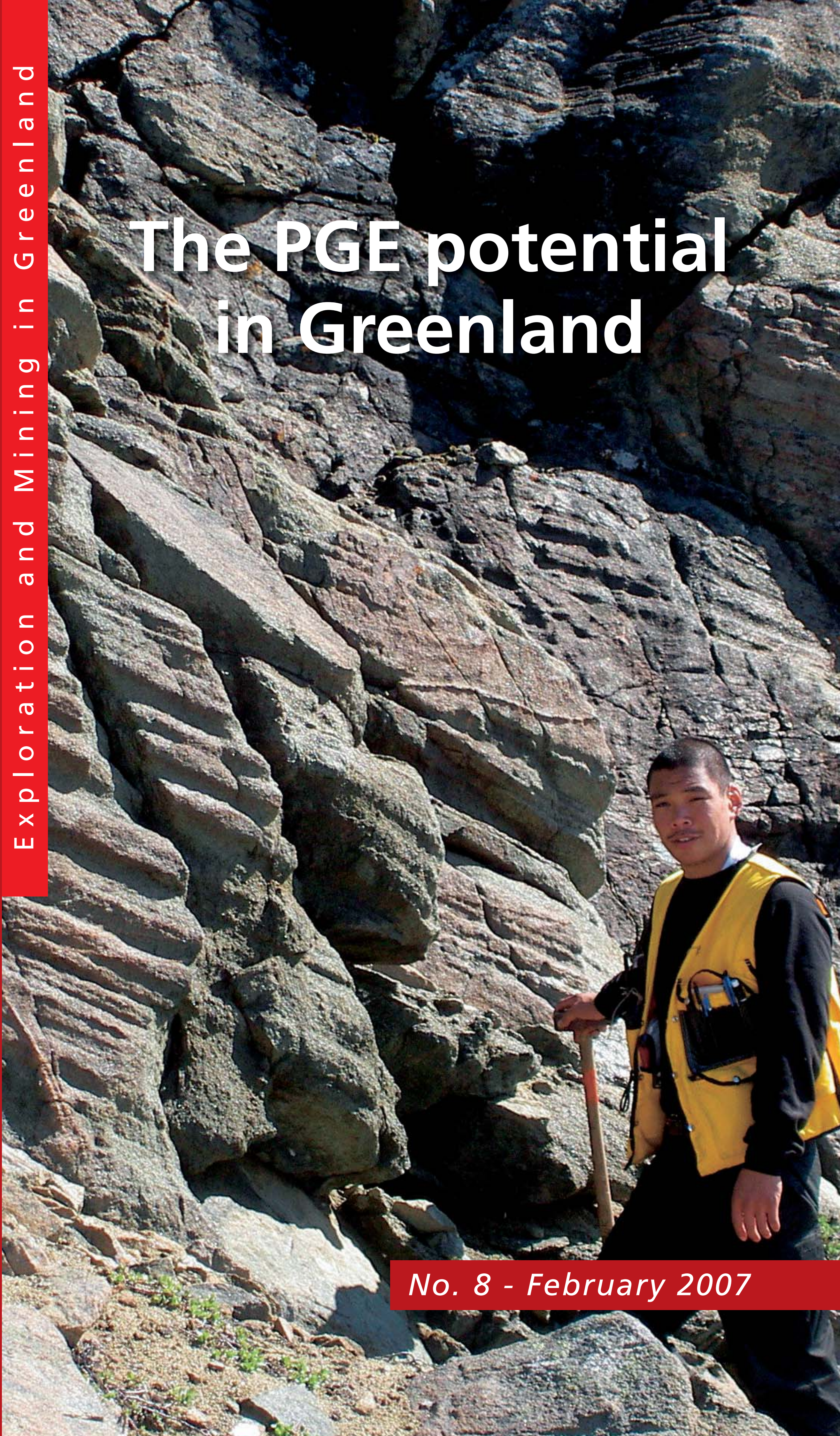
GEOLOGY AND ORE

Exploration and Mining in Greenland

The PGE potential in Greenland



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The PGE potential in Greenland

Index map of localities on Greenland.

The potential for Platinum Group Element (PGE) resources in Greenland is clear and encompasses mineralisation in Precambrian to Palaeogene environments. The PGE potential in Greenland attracted interest already in the 1960s and has been part of the Survey's considerations since the 1970s .

