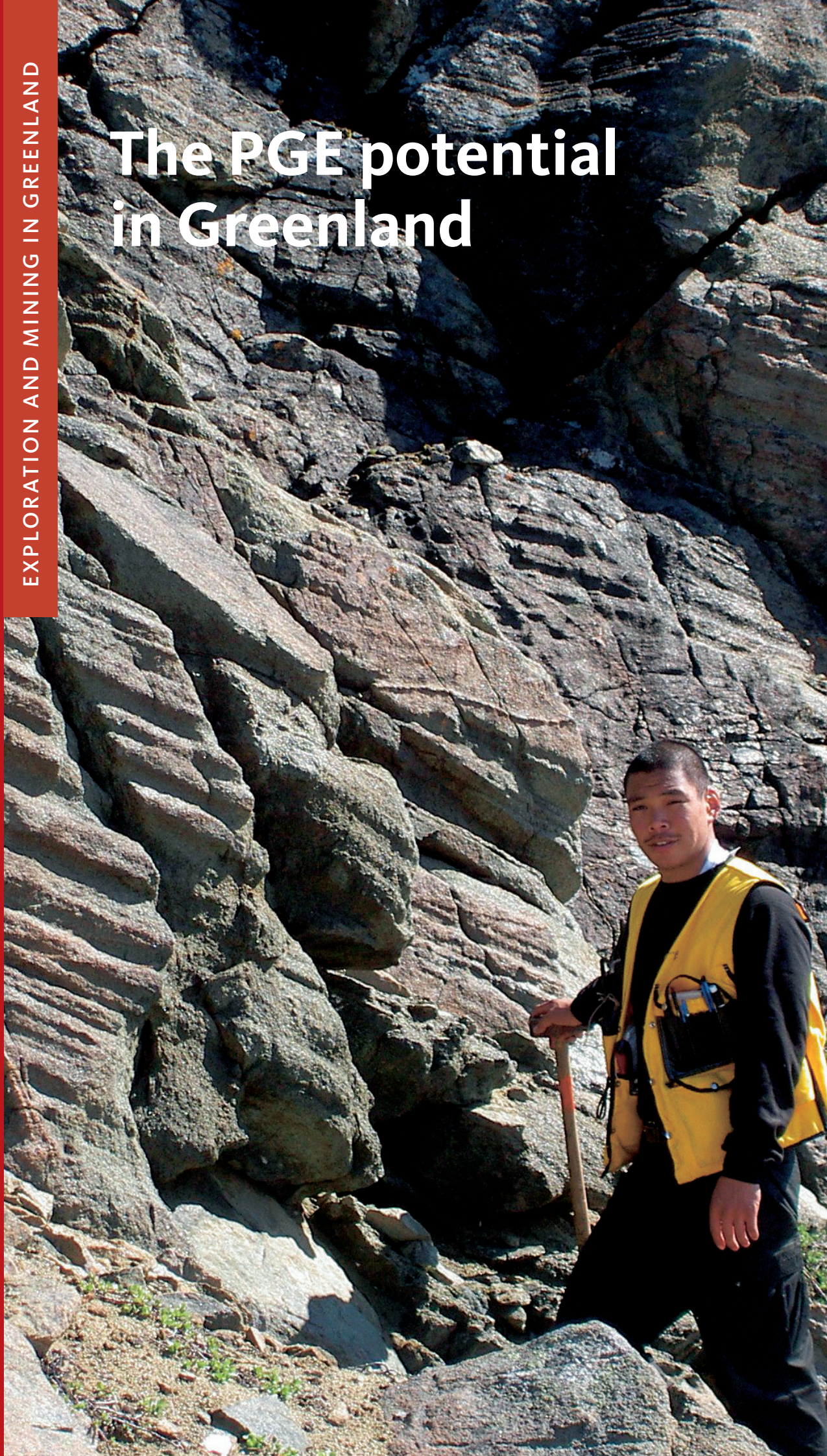
GEOLOGY AND ORE

EXPLORATION AND MINING IN GREENLAND

# The PGE potential in Greenland



# The PGE potential in Greenland

**The potential for Platinum Group Element (PGE) resources in Greenland attracted interest already in the 1960's and has been part of the Survey's considerations for more than 50 years. The PGE potential is found in Precambrian to Palaeogene environments. The most promising occurrence is in the Skaergaard intrusion in East Greenland.**

