991. A gold-bearing horizon in the Skaergaard Intrusion, East Greenland. Economic Geology, 86(5): 1083-1092.

Bohse, H., Brooks, C.K. and Kunzendorf, H., 1971. Field observations on the kakortokites of the Ilímaussaq intrusion, South Greenland, including mapping and analyses by portable X-ray fluorescence equipment for zirconium and niobium, 38. Geological Survey of Greenland Report, Copenhagen, 43 pp.

Bohse, H., Rose-Hansen, J., Sørensen, H., Steenfelt, A., Løvborg, L. and Kunzendorf, H., 1974. On the behaviour of uranium during crystallization of magmas – with special emphasis on alkaline magmas, Formation of uranium ore deposits. International Atomic Energy Agency, Vienna, Athens, pp. 49-60.

Bridgwater, D. and Coe, K., 1970. The rôle of stoping in the emplacement of the giant dykes of Isortoq, South Greenland. In: G. Newall and N. Rast (Editors), Mechanics of igneous intrusion. Geological Journal Special Issue, 2, pp. 67-78.

Bridgwater, D., Davies, F.B., Gill, R.C.O., Gorman, B.E., Myers, J.S., Pedersen, S. and Taylor, P., 1978. Precambrian and Tertiary geology between Kangerdlugssuag and Angmagssalik, East Greenland: a preliminary report. Rapport Grønlands Geologiske Undersøgelse, 83. Rapport Grønlands Geologiske Undersøgelse, Copenhagen, 17 pp.

Brooks, C.K., 1973. Rifting and doming in southern East Greenland. Nature Physical Science, 244: 23-25.

Brooks, C.K., 2011. The East Greenland rifted volcanic margin, 24. Geological Survey of Denmark and Greenland Bulletin, Copenhagen, 96 pp.

Brooks, C.K. and Nielsen, T.F.D., 1982. The Phanerozoic development of the Kangerdlugssuaq area, East Greenland. Meddelelser om Grønland, Geoscience, 9: 1-30.

Brooks, C.K., Tegner, C., Stein, H. and Thomassen, B., 2004. Re-Os and $^{40}Ar/^{39}Ar$ ages of porphyry molybdenum deposits in the East Greenland volcanic-rifted margin. Economic Geology, 99(6): 1215-1222.

Connelly, J.N. and Mengel, F.C., 2000. Evolution of Archean components in the Nagssugtoqidian Orogen, West Greenland. Geological Society of America Bulletin, 112: 747-763.

Connelly, J.N., Thrane, K., Krawiec, A.W. and Garde, A.A., 2006. Linking the Palaeoproterozoic Nagssugtoqidian and Rinkian orogens through the Disko Bugt region of West Greenland. Journal of the Geological Society of London, 163: 319-335.

Coppard, J. and Harris, C., 1996. Greenland Isua exclusive exploration licence 14/94, 1995 year end report. GEUS Archive No. 21432, RTZ Mining and Exploration Ltd. Number of 94 pp.

Coppard, J., Swatton, S. and Harris, C.J., 1992. Karrat exclusive exploration license: 1992 year end report, RTZ Mining and Exploration Limited Number of 125 pp.

Dawes, P.R., 2006. Explanatory notes to the geological map of Greenland, 1:500000, Thule, Sheet 5, Map Series 2. Geological Survey of Denmark and Greenland, Copenhagen.

Dawes, P.R., 2009. Precambrian–Palaeozoic geology of Smith Sound, Canada and Greenland: key constraint to palaeogeographic reconstructions of northern Laurentia and the North Atlantic region. Terra Nova, 21: 1-21.

Della Valle, G., Dilles, J., Rose, N.M. and Thomassen, B., 2010. Flammefjeld property Kangerlussuaq area, South-East Greenland. GEUS Report File No. 22536, Avannaa Exploration Limited Number of 56 pp.

Druecker, M. and Simpson, R.G., 2012. Technical report on the Sarfartoq project, West Greenland, Hudson Resources Inc Number of 91 pp.

Escher, J.C. and Pulvertaft, T.C.R., 1995. Geological map of Greenland scale 1:2,500,000. Geological Survey of Greenland, Copenhagen.

Frei, R., Bridgwater, D., Rosing, M. and Stecher, O., 1999. Controversial Pb-Pb and Sm-Nd isotope results in the early Archean Isua (West Greenland) oxide iron formation: preservation of primary signatures versus secondary disturbances. Geochimica et Cosmochimica Acta, 63(3-4): 473-488.