The corporate interest in PGE targets in Greenland was initiated by Kryolitselskabet Øresund in the early 1960s and was related to a suite of norites in West Greenland. Platinomino A/S was established in 1968 to search for Merensky Reef type deposits in the Fiskenæsset Complex. In the late 1980s, Platinova Resources prospected known PGE indications in Amitsoq peridotites in southern Greenland. Since 1995 norites in the Tasiilaq region, East Greenland have been the target for Cu-Ni-PGE exploration by several companies. In 2005 NunaMinerals initiated PGE exploration in the mafic intrusions of the Fiskefjord area. In the 1980s GEUS and university groups focused on the formation of massive sulphides in the Palaeogene basalts of Disko Island, which has led to continued exploration for Noril´sk type mineralisations. Renewed academic studies and exploration by Platinova Resources in the classic Skaergaard intrusion (East Greenland) resulted in 1987 in the discovery of a reef-type, world class PGE deposit.

Geological environment for PGEs

Traces and showings of PGE mineralisation are numerous in the Precambrian terrains of Greenland. The Archaean of south-west Greenland hosts anorthositic suites, like the reworked Fiskenæsset complex (south of Nuuk). The complex hosts accumulation of chromite in anorthosite, and traces of PGE mineralisation in Ni-sulphide segregations in amphibolite. The Archaean shield north of Nuuk hosts the Maniitsoq Norite Belt; a suite of leuconorite and gabbro rocks in irregular bodies with traces of PGEs related to Ni-Cu-sulphide mineralisation. Within the same region, large ultramafic bodies and mafic layered complexes locally show traces of PGE-mineralisation. The Proteroizoic Ammassalik Belt on the East coast of Greenland hosts a suite of norites to which are related massive sulphide occurrences, potentially PGE-bearing.

Palaeogene Ni-sulphide occurrences with potential PGE concentrations are known in the West Greenland Basalt Province. Exploration has been carried out for more than a century in the Disko Bay region. Known occurrences are mainly hosted in presumably contaminated lavas, and in dykes at the base of the volcanic succession. Only reconnaissance investigations have been performed in similar environments in East Greenland.

The main focus of PGE exploration in the Palaeogene of East Greenland has been the layered mafic intrusions in which many mineralisations have been located, including the Kap Edvard Holm complex and the world class Platinova Reef within the Skaergaard intrusion.

Archaean and Palaeoproterozoic settings

Fiskenæsset anorthosite complex:

Chromitite layered anorthosite intrusion.

The Archaean Fiskenæsset anorthosite complex, with a strike length of > 200 km, is hosted in high grade tonalitic gneiss. The complex is named after the village Fiskenæsset/Qeqertarsuatsiaat. The floor of the intrusion has not been identified, but the roof found immediately below flows of mafic pillow lava. A detailed stratigraphy shows a succession with a lower gabbro unit followed by an ultramafic unit with mineral-graded dunites, peridotites and hornblendites. These are followed by a lower leucograbbro unit with minor ultramafic layers and a middle gabbro unit with minor layers of anorthosite and ultramafics and peridotites (hornblende-orthopyroxene-spinel). Above these units follow the upper leucogabbro unit with abundant chromitite bands, an anorthosite unit and the upper gabbro unit. The complex has been repeatedly deformed and metamor-

Chromitite banded anorthosites from the Fiskenæsset anorthosites complex, southern West Greenland. Photo: GEUS.

phosed under amphibolite – and locally granulite facies conditions.