**The corporate interest in PGE targets in Greenland was initiated by Kryolitselskabet Øresund in the early 1960's and related to a suite of norites in the Archaean of West Greenland. In 1968, Platinomino A/S was established to search for Merensky Reef type deposits in the gabbroic Fiskenæsset Complex. GEUS and university groups focused In the 1980's on the formation of massive sulphides in the Palaeogene basalts of West Greenland. The research has led to continued exploration for Noril'sk type occurrences.**

**In the 1980's, Platinova Resources prospected known PGE indications in Amitsoq peridotites in Southern Greenland. From 1986 and into the 90'es their focus shifted to Paleaogene mafic intrusions in East Greenland leading to the discovery of a world-class PGE and Au deposit in the Skaergaard intrusion. Sub-economic occurrences were identified in more of the Paleaogene intrusive complexes and macrodykes. The exploration has continued to date. 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 exploration for PGE in the mafic intrusions of the Fiskefjord area.**


*Index map of localities on Greenland.*

## Geological environment for PGEs

Traces of PGE mineralisation are numerous in the 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, such as Amikoq, locally show sub-economic PGE concentrations. The Proterozoic Ammassalik Belt on the East coast of Greenland hosts a suite of norites enveloped in supracrustals with komatiites 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 lavas contaminated with crustal lithologies, and in dykes at the base of the volcanic succession. Reconnaissance investigations for similar mineralisation environments have been conducted in East Greenland.

The PGE exploration in the Palaeogene of East Greenland has been most successful. Here, layered gabbroic intrusions host PGE occurrences, including the world class Skaergaard PGE-Au Mineralization.

## Archaean to Palaeoproterozoic settings

**Fiskenæsset complex:**
Chromitite layered mafic intrusion

The Archaean Fiskenæsset 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 is found immediately below flows of mafic pillow lava. A detailed stratigraphy shows a succession

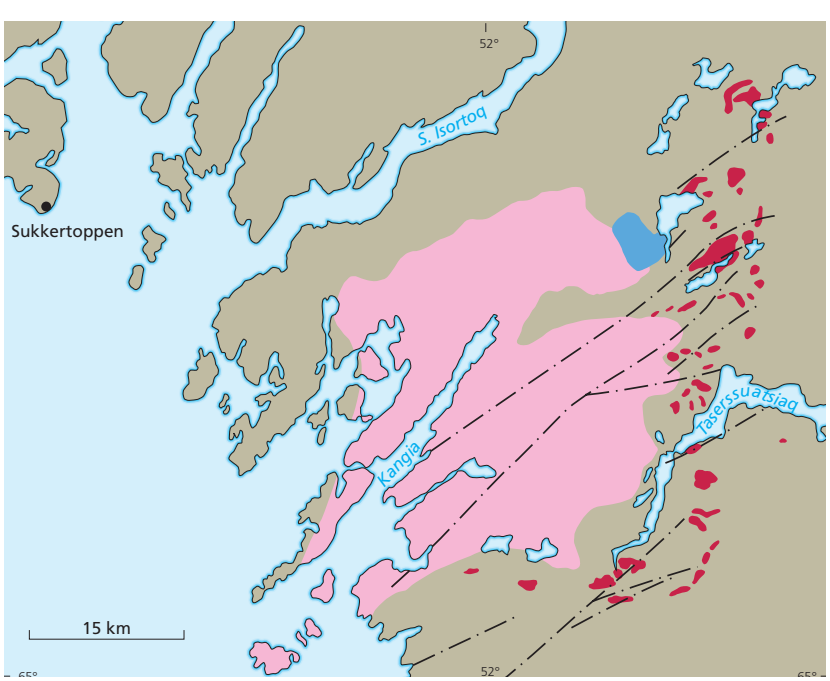
*Chromitite banded anorthosites from the Fiskenæsset anorthosites complex, southern West Greenland. Photo: GEUS.*

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 including hornblende-bearing peridotites). 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 metamorphosed under amphibolite, and locally granulite, facies conditions.

**Exploration**

In the 1970's 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 with improved analytical techniques.

