DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2015/61

Thule black sand province and regional geology - review and summary of data and work

Bo Møller Stensgaard, Kristine Thrane, Peter R. Dawes & Ole Bennike

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Frontispiece *View southeast from Moriusaq towards Interlak and behind that Kap Abernathy in the distance with the heavy sand-bearing raised beaches immediately inland.*
Photo: GEUS, 2015.

1. Introduction

The Thule black sand province in North-West Greenland (76°–78°N) composes a coastline several hundred kilometres long. Both ilmenite-rich and magnetite-rich sands occur with the former appearing to be the most extensive.

Elevated ilmenite concentrations (up to 60 wt% ilmenite with an average of 37%) are recorded on both active and uplifted beaches. The main source of the ilmenite sands is a regional Precambrian basaltic sill and dyke complex that intrudes the Precambrian basement. The sills have unusually high titanium content; up to 5.25 wt.% in whole-rock analysis. As a regional magmatic suite the rocks represent some of the most titanium-rich basalts in Greenland.

The chemical composition of the ilmenite is between 46–48 wt.% TiO_2 with moderate high vanadium content. CaO and MgO are consistently low; with average value of 0.1 wt.% for CaO and 0.67 wt.% for MgO. Uranium and and thorium content are also low. Earlier commercial studies on the black sand deposits have concluded that a high TiO2 content slag of a Moriusaq ilmenite concentrate could be produced because the level of other oxides is lower than most ilmenite smelted.

This report reviews the regional geology and known mineralisations in the area, especially the black sand deposits at Moriusaq. The exploration and research history is outlined and a list of the most important references is given as well as a list of sample material archived at GEUS.

2. Regional geology

The geology of the Thule district in North-West Greenland is described in detail by Dawes (2006) and much of the description in this section are extracted from this work.

In summary, the bedrock is dominated by two Precambrian provinces that extend across Baffin Bay into Canada: the high-grade Archaean-Palaeoproterozoic shield overlain by the intracratonic Mesoproterozoic-Neoproterozoic Thule Basin (Fig. 1).