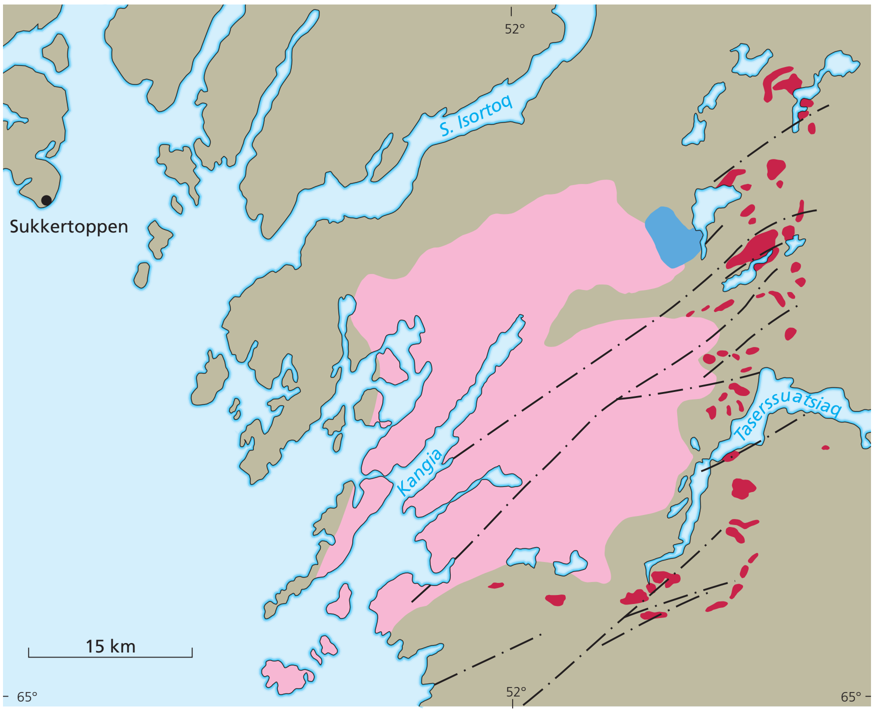
Exploration

PGE exploration has been limited. In the 1970s Platinomino A/S searched for Merensky type platinum deposits. The impetus was the discovery of an approx. 1 metre wide bronzitite layer with discrete chromite banding. The bronzitite contains minor nickel sulphides. Assays gave very promising results of up to 0.6 ppm Pt and 3 ppm Pd which, however, could not be confirmed.

In 1980 study of one stratigraphical section in the anorthosite complex showed that PGEs are concentrated mainly in ultramafic lithologies and chromitites. The latter contain up to 310 ppb Pt, 175 ppb Pd and 220 ppb Rh. Similar concentrations also occur in anorthosites and leucogabbros rich in disseminated sulphides.

In 1991 GEUS resampled the bronzitite and a few other parts of the anorthosite complex. The bronzitite gave 74 ppb Pt and 115 ppb Pd. In other parts of the anorthosite complex, several-hundred-metre-thick

Bronzitite layer in anorthosites from the Fiskenæsset anorthosites complex, southern West Greenland. Photo: GEUS.



Sketch map of the West Greenland Norite Belt.

lenses of ultrabasites with small amounts of sulphide have been found. Some have been chip and channel sampled. The best results so far are 83 ppb Pt and 693 ppb Pd, average over 2 metres. An ultramafic sheet near the bronzitite unit yielded 68 ppb Pt and 361 ppb Pd over 1 metre.

Sillisissanguit Nunaat - Maniitsoq Norite Belt:

Mafic intrusions and amphibolite layers.

The Norite Belt (15 x 75 km) is located east of Maniitsoq and hosts a suite of irregular bodies of basic rocks intruding into the regional gneiss complex of the Akia terrane. The bodies vary in size from 2 x 4 km down to 10 x 20 m. They are predominantly composed of gabbronorite and leucogabbro, collectively referred to as norite. Primary textures, such as igneous layering, are locally preserved. Elevated Ni, Cu and PGE concentrations are found in sulphide showings of apparently magmatic origin. The sulphides may show some degree of metamorphic remobilisation.

The norite rocks are very homogeneous bodies with rare igneous banding composed of alternating layers of plagioclase and hypersthene with accessory chromite. Amphibolite layers are locally associated to the norites.

Geotectonic setting

The Norite Belt is located along the eastern flank of the dome of the Finnefjeld gneiss complex. The structure of the belt seems controlled by the 3034 Ma old Finnefjeld gneiss. The norites appear little affected by the high grade retrograde metamorphism observed in the surrounding basement. The Norite Belt can be divided in a northern part characterised by few large norite bodies and a southern part of several, but smaller bodies and pods of norite.

The age of the Norite Belt is uncertain, but is probably around 3.0 Ga. Post-kinematic diorite intrusions in the Niaqunngunaq/Fiskefjord region (south of the Norite Belt) are tentatively correlated to the Norite Belt. The diorites are 2975 ± 13 Ma old.

Exploration

The norite bodies have been targets for exploration since 1965, but only a few PGE analyses are available from the early exploration. Kryolitselskabet Øresund A/S reported a typical Ni:Pd+Pt ratio in sulphide mineralisation of 50 000:1. New analyses from 2001 gave:

Igneous layering in a norite body from the West Greenland Norite Belt, Sillissisanguit nunat. Photo: GEUS.

Typical weathered surface of a norite boulder from the West Greenland Norite Belt, Sillissisanguit nunat. Photo: GEUS.

Rustzone enriched in PGE (Σ 2.8 ppm) in an amphibolitic sequence along the eastern flank of the West Greenland Norite Belt. Photo:GEUS.

- Peak values for Pd of 0.6 ppm in three sulphide-bearing samples of norite and amphibolite, and of 0.2–0.4 ppm in five sulphide-bearing samples of norite and amphibolite.

- A peak value for Pt of 2.2 ppm in one sample and of 0.7 ppm in four samples, all from heavily mineralised and altered gabbro and amphibolite related to the norites. Five samples of mineralised norite showed concentrations of 0.2–0.6 ppm.