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




Carbonatite
Norite
Finnefjeld gneis
Gneis undifferentiated
Fault

*Sketch map of the West Greenland Norite Belt.*

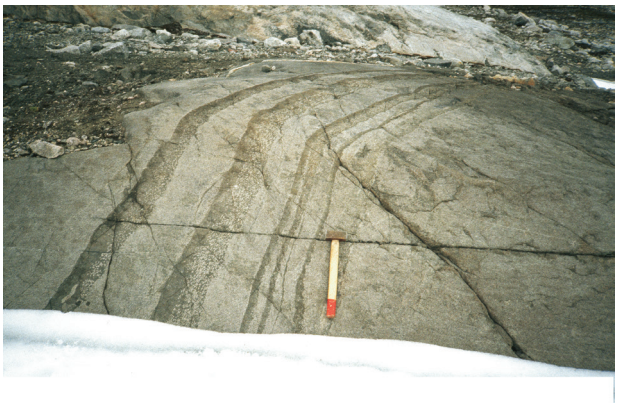
In 1980 the study of a single stratigraphic section in the anorthosite complex showed that PGEs are concentrated mainly in ultramafic lithologies and chromitites. The latter contain up to 310 ppb Pt, 175 ppb Pd and 220 ppb Rh. Similar concentrations also occur in anorthosites and leucogabbros rich in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

The most recent exploration by 21st North yielded grab samples with up to 6.6 g/t total PGE from a 30 to 70 metres thick ultramafic sequence that can be traced for >10 km. Wider sections returned up to 1.34 g/t PGE over 3 meters, 0.98 g/t PGE over 6 meters and 0.44 g/t PGE over 23 meters. The Pt/Pd ratio of c. 1:4.6 and up to 0.21 g/t Rh is found in selected samples.

**Sillisissanguit Nunaat - Maniitsoq Norite Belt:**
Mafic intrusions and amphibolite layers.

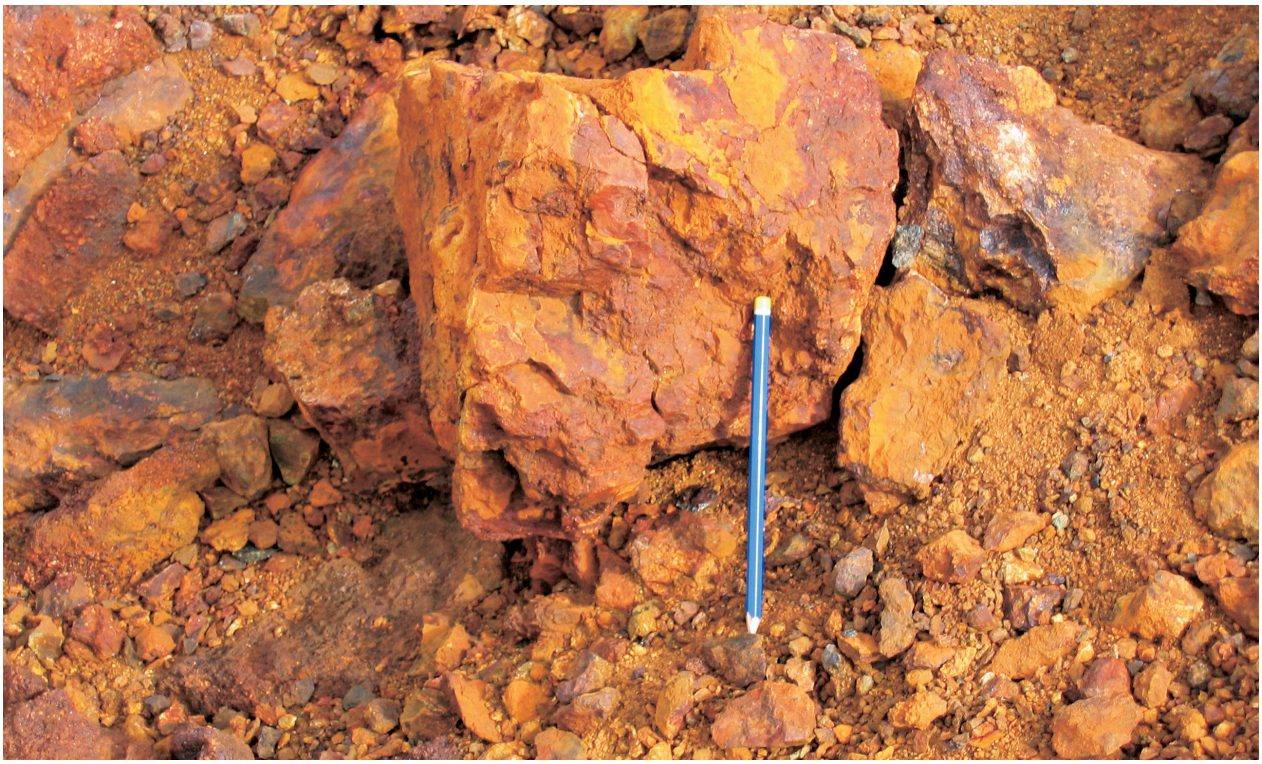
The Norite Belt (15 x 75 km) is located east of Maniitsoq and hosts a suite of irregular bodies of basic rocks intruding into the regional gneiss complex of the Akia terrane. The bodies vary in size from 2 x 4 km down to 10 x 20 m. They are predominantly composed of gabbronorite and leucogabbro, collectively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