Friend, C.R.L. and Nutman, A.P., 2001. U-Pb zircon study of tectonically bounded blocks of 2940-2840 Ma crust with different metamorphic histories, Paamiut region, South-West Greenland: implications for the tectonic assembly of the North Atlantic craton. Precambrian Research, 105(2-4): 143-164.

Friend, C.R.L. and Nutman, A.P., 2005. New pieces to the Archaean terrane jigsaw puzzle in the Nuuk region, southern West Greenland: steps in transforming a simple insight into a complex regional tectonothermal model. Journal of the Geological Society London, 162: 147 - 162.

Garde, A.A. and Pulvertaft, T.C.R., 1976. Age relations of the Precambrian Mârmorilik Marble Formation, central West Greenland. Rapp. Grønlands Geol. Unders. 80, 49–53. Report of the Greenlandic Geological Survey, 80: 49-53.

Garde, A.A. and Steenfelt, A., 1999. Precambrian geology of Nuussuaq and the area north-east of Disko Bugt, West Greenland. Geology of Greenland Bulletin, 191: 6-40.

Geyti, A. and Thomassen, B., 1983. Porphyry molybdenum in the Malmbjerg-Mellempas area, Nordisk Mineselskab report, pp. 98.

Geyti, A. and Thomassen, B., 1984. Molybdenum and precious metal mineralization at Flammefjeld, Southeast Greenland. Economic Geology, 79: 1921-1929.

Goodenough, K.M., Upton, B.G.J. and Ellam, R.M., 2000. Geochemical evolution of the Ivigtut granite, South Greenland: a fluoride-rich "A-type" intrusion. Lithos, 51(3): 205-221.

Grocott, J. and Pulvertaft, T.C.R., 1990. The early Proterozoic Rinkian belt of central West Greenland. In: J.F. Lewry and M.R. Stauffer (Editors), The Early Proterozoic Trans-Hudson Orogen of North America. Geological Association of Canada, Paper 37, pp. 443-463.

Harpøth, O., Pedersen, J.L., Schønwandt, H.K. and Thomassen, B., 1986. The mineral occurrences of central East Greenland. Meddelelser om Grønland, Geoscience, 17. The Commission for Scientific Research in Greenland, Copenhagen, 139 pp.

Henderson, G. and Pulvertaft, T.C.R., 1967. The stratigraphy and structure of the Precambrian rocks of the Umanak area, West Greenland. Meddelelser fra Dansk Geologisk Forening, 17: 1-20.

Henderson, G. and Pulvertaft, T.C.R., 1987. Geological map of Greenland, 1:100 000, Mârmorilik 71 V.2 Syd, Nûgâtsiaq 71 V.2 Nord and Pangnertôq 72 V.2 Syd, descriptive text. Geological Survey of Greenland, Copenhagen.

Henriksen, N. and Higgins, A.K., 2008. Geological research and mapping in the Caledonian orogen of East Greenland, 70°N–82°N. Geological Society of America Memoirs, 202: 1-27.

Henriksen, N., Higgins, A.K., Kalsbeek, F. and Pulvertaft, T.C.R., 2009. Greenland from Archaean to Qaternary. Geological Survey of Denmark and Greenland Bulletin, 18: 126.

Higgins, A.K., Ineson, J.R., Peel, J.S., Surlyk, F. and Sønderholm, M., 1991. Lower Palaeozoic Franklinian Basin of North Greenland. Geological Survey of Greenland Bulletin, 160: 71-139.

Higgins, A.K., Soper, N.J. and Leslie, A.G., 2000. The Ellesmerian and Caledonian Orogenic belts of Greenland. Polarforschung, 68: 141-151.

Holwell, D.A., Abraham-James, T., Keays, R.R. and Boyce, A.J., 2012a. The nature and genesis of marginal Cu-PGE-Au sulphide mineralisation in Paleogene Macrodykes of the Kangerlussuaq region, East Greenland. Mineralium Deposita, 47: 3-21.

Holwell, D.A. and Keays, R.R., 2014. The formation of low-volume, high-tenor magmatic PGE-Au sulfide mineralization in closed systems: Evidence from precious and base metal geochemistry of the Platinova Reef, Skaergaard intrusion, East Greenland. Economic Geology, 109(2): 387-406.