- Four mineralised samples show a total PGE (Pd+Pt) of 1.0–2.7 ppm

Mineralisation and associated rock types

Elevated PGE numbers are found in norites and amphibolites related to zones enriched in sulphides. Rust zones and gossans identify zones enriched in sulphides. The sulphides occur as disseminations, veinlets, interstitial fillings and as more massive lenses. The showings are generally a few tens of metres long. The sulphide occurrences show an uneven distribution. No economic deposit has been located, despite the common occurrence of sulphide accumulations. The mineral assemblage is rather uniform, with pyrrhotite as the predominant mineral accompanied by chalcopyrite, pyrite and pentlandite in a primary texture together with pyrite, linneaite, bravoite and magnetite in replace-

Slope with weathered dunite from the Fiskevandet region, southern West Greenland. Photo: NunaMinerals A/S.

Drilling in dunite by NunaMinerals A/S in the Fiskevandet region, southern West Greenland. Photo: NunaMinerals A/S.

ment textures. The average sulphide content in the mineralised rocks is around 2 vol.% and locally up to 25 vol.%.

The Ni-Cu sulphide occurrences show a rather uniform Pd /Pt, but the absolute concentration is dependent on the sulphide content. High concentration - up to 2.7 ppm - is believed to be the result of remobilisation.

Fiskefjord–Amikoq:

Ultramafic intrusions: irregular bodies of dunite and peridotite.

Several layered mafic to ultramafic intrusions are embedded in a supracrustal belt within the Archean gneiss terrain. Igneous layering is common, despite strong deformation.

Exploration and ore composition

NunaMinerals A/S acquired the Fiskefjord licenses in 2005 and initiated PGE exploration soon after. Stream sediment samples demonstrate a wide range of PGE concentrations from weakly anomalous to a maximum content of >600 ppb, combined Pt and Pd. NunaMinerals named the two prospect subareas Amikoq and Fiskevandet. Exploration drilling is ongoing in the Amikoq area.

Analysis of whole-rock samples has returned values up to 4.5 ppm PGE (com-

Sampling site in scree with Pt-enriched weathered amphibolite bordering dunite, Fiskevandet region, southern West Greenland. Photo: NunaMinerals A/S.

Hornblendite intrusion from the Amitsoq locality, South Greenland. Photo: GEUS.

bined) and samples show high Pt/Pd ratios. Most samples have high contents of Cr and Ni (up to 3.7 % and 2.8 %, respectively) and moderately high Cu. The majority of samples are depleted in S and sulphides are rarely observed in hand specimens.

Whole-rock samples are Pt-dominated with Pt/Pd ratios around 2.7. Cu/Pd displays a wide range, indicating that the physical conditions were favourable for substantial PGE enrichment in the melt during mantle melting. The parental magma(s) were relatively PGE-rich and S-undersaturated and could potentially have generated significant PGE mineralisation. A high Pt/Pd ratio is observed at three localities.

Tasiilaq:

Ammassalik Igneous complex.

The syntectonic norite complex is located within the northern half of the Ammassalik Mobile Belt, assumed to be the eastern continuation of the Paleoproterozoic Nagssugtoqidian orogen in West Greenland and the Torngat orogen in Canada. The belt consists of alternating re-worked Archaean rocks, with tectonically interleaved sheets of quartzo-feldspathic orthogneisses and early Proterozoic supracrustal rocks including komatiitic ultramafics.

The Ammassalik Igneous complex in the Tasiilaq area is enveloped by supracrustal gneisses and has been the object of exploration since 1995. Exploration in the Ammassalik Island and Kitak concessions has been conducted since 1998 by NunaMinerals A/S and later by Inco Ltd and Diamond Fields International. A joint venture operation between Diamond Fields International and GEOARC/PF&U was initiated in 2003.

Exploration

Early exploration led to the discovery of Ni-Cu sulphides hosted in a komatiitic setting. A lens of massive sulphide (440 m^2) was found in partly serpentinised ultramafic rocks hosted in gossanous supracrustals on the south coast of the Ammassalik Island. Systematic surface sampling of the lense showed an average of 0.98 % nickel, 0.33 % copper, 553 ppm cobalt and 510 ppb combined Au-PGE.

The Ammassalik occurrence displays Proterozoic komatiite-related Ni-Cu deposits. The komatiitic host rock has a high magnesium content ranging from 25 to 30 wt.%. Diamond drilling at three localities in 2005 outlined a new sulphide occurrence with up to 1.5% nickel.

Amitsoq:

Amitsoq-Nanortalik peridotite intrusions.

Four PGE-bearing ultramafic hornblende peridotite intrusions have been recorded on Nanortalik peninsula and the island of Amitsoq in South Greenland. The intrusions were investigated in 1987 by Platinova Resources Ltd. and Boulder Gold N.L. Exploration ceased after a few years due to modest PGE contents. The ultramafic plugs in the Nanortalik region may be related to an appinite suite observed throughout the Ketilidian orogen across the southern tip of Greenland.