**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 3.0 Ga.



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

*Typical weathered surface of a norite boulder from the West Greenland Norite Belt, Sillisissanguit 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*

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.

**Mineralisation and association rock types**

Elevated PGE concentrations 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, in veinlets, in interstitial fillings and as more massive lenses in a commonly homogenous and featureless norites. The showings are generally a few tens of metres long and unevenly distributed. The sulphide assemblage is rather uniform and dominated by pyrrhotite followed by chalcopyrite, pyrite and pentlandite in a primary texture, together with pyrite, linneaite, bravoite and magnetite in replacement textures.

**Exploration**

The norite bodies have been targets for exploration since 1965. 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 peak values <1 ppm PGE in sulphide-bearing samples of norite and amphibolite. Samples from related gabbros and amphibolites returned up to 2.2 g/t PGE

In the last decade the norites have been subject of continued nickel, copper and cobalt exploration by Premium Resources Ltd. (formerly North American Nickel). Despite Ni concentrations up to 5 wt% in metre thick sections of norite, PGE concentrations found to date remain low and <0.5 g/t. High concentrations of PGE up to 2.7 ppm in grab samples are believed to be the result of remobilisation.

*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.*

**Fiskefjord–Amikoq:**
Deformed and discontinuous norite sheets with ultramafics and amphibolites.

Several layered mafic to ultramafic complexes are embedded in a supracrustal belt within the Archean gneiss terrain. Igneous layering is common, despite strong deformation. The complexes are up to 150 metres thick and can be traced for >15 km. In the Amikoq complex the mineral occurrences are related to pyroxenite close to the margin to supracrustal paragneiss.

**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, of combined Pt and Pd. NunaMinerals named the two prospect subareas Amikoq and Fiskevandet.

Whole-rock samples returned up to 4.5 ppm PGE (combined) with a high Pt/Pd. 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 specimen. Drilling confirmed a continuous mineralised horizon with average concentrations of 0.5-0.78 g/t Pt+Pt over width of 4 metres. In the Arnaqquassaaq subarea, grab samples from the pyroxenite yielded up to 1.25 g/t Pt+Pd in the base of a feldspatic leuconorite.

**Tasiilaq:**
Komatiite related massive sulphide occurrences

The Ammassalik Mobile Belt is regarded 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 inter-leaved sheets of quartzo-feldspathic ortho-gneisses and early Proterozoic supracrustal rocks,

*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.*

including komatiitic ultramafics. The supracrustals envelop three syntectonic norite complexes from the icecap in the west to Kulusuk island on shores of the North Atlantic. The Ammassalik occurrence recalls Proterozoic komatiite-related Ni-Cu deposits. The komatiitic host rocks have magnesium contents ranging from 25 to 30 wt.%.

**Exploration**

The norites and komatiitic units of the supracrustals have been the object of exploration since 1995. The exploration was conducted by NunaMinerals A/S, followed by Inco Ltd and Diamond Fields International, GEOARC/PF&U, and 21st North.

The 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 near the margin of the Ammassalik norite complex on Ammassalik Island. Systematic surface sampling of the lens showed an average of 0.98% nickel, 0.33% copper, 553 ppm cobalt and 510 ppb combined Au-PGE. Diamond drilling at three localities, in 2005, outlined a new sulphide occurrence with up to 1.5% nickel. Grab samples from two sulphide occurrences on Ammassalik island showed up to 1.5 wt% Ni. 0.25 wt% Cu, 660 ppm Co and 623 ppm PGE+Au. Other komatiite-related sulphide occurrences were located 16 km to the NE on the northern side of the norite belt. Two grab samples showed up to 1.5 wt% Ni, 0.23 wt% Cu, 650 ppm Co with >600 ppm PGE+Au, and 1.5 wt% Ni, 0.30 wt% Cu, 995 ppm Co and 133 PGE+Au.