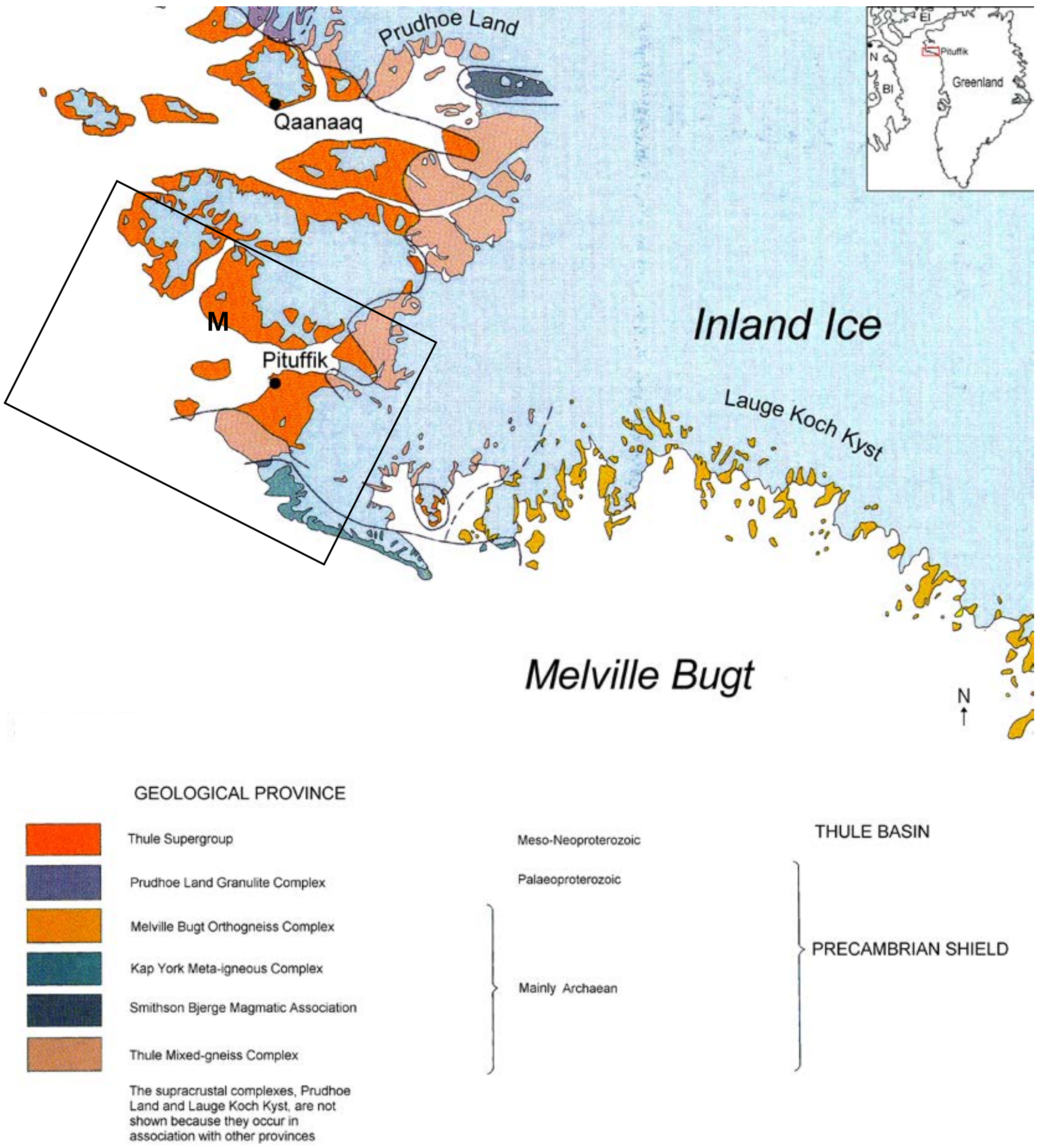

Figure 1. *Overview of the geological provinces present in the Thule region. The area in focus for this report is outlined by the box. Pituffik is the authorized Greenlandic name for the U.S. military air base that is known internationally by the name 'Thule'. The former settlement of Moriusaq is indicated with an 'M'.*

2.1 The Archaean shield

The crystalline shield consists of four different orthogneiss complexes (Fig. 1). The oldest gneisses yield an age of c. 2900 Ma, while detrital zircons as old as c. 3200 Ma have been found.

The high-grade orthogneisses and paragneisses of the Thule mixed-gneiss complex were intruded by two plutonic suites, the Kap York meta-igneous complex at c. 2700 Ma and the Smithson Bjerge magmatic association that includes a major anorthosite body. Subsequent deformation, metamorphism and migmatisation led to the formation of gneisses recognized within the Melville Bugt orthogneiss complex. Palaeoproterozoic sedimentation and volcanism represented by the Prudhoe Land supracrustal complex took place after c. 2250 Ma but had ceased by c. 1985 Ma when the Prudhoe Land granulite complex was emplaced. Rocks within the Lauge Koch Kyst supracrustal complex may correlate with the Palaeoproterozoic Karrat Group of West Greenland. Polyphase deformation with isoclinal folding, and regional metamorphism up to granulite-facies grade, affected the region c. 1900 Ma ago, with cooling until c. 1650. The shield hosts the regional Thule iron province with banded iron-formations.

A summary of the different complexes are given in Thomassen & Tukiainen (2009) and recited here below:

Thule mixed-gneiss complex. Highly deformed amphibolite- to granulite-facies gneisses making up the complex are exposed in the central part of the study area (Fig. 1). Main lithologies are quartzo-feldspathic to pelitic paragneisses, multiphase orthogneisses with genetically related granitic rocks, as well as minor mafic and ultramafic bodies.

Kap York meta-igneous complex. This suite of plutonic rocks occupying the whole of the Kap York peninsula contains metagabbro, metadolerite, diorite and tonalite with smaller units of light-coloured granodioritic and granitic rocks (Fig. 1). The rocks are thought to have been emplaced into the gneisses of the previous unit (Dawes 1976).

Melville Bugt orthogneiss complex. This complex forming the coastland of Melville Bugt is composed of massive to foliated amphibolite-facies gneisses and granitoids (Fig. 1). It contains at least some rocks that have been derived from the previous units.

Lauge Koch Kyst supracrustal complex. These supracrustal rocks, exposed mainly on nunataks and ice-draped peninsulas, make up a rusty-weathering succession of pelitic and mafic schists, quartzites and siliceous schists with banded iron-formation as well as amphibolite and pyribolite (Fig. 1). The age of the rocks is unknown; some could be Palaeoproterozoic.

2.2 Thule Basin

Extensional faulting, intracratonic basin formation and periods of basaltic magmatism occurred during Meso-Neoproterozoic time. After intrusion of the Melville Bugt dyke swarm at

c. 1630 the area was peneplained and the Thule Basin developed as an interior fracture and sag depocentre across the area that is now the northernmost Baffin Bay (Fig. 1). The basin is made up by the 6 km thick Thule Supergroup consisting of multicolour continental, fluvial, littoral to shallow-marine sedimentation and tholeiitic volcanism (minimum age: 1270 Ma). The lithostratigraphy of the supergroup is made up of five sedimentary groups of which four are present in the Thule area (Fig. 2; the Smith Sound Group constitute the northern basin margin facies of the Thule Basin and is not present in the Pituffik area). The Thule half-graben system (Fig. 3) in which the Thule Supergroup was deposited formed on top of the Archaean shield. The basin is cut by prominent basaltic rocks as sills (the Steensby Land sill complex) and dikes (the Thule dyke swarm), which yield ages of 1200-1000 Ma and 750-650 Ma, respectively. These sills have unusually high titanium content – up to 6% in whole-rock analysis. As a regional magmatic suite the rocks represent some of the most titanium-rich basalts in Greenland. Furthermore, the Thule Supergroup hosts pyrite and minor chalcopyrite mineralisation at the sill-sediment contact zones.