Holwell, D.A., Keays, R.R., McDonald, I. and Williams, M.R., 2015. Extreme enrichment of Se, Te, PGE and Au in Cu sulfide microdroplets: evidence from LA-ICP-MS analysis of sulfides in the Skaergaard Intrusion, east Greenland. Contributions to Mineralogy and Petrology, 170(53).

Holwell, D.A., Selby, D., Boyce, A.J., Gilbertson, J.A. and Braham-James, T.A., 2012b. An Re-Os date for molybdenite-bearing quartz vein mineralization within the Kangerlussuaq Alkaline Complex, East Greenland: Implications for the timing of regional metallogenesis. Economic Geology, 107(4): 713-722.

Hutchison, M.T. and Frei, D., 2009. Kimberlite and related rocks from Garnet Lake, West Greenland, including their mantle constituents, diamond occurrence, age and provenance. Lithos, 112, Supplement 1(0): 318-333.

Irvine, T.N., Andersen, J.C.Ø. and Brooks, C.K., 1998. Included blocks (and blocks within blocks) in the Skaergaard intrusion: Geologic relations and the origins of rhytmic modally graded layers. Geological Society of America Bulletin, 110(11): 1398-1447.

Kalsbeek, F., Pulvertaft, T.C.R. and Nutman, A.P., 1998. Geochemistry, age and origin of metagreywackes from the Palaeoproterozoic Karrat Group, Rinkian Belt, West Greenland. Precambrian Research, 91: 383-399.

Keto, L., 1970. Isua a major iron ore discovery in Greeland. Internal report, Kryolitselskabet Øresund A/S Number of 18 pp.

Kolb, J., 2014. Structure of the Palaeoproterozoic Nagssugtoqidian Orogen, South-East Greenland: model for the tectonic evolution. Precambrian Research, 255: 809-822.

Kolb, J., Bagas, L. and Fiorentini, M.L., 2015. Metallogeny of the North Atlantic Craton in Greenland. Mineralogical Magazine, 79(4): 815-855.

Kolb, J., Keiding, J.K., Secher, K., Keulen, N., Rosa, D., Steenfelt, A. and Stensgaard, B.M., in review. Metallogeny of Greenland. Ore Geology Reviews.

Kolb, J., Thrane, K. and Bagas, L., 2013. Field relationship of high-grade Neo- to Mesoarchaean rocks of South-East Greenland: Tectonometamorphic and magmatic evolution. Gondwana Research, 23: 471-491.

Kragh, K., Jensen, S.M. and Fougt, H., 1997. Ore geological studies of the Citronen Fjord zinc deposit, North Greenland: project ´resources of the sedimentary basins of North and East Greenland'. Geological Survey of Greenland Bulletin, 176: 44-49.

Larsen, L.M., 1991. Occurrences of kimberlite, lamproite and ultramafic lamprophyre in Greenland. Open File Series, 91/2. Geological Survey of Greenland, Copenhagen.

Larsen, L.M., Pedersen, A.K., Tegner, C. and Duncan, R.A., 2014. Eocene to Miocene igneous activity in NE

Greenland: northward younging of magmatism along the East Greenland margin. Geolological Society of London 171: 539-553.

Larsen, L.M. and Rex, D.C., 1992. A review of the 2500 Ma span of alkaline-ultramafic, potassic and carbonatitic magmatism in West Greenland. Lithos, 28: 367–402.

Larsen, L.M., Watt, W.S. and Watt, M., 1989. Geology and petrology of the Lower Tertiary plateau basalts of the Scoresby Sund region, East Greenland, 157. Geological Survey of Greenland Bulletin, 164 pp.

Leslie, A.G. and Higgins, A.K., 2008. Foreland-propagating Caledonian thrust systems in East Greenland. Geological Society of America Memoirs, 202: 169-199.

Lewis, E., Russil, J. and Lumley, J., 2012. Report on 2011 field activities, Lincence no. 2010/46 Motzfeldt Lake. GEUS Archive No. 23625, Greenland Resources Ltd. Number of 42 pp.

Marks, M., Vennemann, T., Siebel, W. and Markl, G., 2004. Nd-, O-, and H-isotopic evidence for complex, closed-system fluid evolution of the peralkaline Ilímaussaq intrusion, South Greenland. Geochimica et Cosmochimica Acta, 68: 3379-3395.