Rusty layer of iron basalt at the Asuk beach on the northern coast of Disko, central West Greenland. Photo: A.K.Pedersen.

Two small plugs of layered ultramafics occur on the south shore of Søndre Sermilik.

- A hornblende peridotite body is exposed five km south of the Ippatit valley. It hosts the "Waldorf" PGE showing. The peridotite body is exposed > 200 metres along the shore and 350 metres inland. Small exposures of peridotite indicate that the body is >2.5 km across. The peridotite contains about 1 vol.% disseminated sulphides. Grab samples showed up to 280 ppb platinum and 330 ppb palladium, and drill-core samples yielded up to 100 ppb Pt and only 40 ppb Pd.
- A hornblendite-peridotite intrusion occurs on central Amitsoq. It has been observed over a length of 1.5 km, and from the shore and inland to 335 m a.s.l. It is an E-W striking dyke-like body that pinches and swells in three dimensions. Widths vary between 90 and 250 metres. The sulphide content is about 0.2 vol. % , but reaches 15% in 10-20 cm wide zones. Pyrrhotite, pentlandite, chalcopyrite, and cubanite dominate the sulphides, accompanied by 5-10 vol. % magnetite. Traces of gold, platinum, and palladium were reported from the showing in 1970.

Basalt chunk with accumulation of metallic iron, Disko Island, central West Greenland. Photo: A.K.Pedersen.

Palaeogene settings (West and East coast)

Disko Island:

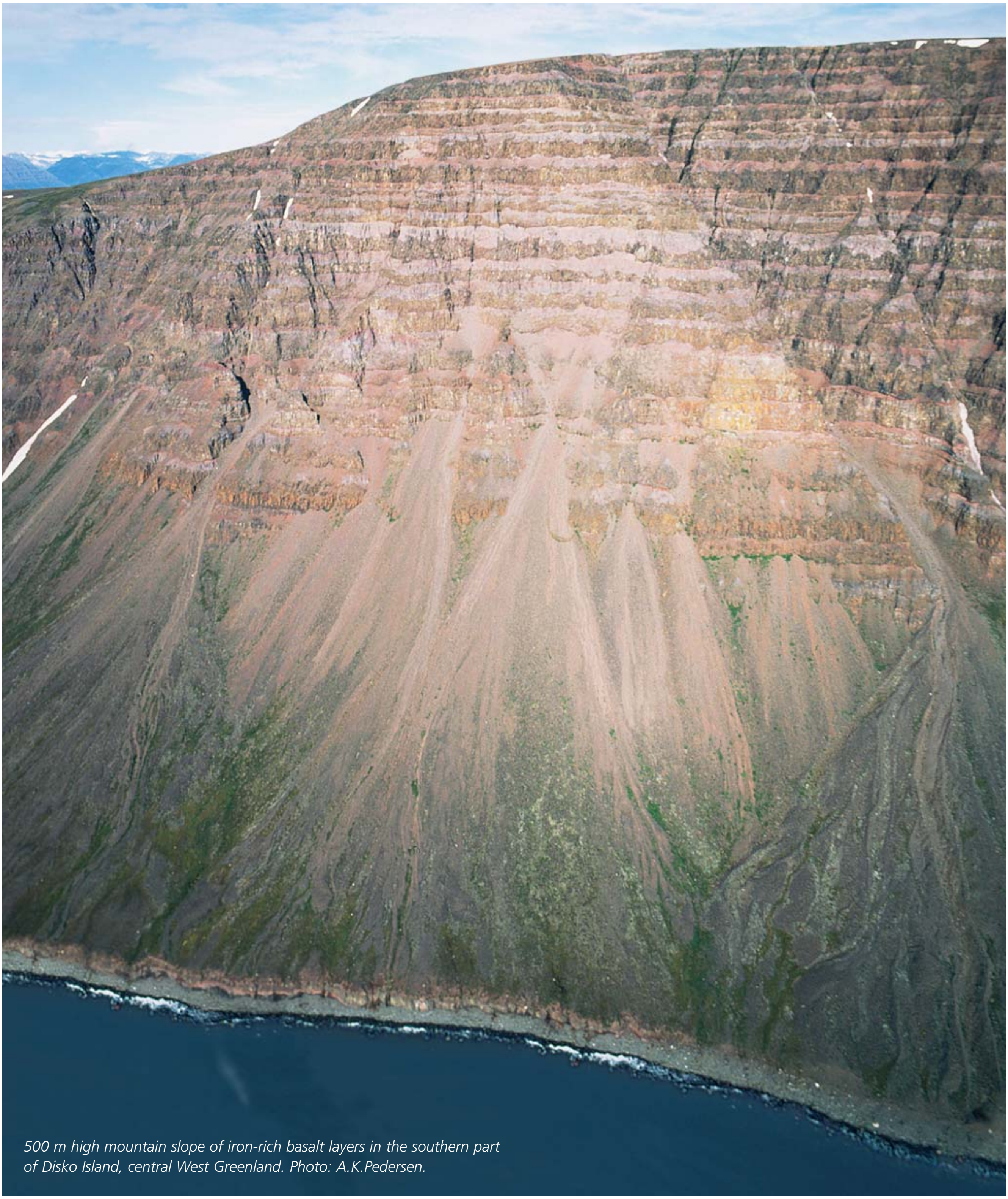
Flood basalt related Palaeogene Ni-sulphide occurrences with PGE (Noril´sk type).