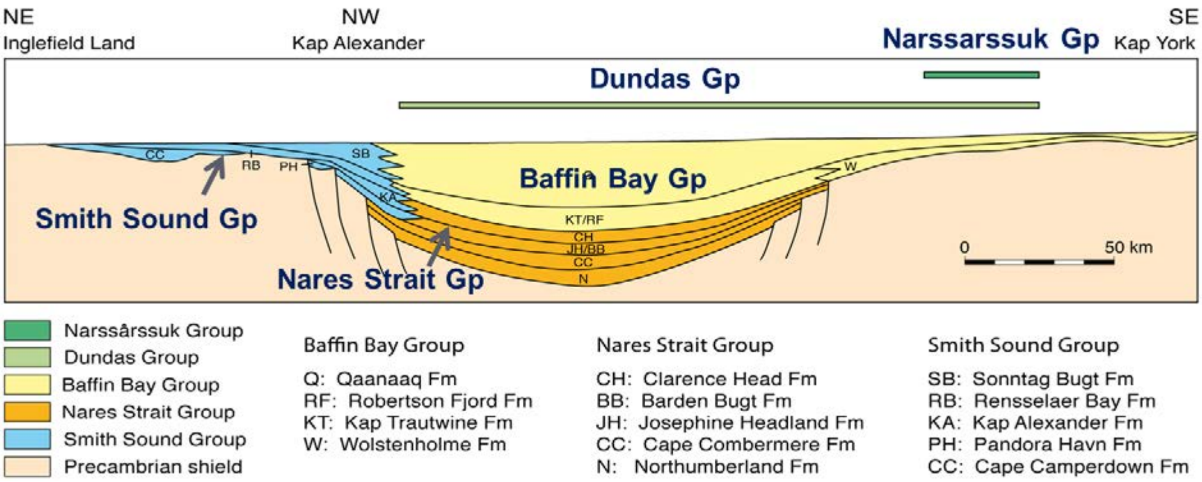

Figure 2. *Cross-section of the lower Thule Supergroup. Figure from Dawes (1997).*

A summary of the sedimentary groups making up the Thule Supergroup are given in Thomassen & Tukiainen (2009) and recited here below:

The *Smith Sound Group* directly overlies the crystalline shield; it represents the northern basin margin equivalent of the Nares Strait Group and the overlying Baffin Bay Group of the south. It is composed of varicoloured sandstones and shales, including red beds, with subordinate stromatolitic carbonates.

The *Nares Strait Group* forms the basal strata exposed in the north-western part of the study area where it is up to 500 m thick. It is dominated by sandstones – both redbeds and clean white quartz arenites – with one main interval of basaltic volcanics including flows, sills and volcaniclastic deposits (Cape Combermere Formation). Siltstone/shale intervals also occur. The group represents deposition in alluvial plain, littoral and offshore environments.

The *Baffin Bay Group* conformably overlies the Nares Strait Group and in the east overlaps onto the crystalline shield. In the study area it has a maximum thickness of 500 m, thinning to the east to less than 200 m. The group consists of multi-coloured siliciclastic rocks: sandstones, quartz grits and quartz-pebble conglomerates, with important intervals of shales and siltstones, representing mixed continental to marine shoreline environments. The uppermost strata (Qaanaaq Formation) represent a gradually deepening depositional regime from predominantly alluvial plain to shallow-shelf, tide-dominated deposition that is part of a regional transgression that continues into the more basinal sequence of the Dundas Group.

The *Dundas Group* is a dark-weathering succession conformably overlying the previous group along a gradational contact. Its upper limit is marked by Quaternary deposits and the present erosion surface. In the study area, the *c.* 2 km thick sequence comprises fine grained sandstones, siltstones and shales with some carbonate units. Dark shales can contain stratiform pyrite. Deposition was in an overall deltaic to offshore environment. Sills and dykes of mainly tholeiitic composition and unusually rich in titanium are common, and the so-called Steensby Land sill complex contains about fifteen master sills of probable Neoproterozoic age. The thickest of these is over 100 m with sill rock composing 30–40% of the stratigraphic section (Dawes 1989).

The *Narssârssuk Group*, 1.5–2.5 km thick, outcrops in a graben stretching from Pituffik to Saunders Ø. The dominantly fine-grained carbonate–redbed siliciclastic sequence with evaporites represents cyclic deposition in a low energy, hypersaline, peri-tidal environment in conditions perhaps analogous to modern coastal sabkhas.