McBirney, A.R., 1996. The Skaergaard Intrusion. In: R.G. Cawthorn (Editor), Layered intrusions. Developments in petrology 15. Elsevier. Amsterdam, pp. 147-180.

McCreath, J.A., Finch, A.A., Simonsen, S.L., Donaldson, C.H. and Armour-Brown, A., 2012. Independent ages of magmatic and hydrothermal activity in alkaline igneous rocks: The Motzfeldt Centre, Gardar Province, South Greenland. Contributions to Mineralogy and Petrology, 163: 967-982.

Nielsen, B.L., 1973. A survey of the economic geology of Greenland (exclusive fossil fuels), Report 56. Geological Survey of Greenland, Copenhagen.

Nielsen, B.L., 1976. Economic minerals. In: A. Escher and W.S. Watt (Editors), Geology of Greenland. The Geological Survey of Greenland. Copenhagen, pp. 460-487.

Nielsen, T.F.D., Andersen, J.C.Ø. and Brooks, C.K., 2005. The Platinova reef of the Skaergaard intrusion. In: J.E. Mungall (Editor), Exploration for deposits of platinum-group elements. Short Course Series. Mineralogical association of Canada, 35, pp. 431-456.

Nielsen, T.F.D., Andersen, J.C.Ø., Holness, M.B., Keiding, J.K., Rudashevsky, N.S., Rudashevsky, V.N., Salmonsen, L.P., Tegner, C. and Veksler, I.V., 2015. The Skaergaard PGE and gold deposit: the result of in-situ fractionation, sulphide saturation, and magma chamber-scale precious metal redistribution by immiscible Fe-rich melt. Journal of Petrology, 56(8): 1643-1676.

Nielsen, T.F.D., Jensen, S.M., Secher, K. and Sand, K.K., 2009. Distribution of kimberlite and aillikite in the Diamond Province of southern West Greenland: A regional perspective based on groundmass mineral chemistry and bulk compositions. Lithos, 112, Supplement 1(0): 358-371.

Nutman, A.P., Dawes, P.R., Kalsbeek, F. and Hamilton, M.A., 2008a. Palaeoproterozoic and Archaean gneiss complexes in northern Greenland: Palaeoproterozoic terrane assembly in the High Arctic. Precambrian Research, 161: 419-451.

Nutman, A.P. and Friend, C.R.L., 2009. New 1:20,000 scale geological maps, synthesis and history of investigation of the Isua supracrustal belt and adjacent orthogneisses, southern West Greenland: A glimpse of Eoarchaean crust formation and orogeny. Precambrian Research, 172(3-4): 189-211.

Nutman, A.P., Kalsbeek, F. and Friend, C.R.L., 2008b. The Nagssugtoqidian Orogen in South-East Greenland: evidence for Paleoproterozoic collision and plate assembly. American Journal of Science, 308: 529-572.

Pauly, H., 1960. Det radioaktive mønster om Ivigtut. GEUS Archive No. 21546, Kryolitselskabet Øresund A/S Number of 29 pp.

Pauly, H. and Bailey, J.C., 1999. Genesis and evolution of the Ivigtut cryolite deposit, SW Greenland. Meddelelser om Grønland, Geoscience 37 Geological Survey of Denmark and Greenland, Copenhagen, 60 pp.

Pedersen, A.K., Watt, M., Watt, W.S. and Larsen, L.M., 1997. Structure and stratigraphy of the Early Tertiary basalts of the Blosseville Kyst, East Greenland. Journal of Geological Society of London, 154: 565-570.

Pedersen, F.D., 1980. Remobilization of the massive sulphide ore of the Black Angel mine, central West Greenland. Economic Geology, 75: 1022-1041.

Pedersen, F.D., 1981. Polyphase deformation of the massive sulphide ore of the Black Angel Mine, central West Greenland. Mineralium Deposita, 16(1): 157-176.

Rosa, D., Rasmussen, J.A., Sørensen, E.V. and Kalvig, P., 2014. Reconnaissance for Mississippi Valley-type and SEDEX Zn-Pb deposits in the Franklinian Basin, Eastern North Greenland – Results of the 2013 Season, 2014/6. Geological Survey of Denmark and Greenland Report, Copenhagen, 41 pp.

Rosa, D., Stensgaard, B.M. and Sørensen, L.L., 2013. Magmatic nickel potential in Greenland, 2013/53. Geological Survey of Denmark and Greenland Report, Copenhagen.