For more than a century the Palaeogene West Greenland Basalt province has seen exploration for Ni-sulphides and PGE. The known occurrences in the Disko Bugt region are mainly hosted in contaminated lavas, and in dykes at the base of the volcanic succession. The province is believed to have a significant potential for PGE-Ni-mineralisation.

Palaeogene picrite and basalt lavas overlie thick Upper Cretaceous and Palaeogene sediments. Most of the voluminous onshore volcanics were deposited in a short period of time 61–59 Ma ago. The Palaeogene dyke intrusions, such as the Hammer Dal complex on northwest Disko, contain nickel-bearing pyrrhotite and native iron formed by processes akin to Noril´sk type Ni-Cu-PGE deposits. The analogy to Noril´sk has attracted exploration, e.g. by Falconbridge and Vismand. The Hammer Dal complex on Disko belongs to a swarm of mineralised dykes fed by contaminated magma and the complex has a number of attractive characteristics. It is the richest metallic iron deposit in the region and it relates spatially to the most intense hydrothermal alteration field on Disko. A field that may imply the existence of a large intrusion at depth. Ground geophysics have revealed a large conductor at 400–500 m below the present surface. The conducter could represent a volcanic body with sulphides and metallic iron.

Exploration and evaluation of potential resources

The prospective area on north-west Disko (Hammer Dal) is defined by a swarm of NW-SE to N-S striking dykes and subvolcanic intrusions of basaltic melt. The dykes were probably feeders to large volumes of contaminated lavas. The intrusions host deposits of metallic iron and sulphides, all of which at the moment are too small to be economically viable. "Branched iron

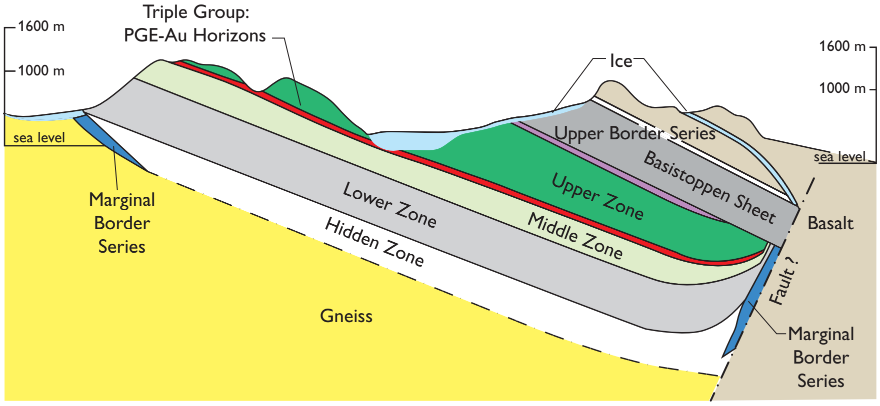


500 m high mountain slope of iron-rich basalt layers in the southern part of Disko Island, central West Greenland. Photo: A.K.Pedersen.

bodies" dominate the ore cumulates deposited along the steep (70º) contacts by a mechanism that is not completely understood.

The presence of iron cumulates suggests considerable magma transport capability in the magma. The amount of deposited iron typically reflects local conditions of deposition rather than the general potential of the intrusive system. Apart from native (metallic) iron (and alloys), pyrrhotite and pentlandite are common. Sulphide-enriched basalt (together with accumulated, metallic iron) shows > 1% Ni and elevated PGE contents, up to 0.5 ppm. A final evaluation of the PGE potential in this setting is not possible at present.

Exploration was carried out in the area in the 1980s by Greenex/Cominco Ltd. A Platinova A/S-Falconbridge Greenland A/S joint venture conducted an extensive pro-



Map of a N–S section through the Skaergaard intrusion in southern East Greenland.

gramme between 1991 and 1996. The programme included regional mapping and sampling and diamond drilling.