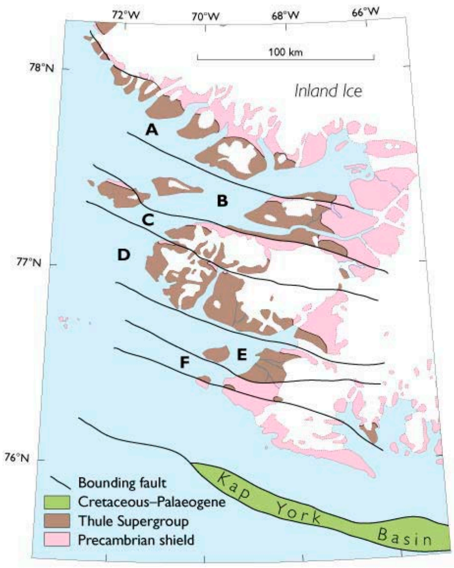

Figure 3. *The Thule half-graben system composed of six half-grabens with bounding faults on the southern side along which the Thule Supergroup is down-dropped against the shield. Intra-graben faults are not shown. From north to south: A, Prudhoe half-graben / Murchison Fault; B, Olrik half-graben / Itilleq Fault; C, Itillersuaq half-graben /Granvillle Fault; D, Moriusaq half-graben / Moltke Fault; F, Qeqertarsuaq half-graben / Magnetitbugt Fault. The Kap York Basin, an offshore Cretaceous-Palaeogene half-graben of similar polarity, is taken from Whittaker et al. (1977). Figure and caption from Dawes (2006).*

2.3 Quaternary

No systematic investigations of the Quaternary units have been undertaken in the Thule region. Only specific investigations and mapping on the Quaternary have been undertaken (Dawes, 2006). An attempt to subdivide the Quaternary into five map units is shown on the larger scale maps (1:100 000) of Dawes (1988), on which e.g. the marine deposits are subdivide and features such as fluvial and marine terraces, raised beaches and high-level lateral moraines are marked.

Of special interest, because these host the ilmenite-magnetite heavy sand placer deposits in several places, e.g. at Moriusaq, are the isostatically raised marine to littoral deposits scatted along the coastline. These are described as forming extensive plains, tiered beaches and delta terraces. The beach deposits vary from grey silt and sand, variously stratified and laminated, to coarse pebble and gravel to loose cobbles and boulders. The highest shell-bearing marine silt and sand in the Thule region are c. 60 m a.s.l. (Dawes 2006). The well-developed, raised terraced beach systems contain up to a dozen tiered low-gradient levels. Several of the beach deposits are continuous from the marine limit down to modern storm-wave beach ridges.

In the areas between Smith Sound in the north to around the island Qeqertarsuaq, Hvalsund (south of Qaanaaq), the established marine limit is at 86 m a.s.l.. To the south, between Bylot Sund and Inglefield Bredning, this limit is markedly lower, between 35 and 65 m a.s.l. (Dawes 2006).

Both interglacial and post-glacial marine deposits occur in the Thule area. The raised beaches at Moriusaq are of post-glacial age.

The last deglaciation of the Moriusaq area occurred prior to 11,200 years BP (BP = before present; Kelly et al. 1999; Bennike & Björck 2002). As the margin of the Greenland Ice Sheet retreated, the sea invaded Wolstenholme Fjord. Due to glacio-isostatic uplift, raised beaches can be found along the shores of the fjord, at elevation up to 46 metres above the present sea level (Kelly et al. 1999). An uplift curve showing relative sea level changes after the last deglaciation was published for a locality in inner Inglefield Bredning, c. 115 km northeast of Moriusaq by Fredskild (1985). However, the curve has been interpreted based on only three radiocarbon dates. According to this curve the relative sea level fell rapidly from c. 10,000 to 8,000 years BP, followed by a period of slower relative sea level changes. The curve stops at c. 6,000 years BP.

Several modelling studies of glacial rebound have been performed that cover North-West Greenland. Fleming & Lambeck (2004) published two curves that predict relative sea level changes, one labelled Thule (Fig. 4) and another labelled Iterluk. Both are from areas to the east of Moriusaq, and both show a rapid fall of the relative sea level from deglaciation until *c.* 7,000 years BP, followed by a rise in the relative sea level. At 7,000 years BP the relative sea level was 35 m below present sea level at Thule and 20 m at Iterluk. A more recent model was developed by Simpson et al. (2009). They did not present a curve for the Wolstenholme Fjord region, but their model confirmed that non-Greenland ice, in particular the Laurentide Ice Sheet played a major role in sea level changes in Greenland.