### Amitsoq:

Amitsoq-Nanortalik peridotite intrusions.

Four PGE-bearing ultramafic hornblende peridotite intrusions have been recorded on Nanortalik peninsula and Amitsoq island in South Greenland. 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. One hornblende peridotite body five km south of the Ippatit valley hosts the "Waldorf" PGE showing. The peridotite is exposed >200 metres along the shore and inland suggesting the body to be >2.5 km across.

The peridotite contains about 1 vol.% disseminated sulphides. Historical grab sample analyses show up to 280 ppb platinum and 330 ppb palladium. The intrusions were re-investigated in 1987 by Platinova Resources Ltd. and Boulder Gold N.L. but drill-core samples only yielded up to 100 ppb Pt and only 40 ppb Pd. Exploration ceased after a few years due to the very modest PGE contents.

## Palaeogene provinces

### West Greenland: Disko Island and Nuussuaq peninsula

Noril´sk type occurrences with PGE related to flood basalt

Historically, Disko island has been known for its occurrence of native iron and, for more than a century, the province has seen exploration for

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

Ni-sulphides and PGE. The known occurrences are hosted in contaminated lavas, and in dykes at the base of the volcanic succession.

Palaeogene picritic to basaltic lavas overlie thick Upper Cretaceous and Palaeogene sediments and were extruded between 61 and 59 Ma ago. The dyke intrusions on northwest Disko, such as the host of the Hammer Dal complex, contain nickel-bearing pyrrhotite and native iron formed due to contamination processes akin to those proposed for the Noril'sk type Ni-Cu-PGE deposits. The contaminated dykes were probable feeders to the large volumes of contaminated lavas. The dykes are spatially related to the most intense hydrothermal alteration on Disko and may imply the existence of a large intrusion at depth.

The known occurrences of metallic iron and sulphides are too small to be economically viable but are indicative for processes at depth. The presence of cumulates of native iron suggests considerable magma transport capability in the dykes. "Branched iron bodies" dominate the ore cumulates deposited on the steep (70°) contacts by a mechanism that is not completely understood. The amount of native iron at a given locality 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, metalic iron) shows >1 wt% Ni and elevated PGE, up to 0.5 ppm.

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

**Exploration and evaluation of potential resources**

The analogy to Noril'sk has attracted exploration by many exploration and mining companies. Exploration was carried out in the area in the 1980's by Greenex/Cominco Ltd. A Platinova A/S-Falconbridge Greenland A/S joint venture conducted an extensive programme between 1991 and 1996. The programme included regional mapping and sampling and diamond drilling.

From 2003 Vismand Exploration Inc., followed by a suite of exploration companies including Avannaaa Resources Ltd., have searched for possible deposits on Disko Island and Nussuaq. Vismand collected three geophysical "Titan 24" cross-sections in the northern part of the Island. The aim was to locate nickel-enriched, deeper-lying, lava conduits that connect to successions of contaminated flood basalts. The geophysical modelling suggests the presence of a large conductor at 400–500 m below the present surface that could represent a volcanic body with sulphides and metallic iron.

In the last decade the main focus has been on geophysical modelling for the identification of drilling targets. To date seven of such targets are identified and subject for further tests and modelling. Several concessionaires cover the volcanic province including 80Mile Plc. (formerly Bluejay Exploration Ltd.) and cooperation partners, e.g. KoBold Metals.

## East Greenland Palaeogene intrusions

Layered gabbro intrusions and related macrodykes.

More than sixty intrusions are recorded in the Palaeogene East Greenland volcanic rifted margin. The plutonic suite ranges from ultramafic to felsic, from depleted basaltic to highly alkaline, and