Since 2003 Vismand Exploration Inc. has searched for possible deposits on Disko Island. The company collected three geophysical "Titan 24" cross-sections in the northern part of Disko Island. The aim was to locate nickel-enriched, deeper-lying, lava conduits that connect to successions of contaminated flood basalts. A large conductor at 400–500 m below the present surface may be such a mineralised magma conduit.

East Greenland Palaeogene intrusions:

Layered gabbro intrusions.

More than sixty intrusions are recorded in the Palaeogene East Greenland volcanic rifted margin. The plutonic suites range from ultramafic to felsic, from depleted basaltic to highly alkaline, and from upper crustal intrusions to subvolcanic centres and breccia pipes with related epithermal vein systems. The East Greenland magmatism occurred from 61 to 13 Ma ago. The province hosts the world-class Skaergaard PGE and Au deposit.

The East Greenland volcanic rifted margin developed prior to, during and after the onset of seafloor spreading in the North Atlantic. The flood basalt succession is >7km thick. Major sill complexes occur in Mesozoic to Paleocene sediments below the lavas.

A large domal uplift at the "Kangerlussuaq Triple Junction" (68°N) is associated with the surfacing of the proto-Iceland plume (55–50 Ma). Early picritic lavas show strong similarities to Hawaiian lavas, whereas overlying flood basalts show increasing Icelandic affinities. A transition from intraplate to spreading-ridge magmatism is illustrated.

Coast-parallel dyke swarm systems are mostly related to magmatic centres dotted along the East Greenland coast. Deep erosion has exposed a number of magmatic centres at and south of 68°N. They comprise early gabbros - some with PGE and Au mineralisations, followed by intermediate to felsic intrusions.

Exploration and resources

Mafic intrusions at Kangerlussuaq (68°N) and down the east coast to Nualik (67°N) have seen focussed PGE exploration since 1987. Plationova A/S, Quadrant Resources and later Galahad Gold Ltd and Skaergaard Minerals Corp. have conducted the exploration. In 1987 the Skaergaard intrusion was recognised as a large low-grade PGE and Au deposit. The concession is presently held by Platina Resources Ltd. Several other mafic intrusions show PGE mineralisation, but apart from Skaergaard, no significant deposits have been identified.

The Skaergaard intrusion (68°N) and the Kap Edvard Holm complex (68°N) are representatives of stratiform PGE and Au mineral accumulation where the mineralisation is caused by sulphur saturation. Drilling in the Skaergaard intrusion has delineated a 1500 million tonne multi-element (platinum group elements, gold, silver, copper, titanium and vanadium) occurrence. The Kap Edvard Holm complex contains large-tonnage, low-grade, stratiform PGE-Au horizon developed in a replenish magma chamber.

The Kruuse Fjord intrusion (67°N) and Mikis Fjord Macrodyke (68°N) are representatives of contact-related and sulphide-hosted PGE mineralisation. Sulphides rich in platinum group elements are found at

Channel sampling of mineralised layers in the Upper Zone, of the Skaergaard Intrusion, southern East Greenland. Photo: GEUS.

contacts between mafic intrusive units and basement or other intrusive units.

The Skaergaard intrusion

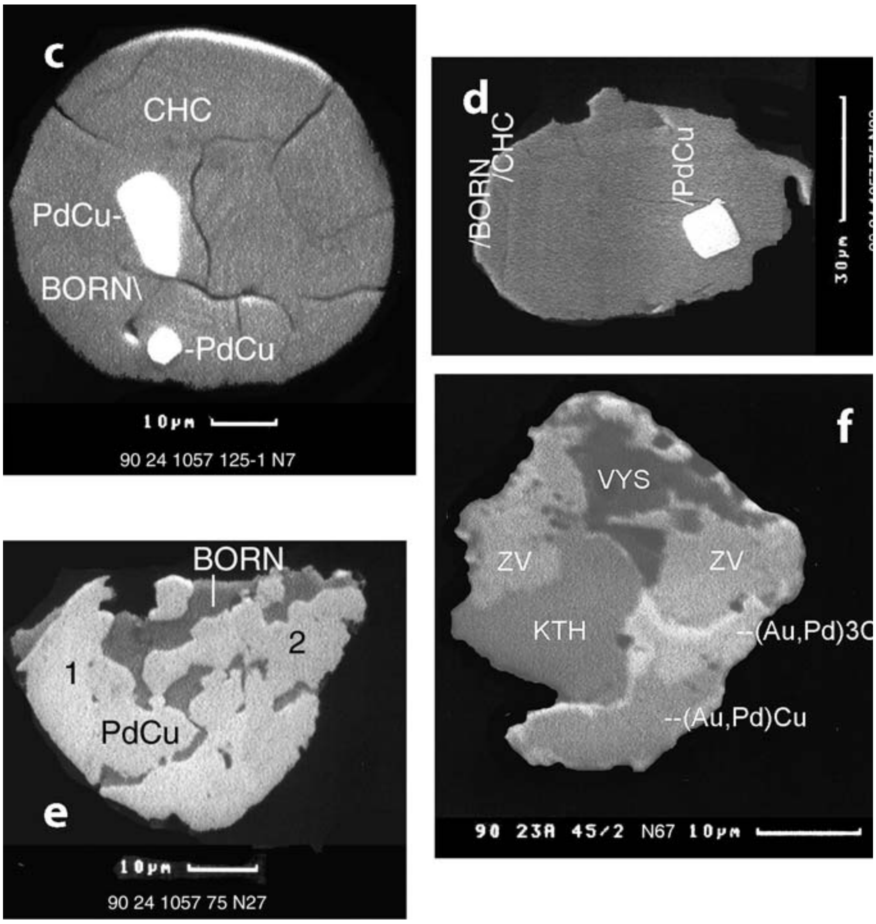
The intrusion was emplaced during the build up of the regional flood basalts and the initial stages of continental rifting and seafloor spreading in the North Atlantic. The intrusion is currently modelled as a box-like magma chamber c. 11 by 7.5 km in surface area with an original stratigraphy of c. 3.8 km.