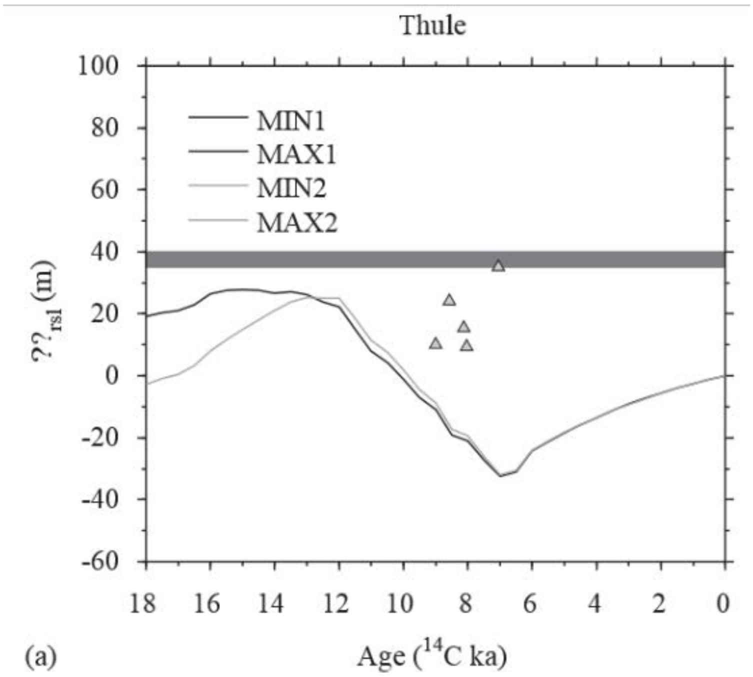

Figure 4. *Observed and scaled-predicted relative sea-level curve for Thule presented in Fleming & Lambeck (2004) indicating a sea level fall from c. 13,000 years ago to minus 35 m. below present sea level, followed by a raise from 7,000 years ago to present day sea level. Dark-grey shading indicated the estimated local marine limits. Symbols: triangles—lower limits, diamonds—mean sea level, inverted triangles—upper limits. Figure from Fleming & Lambeck (2004); for further details refer to this publication.*

3. Mineralisation

Several types of mineralisation are found within the greater Thule region.

3.1 Black sands

Black heavy mineral sands have been recorded in the region bounded by Kap Edward Holm in the south (76°) to Kap Alexander in the north (78°) (Fig. 5). The sands are enriched in ilmenite and/or magnetite, derived from Neoproterozoic titanium-rich dolerite sills and dykes in the immediate hinterland of the beaches.

In the 1:500,000 geological map (Dawes 1991) these magmatic units are referred to as D_2 and S_1; this terminology is also used here. The D_2 dykes are mainly WNW-ESE-trending with variation to E–W and NW–SE. Most of them are vertical or nearly-vertical (dip down to 75°N or 75°S). They are referred to as the 'Thule WNW dyke swarm' by Nielsen (1987) or simply the 'Thule dyke swarm' (Dawes 1988, Dawes 2004). The D_2 dykes are volumetrically dominant in the region. They are parallel to faults of the Thule half-graben system the dykes are yielding ages in the range of 675–630 Ma (Dawes 2006). They post-date the Thule Basin sedimentation and, according to Dawes (2006), also the early S_1 sills. Some of the sills marked S on the 1:500,000 geological map are inferred to be related to early extensional faulting. The Neoproterozoic S_1 sills are concentrated within the Dundas Group of the Thule Supergroup. The S_1 sills vary from a few metres to *c.* 100 m thick with the majority being between 20 to 50 m. These sills are described as being deeply weathered, and on flat tablelands where the upper chill margin is eroded away, the gabbroic cores are in a state of disintegration to coarse sand (Davies et al 1963, cf. Dawes 2006).

Compositionally, both the dykes and sills are defined as high TiO_2 and P_2O_5 tholeiitic basalt with minor alkaline units. They are high in TiO_2 and P_2O_5 (7 analysed samples of D_2 dykes and S_1 sill's gives values between 3.68 and 5.25 weight percent TiO_2 and between 2.63 to 1.21 weight percent P_2O_5; Dawes 2006). Sill rock is being described as being particularly rich in opaque minerals with ilmenite reaching up to 15% by volume (Dawes 1989; Dawes 2006). As a regional magmatic suite the rocks represent some of the most titanium-rich basalts in Greenland (Dawes 1989). The S_1 sills post-date Thule Basin sedimentation but pre.-date extensional faulting and D_2 dykes. Three samples of the S_1 have yield K-Ar whole-rock ranges of 705–660 Ma (Dawes 2006). The S_1 sills are assumed to be an expression of the Franklin magmatic event, defined from Arctic Canada (Nielsen 1990, Thomassen & Tukiainen 2009).

The thickest stratigraphic section of the S_1 sills is in the Moriusaq half-graben where in southern Steensby Land the clastic strata hosts about 15 master sills that make up between 30 and 40% of the section (Dawes 1989); this is also referred to as the Steensby Land sill complex (Dawes 1997). The sill complex is intruded into the Dundas Group of the Thule Supergroup, represented by the Steensby Land Formation. The sedimentary rock component of this formation is dominated by black-grey, locally pyritic, shales and also contains siltstones, fine-grained sandstones and thin dolomitic units (Dawes 2006, Thomassen & Tukiainen 2009).