Saunders, A.D., Fitton, J.G., Kerr, A.C., Norry, M.J. and Kent, R.W., 1997. The North Atlantic Igneous province. In: J.J. Mahoney and M.F. Coffin (Editors), Large Igneous Provinces. American Geophysical Union Geophysical Monograph, 100. Washington D.C., pp. 45-93.

Schassberger, H.T. and Galey, J.T., 1975. Report on the 1974 core relogging Erzberg project East Greenland. GEUS Archive No. 20667, AMAX Exploration, Denver Colorado Number of 110 pp.

Scott, B.H., 1981. Kimberlite and lamproite dykes from Holsteinsborg, West Greenland. Meddelelser om Grønland Geoscience, 4. Geological Survey of Greenland, Copenhagen.

Secher, K., Heaman, L.M., Nielsen, T.F.D., Jensen, S.M., Schjøth, F. and Creaser, R.A., 2009. Timing of kimberlite, carbonatite, and ultramafic lamprophyre emplacement in the alkaline province located 64°–67° N in southern West Greenland. Lithos, 112S: 400-406.

Secher, K. and Larsen, L.M., 1980. Geology and mineralogy of the Sarfartoq carbonatite complex, southern West Greenland. Lithos, 13(2): 199-212.

Slack, J.F., Rosa, D. and Falck, H., 2015. Oxic to anoxic transition in bottom waters during formation of the Citronen Fjord sediment-hosted Zn-Pb deposit, North Greenland. In: A.-S. André-Mayer, M. Cathelineau, P. Muchez, E. Piraid and S. Sindern (Editors), Mineral resources in a sustainable world: Proceedings of the 13th Biennial SGA Meeting, 5. Nancy, pp. 2013-2016.

Soper, N.J. and Higgins, A.K., 1987. A shallow detachment beneath the North Greenland fold belt: implications for sedimentation and tectonics. Geological Magazine, 124: 441-450.

Soper, N.J. and Higgins, A.K., 1990. Models for the Ellesmerian mountain front in North Greenland: a basin margin inverted by basement uplift. Journal of Structural Geology, 12(1): 83-97.

Sørensen, H., 2001. Brief introduction to the geology of the Ilímaussaq alkaline complex, South Greenland, and its exploration history. Geology of Greenland Survey Bulletin, 190: 1-23.