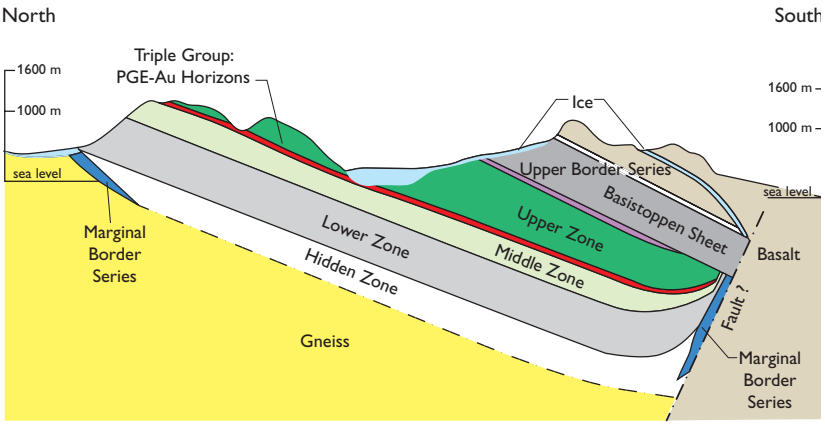
*500 m high mountain slope of iron-rich basalt layers in the southern part of Disko Island, central West Greenland. Photo: A.K.Pedersen.*

from upper crustal intrusions to sub-volcanic centres and breccia pipes with related epithermal vein systems. The East Greenland magmatism was long-lived 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 are >7 km thick. Major sill complexes occur in Meso zoic to Paleocene sediments below the lavas.

The magmatism and a large domal uplift at the "Kangerlussuaq Triple Junction" (68°N) is associated with the surfacing of the proto-Iceland plume (c.55Ma). 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 south of 68°N. They comprise early gabbros, some with PGE and Au occurrences (e.g. Kruuse Fjord complex), followed by intermediate to felsic intrusions




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

**Exploration and resources**

Mafic intrusions at Kangerlussuaq (68°N) and down the east coast to Nualik (67°N) and North to Lilloise intrusion (69°N) have seen PGE exploration since 1986. In 1987, the Skaergaard intrusion was recognized as a large low-grade PGE and Au deposit. Platinova Resources A/S, followed by Galahad Gold Plc., Skaergaard Minerals Corp., Platina Resources Ltd, Major Precious Metals Corp., Longland Resources Ltd. n and, at present, Intrusion Precious Metals Corp., Conico Ltd., Greenland Silver and Moly Aps have continued the exploration in the province. Reconnaissance exploration has been conducted in many other intrusions within the Paleogene province, but major PGE deposits have so far only been identified in the Skaergaard intrusions.

The Skaergaard intrusion (68°N) and the Kap Edvard Holm complex (68°N) host stratiform precious metal occurrences caused by sulphur saturation. Drilling in the Skaergaard intrusion has delineated a 1500 million tonne multi-element deposit with platinum group elements, gold, titanium, vanadium, and gallium. The Kap Edvard Holm complex contains large-tonnage, low-grade, stratiform PGE-Au horizon developed in a replenish magma chamber. Local enrichments show Pt and Au concentration at g/t levels.

The Kruuse Fjord intrusion (67°N), the Mikis Fjord (68 °N) and Togeda Macrodyke (68°N) are representatives of contact-related and sulphide- hosted PGE mineralisation. Sulphides rich in platinum group elements are found at contacts between mafic intrusive units and basement or other intrusive units.

## The Skaergaard intrusion

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

The magma solidified in concentric zones toward the upper central part of the intrusion. Phase layering, i.e., liquidus parageneses, and strong cryptic variation in liquidus minerals allow a subdivision of the intrusion. Olivine evolves from c. Fo70 to Fo1, and plagioclase from c. An70 to An10. The floor of the intrusion is not exposed and the lowermost parts of Layered Series (LS) 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) based on the presence, the loss, and the re-appearance of olivine on the liquidus of the evolving magma.