The southernmost known black sand deposit is located at Kap Edvard in Melville Bugt and the northernmost one being located in Prudhoe Land (Sonntag Bugt, Sioparluk in Robertson Fjord and in McCormick Fjord and Bowdoin Fjord). The widespread occurrence of black sand deposits have been referred to as the 'Thule black sand province' (Fig. 5; Dawes 1989). Both ilmenite-rich and magnetite-rich sand occur as well as combined ilmenite-magnetite occurrences.

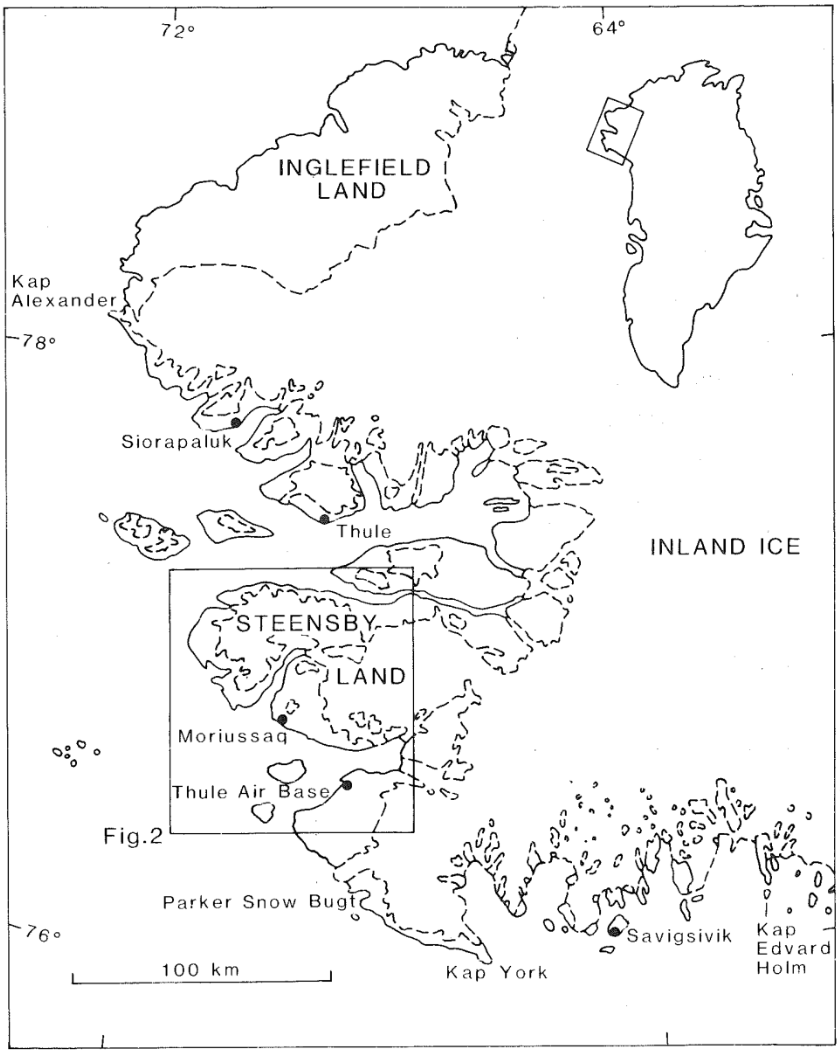

Figure 5. *Location of the Thule black sand province, North-west Greenland, showing the position of the Steensby Land ilmenite showing (inset Fig. 3). Heavy mineral sands have been recorded in the region from Kap Edvard Holm in the south to Kap Alexander in the north (Dawes 1989).*

Furthermore, Dawes (2006) are collectively referring to the black sand deposits along the 80 km long southern coast of the Steensby Land peninsula as "The Steensby Land ilmenite showing". Based on the current state of knowledge, the beaches around the former settlement Moriusaq (Figs 5 and 6) and along the adjacent south-east trending coastline are the most promising black sand occurrences from an economic point of view.

This coast stretch hosts uplifted beaches with ilmenite-rich heavy-sand occurrences within extensive flat coastal plains with an elevation up to 40 m above sea level.

The uplifted beaches form flat-topped benches (Figs 7-10), often with distinct frontal scarps. Uplifted beaches are up to 1 km wide along a 20 km coastal stretch. No detailed investigations on the conditions and extend of thawing and permafrost have been made in the area.

Also, the active beaches carry ilmenite-rich heavy-sand occurrences. Furthermore, tidal-zone and near-coastal zone have further potential for heavy sand occurrences. The active beaches varies in width and extend; with both sandy beaches and intertidal zones being up to 10 m wide; in places it might be wider because of coastal morphology and bathymetry (Figs 11-12) . The sandy beaches are in areas broken by outcropping basaltic rocks forming a craggy coastline. Dawes (1989) notes that were the well-developed beaches occur; the sandy beaches seem to extend someway seaward below tide level.