Sørensen, H., 2006. The Ilímaussaq alkaline complex, South Greenland - an overview of 200 years of research and an outlook. Meddelelser om Grønland Geoscience, 45. Geological Surveu of Denmark and Greenland, Copenhagen.
Steenfelt, A., Kolb, J. and Thrane, K., 2016. Metallongeny of South Greenland. Ore Geology Reviews: accepted for publication.
Stendal, H., Secher, K., Nielsen, B.M., Schønwandt, H.K. and Thorning, L., 2005. Greenland geological environments and mineral resources. Danmarks og Grønlands Geologiske Undersøgelse Rapport, 2005/8, 211 pp.
Taylor, P.N. and Kalsbeek, F., 1990. Dating the metamorphism of Precambrian marbles: examples from Proterozoic mobile belts in Greenland. Chemical Geology, 86: 21-28.
Tegner, C., Brooks, C.K., Heister, L.E. and Bernstein, S., 2008. 40Ar-39Ar ages of intrusions in East Greenland: rift-to-drift transition over the Iceland hotspot. Lithos, 101: 480-500.
Tegner, C., Duncan, R.A., Bernstein, S., Brooks, C.K., Bird, D.K. and Storey, M., 1998. 40Ar-39Ar geochronology of Tertiary mafic intrusions along the East Greenland rifted margin: relation to flood basalts and the Iceland hotspot track. Earth and Planetary Science Letters, 156: 75-88.
Thomassen, B., 1988. The Motzfeldt 87 Project Final Report, 88/1. Geological Survey of Greenland Open File Series, Copenhagen, 81 pp.
Thomassen, B., 1989. Evaluation of the niobium-tantalum potential of the Motzfeldt Centre, South Greenland. Geological Survey of Greenland Report, 145: 66-73.
Thomassen, B., 1991. The Black Angel lead-zinc mine 1973-90. Geological Survey of Greenland Report, 152: 46-50.
Thomassen, B. and Krebs, J.D., 2001. Palaeogene gold- and silver-bearing epithermal veins at Amdrup Fjord, southern East Greenland. Geological Survey of Denmark and Greenland Report, 133: 1-77.
Thrane, K., 2002. Relationships between Archaean and Palaeoproterozoic crystalline basement complexes in the southern part of the East Greenland Caledonides: an ion microprobe study. Precambrian Research, 113(1–2): 19-42.
Tukiainen, T., 1986. Pyrochlore in the Motzfeldt centre of the Igaliko nepheline syenite complex, South Greenland, Final report, Geological Survey of Greenland, unpublished Number of 98 pp.
Tukiainen, T., Bradshaw, C. and Emeleus, C.H., 1984. Geological and radiometric mapping of the Motzfeldt Centre of the Igaliko Complex, South Greenland. Geological Survey of Denmark and Greenland Report, 120: 78-83.
Upton, B.G.J., 2013. Tectono-magmatic evolution of the younger Gardar southern rift, South Greenland, 29. Geological Survey of Denmark and Greenland Bulletin, Copenhagen.
Upton, B.G.J. and Emeleus, C.H., 1987. Mid-Proterozoic alkaline magmatism in southern Greenland: the Gardar province. In: J.G. Fitton and B.G.J. Upton (Editors), Alkaline igneous rocks. Geological Society Special Publication, 30. London, pp. 449-471.
Upton, B.G.J., Emeleus, C.H., Heaman, L.M., Goodenough, K.M. and Finch, A.A., 2003. Magmatism of the mid-Proterozoic Gardar Province, South Greenland: chronology, petrogenesis and geological setting. Lithos, 68: 43-65.
van der Stijl, F.W. and Mosher, G.Z., 1998. The Citronen Fjord massive sulphide deposit, Peary Land, North Greenland: discovery, stratigraphy, mineralization and structural setting, 179. Geological Survey of Greenland Bulletin, Copenhagen, 40 pp.
van Gool, J.A.M., Connelly, J.N., Marker, M. and Mengel, F.C., 2002. The Nagssugtoqidian Orogen of West Greenland: tectonic evolution and regional correlations from a West Greenland perspective. Canadian Journal of Earth Sciences, 39(5): 665-686.
von Guttenberg, R. and van der Stijl, F.W., 1993. North Greenland project 1992, report of work. GEUS archive No. 21304, Nanisivik Mines Ltd., Platinova A/S, Toronto Number of 65 pp.
Wager, L.R. and Brown, G.M., 1968. Layered igneous rocks. Oliver & Boyd, Edinburgh and London, 588 pp.
Wager, L.R. and Deer, W.A., 1939. Geological investigations in East Greenland, Part III. The petrology of the Skaergaard Intrusion, Kangerdlugssuaq, East Greenland. Meddelelser om Grønland, 105: 1–352.
White, D. and McKenzie, D., 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. Journal of Geophysical Research-Solid Earth, 94: 7685-7729.
Woodbury, M., 2003. Qaqqaarsuk exploration licence, EL2000/01. Annual report, January 2002 - December 2002, New Millennium Resources N. L. Number of 12 pp.
Wotzlaw, J.F., Bindeman, I.N., Schaltegger, U., Brooks, C.K. and Naslund, H.R., 2012. High-resolution insights into episodes of crystallization, hydrothermal alteration and remelting in the Skaergaard intrusive complex. Earth and Planetary Science Letters, 355: 199-212.

ONLINE REFERENCES

Avannaa Resources Ltd., 2011. http://www.avannaa.com/project-detail/flammefjeld-molybdenum/
Government of Greenland, 2016. https://www.govmin.gl/images/list_of_licences__20160105.pdf.
Greenland Minerals and Energy Ltd., 2016. www.ggg.gl.
Ironbark Zinc Limited, 2012. http://ironbark.gl/projects/greenland/citronen/
KGHM, 2015. http://kghm.com/en/mineral-resources-and-reserves-report.
Platina Resources Ltd., 2013. http://www.platinaresources.com.au/files/announcements/2013_07_23_-_ASX_-_PGM_-_New_Resource_Estimate_for_Skaergaard_Gold_and_PGM_Project_East_Greenland.pdf.
Red Rock Resources, 2016. http://www.rrrplc.com/projects/greenland/.
Rimbal Pty Ltd., 2016. www.tanbreez.com.
West Melville Metals Inc., 2016. www.westmelville.com.