**The Skaergaard PGE-Au Mineralisation**

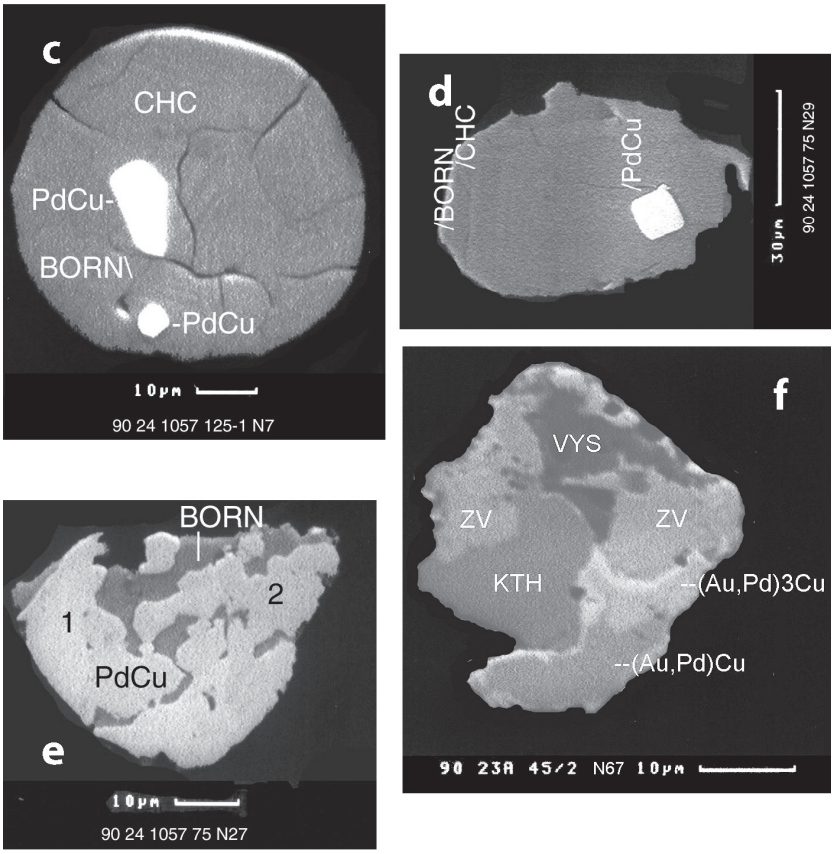
The deposit, hosted in the Triple Group in the upper part of the MZ, and formed after the crystallisation of c. 70% of the parental ferrobasaltic magma. The Triple Group is the name of a c. 100 m thick stratigraphy characterised by three, distinct, leucogabbro layers. The mineralisation is distributed along five main levels of a total ten well-defined 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.

At the margins, only a single Pd-level (Pd5) is highly enriched in PGE and Au, even though all the other overlying Pd-levels can be identified by distinct but sub-economic Pd anomalies. Progressively and toward the south-central part of the intrusion the Pd-levels

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

above Pd5 become enriched – first in Au and then followed by PGE. From the margin to the centre of the mineralisation, the highest concentration of gold jumps from Pd-levels Pd5, to Pd4, Pd3, Pd2, Pd1 and in a single drill core (DDH 90-18) to an overlying mineralisation level only defined by Au. The stratigraphic separation between the base of Pd5 level and the top of the Au-rich zones increases in drill cores from c. 5 metres near the margin to c. 60 metres in the centre of the south-central part of the intrusion.

The mineralisation has a low sulphide content (commonly 0.2 wt% and <0.5 vol. % bornite and chalcocite). The precious metal grains occur in sulphide droplets hosted in liquidus minerals, groundmass sulphide, 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, zviagintsevite ($Pd_3Pb$) at the eastern margin toward flood basalts, and at the western margin to the basements rocks the sulphides vasilite ($(Pd,Cu)_{16}(S,Te)_7$) and vysotskite (PdS). The Au-mineralogy is 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 resource**

Skaergaard is a PGE-Au dominated multi-element deposit. 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. A geological estimate suggest that the lower and main mineralisation level (Pd5) contains 450 million tonnes with an average of 2g/t (PGE + Au) over a stratigraphic height of 4-5 metres. In total, the geological estimate suggests the deposit to have a potential for >30 million oz PGE with a Pd/Pt ratio of 13 and >10 million oz Au.

The most current resource estimates based on drilled parts of the intrusion is quoted from Major Precious Metals (December 2022). It includes an indicated mineral resource of 160 million tonnes (Mt) at 2.23 g/t palladium equivalent (PdEq) resulting in 11.4 million contained ounces PdEq, including 8.04 Moz palladium (Pd), 2.70 Moz gold (Au), and 0.63 Moz platinum (Pt) at a cut-off grade of 1.43 g/t PdEq, and an Inferred Mineral Resource estimate of 205 Mt at 2.14 g/t PdEq resulting in 14.1 Moz PdEq, including 9.11 Moz Pd, 4.13 Moz Au, and 0.74 Moz Pt at a cut-off grade of 1.43 g/t PdEq.

## Concluding remarks

Magmatic provinces in Greenland span all periods of the crustal evolution. In addition to the possible PGE-dominated deposits in layered mafic complexes, PGE exploration can benefit from current exploration efforts for nickel, copper and cobalt for new green energy technologies. Although none are active in Greenland, the potential for development of PGE-producing deposits remains.

*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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