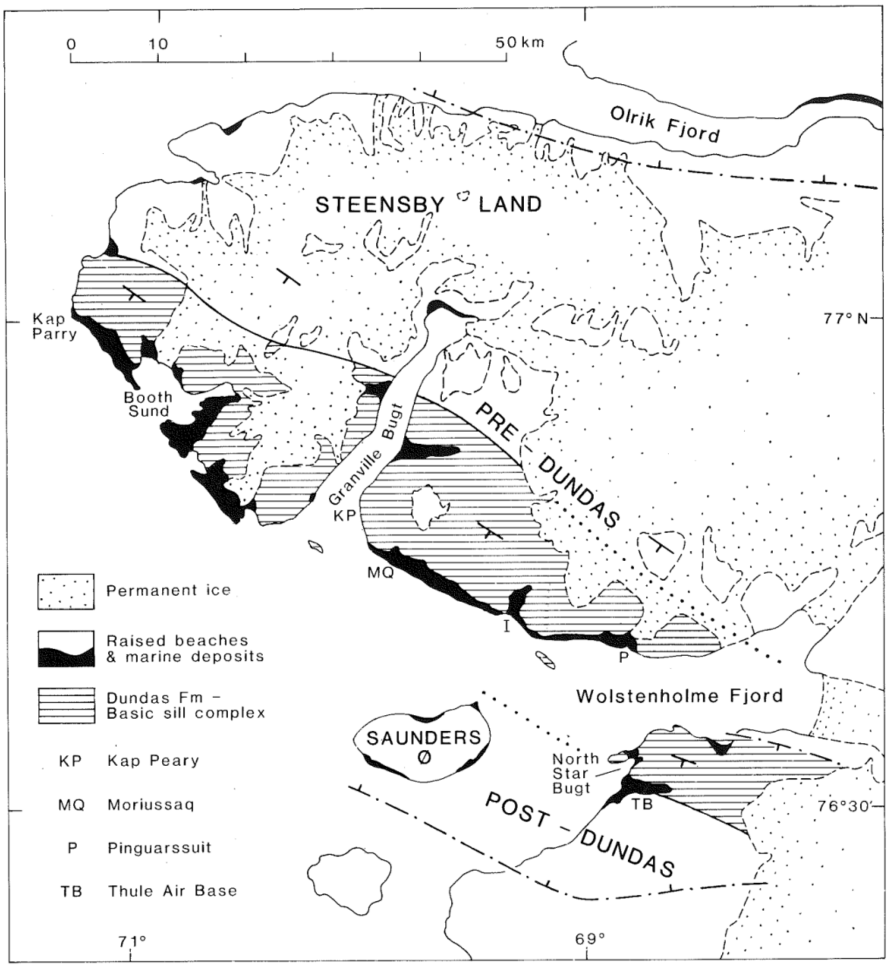

Figure 6. *Location map of the Steensby Land ilmenite showing illustrating the extent and size of the uplifted coastal plain and the outcrop of the Dundas Formation with the titanium-rich basic sill complex, I = Interdlak. (Dawes 1989).*

Figure 7. *View towards the south of the former settlement of Moriusaq. Black coloured heavy mineral sand beaches along the coast. Photo: P. Dawes, 1975.*