The magma solidified in concentric zones toward the centre of the intrusion. Phase layering, i.e., liquidus parageneses, and cryptic variation in liquidus minerals allow a subdivision of the intrusion. The cryptic variation in minerals is significant. Olivine evolves from c. Fo70 to Fo1, and plagioclase from c. An70 to An10.The deepest gabbros in the Layered Series (LS) are not exposed and are referred to as the Hidden Zone (HZ). The exposed rocks of LS are divided in Lower Zone (LZ), Middle Zone (MZ), and Upper Zone (UZ).

The mineralisation is hosted in the Triple Group in the upper part of the MZ after the crystallisation of c. 70 % of the parental ferrobasalt magma. The Triple Group is the name of a c. 100 m thick stratigraphy characterised by three, distinct, leucogabbro layers. The mineralisation is composed of five main levels and in total ten well-defined levels of enrichment in PGE (Pd-levels). The stratigraphic separation between main Pd-levels is c. 10 metres. All Pd-levels are perfectly parallel to the well-developed saucer-shaped magmatic layering in the host gabbros.

The number of developed Pd-levels decreases systematically toward the margins of the intrusion, where only one Pd-level (Pd5) is developed. Au is always concentrated in or just above the top of the locally developed Pd-levels irrespective of the number of developed Pd-levels. The stratigraphic separation between the base of Pd5 level and the top of the Au-rich zones increases from c. 5 metres at the margin to c. 60 metres in the centre of the mineralistion.

The mineralisation has a low suphide content (<0.5 vol. % bornite and chalcosite). The precious metal grains occur in sulphide droplets in liquidus minerals or groundmass or as free precious metal droplets in the groundmass of the Ti-, V- and Fe-rich host rock. The dominant PGE mineral is skaergaardite (PdCu) in the centre of the intrusion, and zviagintsevite (Pd_3Pb) at the eastern margin. The Au mineralogy is more complex, but dominated by tetra-auricupride (AuCu).



Back scatter images of selected Skaergaard minerals. c–d: skaergaardite (PdCu) in a sulphide droplet; e–f: free intergrowths of various noble metals minerals.

The Skaergaard deposit is a PGE-Au dominated multi-element mineralisation. The host rocks are rich in titanium, vanadium and iron. A 44 m profile across the deposit indicates average contents of 6.6% TiO_2, 1.3 kg/t V_2O_5 and 19% Fe_2O_3 in the host rock of the precious metal accumulation. The lowest Pd-level (Pd5) is the main source of PGE and estimated to contain 104 million tonnes with of 0.11 g/t Au, 1.91 g/t Pd and 0.16 g/t Pt. The combined gold zone is estimated to contain 107 million tonnes with 1.68 g/t Au, 0.59 g/t Pd and 0.05 g/t Pt.

Concluding remarks

The magmatic provinces in Greenland's geology cover all periods of crustal evolution. Today PGE exploration can benefit from dedicated exploration efforts for precious elements and an increased search for nickel, which has been carried out in recent years within a variety of magmatic provinces.

Greenland has promising PGE deposits of world-class scale, as well as smaller scale occurrences, some with a proven PGE potential, and others not yet fully explored.

Layered sequences in the Upper Zone of the Skaergaard Intrusion, southern East Greenland. Photo: GEUS.

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Front cover photograph
Layered dunite from the region of Fiskevandet, southern West Greenland. Photo: NunaMinerals A/S.

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