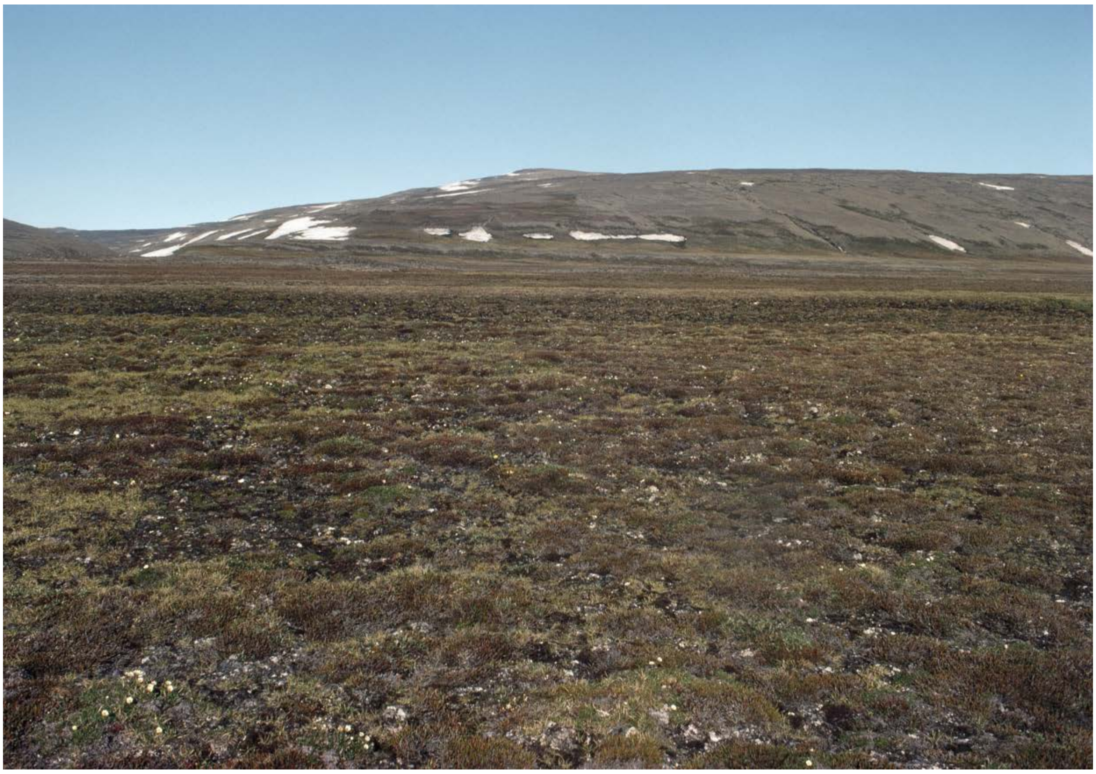

Figure 8. *The wide uplifted coastal plain of southern Steensby Land near Moriusaq. Photo: P. Dawes, 1975.*

Figure 9. *Raised beaches north of Moriusaq. Photo courtesy: Blue Jay Mining Ltd., 2015.*

Figure 10. *Stream cut in raised beaches south of Moriusaq revealing black sands throughout the raised beaches. Photo courtesy: Blue Jay Mining Ltd., 2015.*

3.1.1 Quality and tonnage; Moriusaq heavy mineral sand deposit

The potential, quality and tonnage of the heavy mineral sand occurrences at Moriusaq have been addressed in various reports; these are Ghisler & Thomsen 1971, Greenex A/S 1985, Dawes 1989, Ghisler 1991, Appel et al. 1991, Fergusson & Rowntree 2011. The principal results of these studies are summarized below. For details of the various studies refer to section 3.1.1.1.

TiO_2 content in heavy mineral black sand samples:
The highest grades of TiO_2 in sand samples examined have been obtained at the river flats at Pituffik (Thule Air Base). The black sand contains an opaque fraction of up to 95 % with *c.* 73 % absolute ilmenite (Dawes 1989). The highest TiO_2 grade in sand samples archived at Moriusaq is 46.5 % (Table 1). Average TiO_2 content of black sand samples from active beaches at Moriussaq (data from several studies) is 39.1 % with a range of 11–46.5 % (Table 1; based on 10 samples; data from Cosette 1985, Dawes 1989, Christensen 1985 and Reeves 1997). Samples from various studies of black sand from uplifted beaches returns an average TiO_2 content of 11% with a range of 4–23 %.

Figure 11. *Wide active beach south of moriusaq at mid-tide, very rich in black sand. Photo courtesy: Blue Jay Mining Ltd., 2015.*

Figure 12. *Black sand at very wide active beach in the foreground and raised beaches in the background at Interlak. Photo courtesy: Blue Jay Mining Ltd., 2015.*

Table 1. *Summary of percentages of ilmenite and TiO_2 in black sand samples together percentages of TiO_2% in ilmenite grains from concentrate of the same samples. All from active beaches at Moriussaq*

Sample no.	Reference	Analytical ilmenite % in the sand	TiO_2 % in the sand	TiO_2 % in the ilmenite grains
139272	Cosette 1985; Dawes 1989	33.0	-	46.3
139288		42.0	-	46.5
139292		60.0	-	46.5
243624		39.0	-	44.0
243639		12.0	-	46.2
22416	Christensen 1985	-	-	11.0
22418		-	-	40.86
22419		-	-	43.71
243630-1	Reeves 1997	-	34.9	45.7
243630-4		-	30.9	-

Chemical composition and size of ilmenite grains from concentrates:

TiO_2 content of ilmenite grains from heavy mineral concentrates from both uplifted and active beaches is very constant at about 46–48 wt.% with an average of 47.5 wt.% (average of 71 individual ilmenite grain analysed; range 44–48.98 wt.%; data from Cosette 1985; Ghisler 1991; Fergusson & Rowntree 2011). Microprobe analyses show that the chemical composition of the ilmenite does not exceed 50% TiO_2. Both magnetite and ilmenite are moderately high in vanadium content (average 0.60% V_2O_5; Ferguson & Rowntree 2011) and magnetite also has significant cobalt content (average 10.07% TiO_2, 1.39% V_2O_5 and 1004 ppm CoO; Ferguson & Rowntree 2011).

CaO and MgO are consistently low. Ilmenite grains analysed for CaO have returned an average value of 0.1 wt.% CaO (10 grains analysed; range 0 to 0.16 wt.%; data from Cossette (1985) and Ghisler (1991)). Ilmenite grains analysed for MgO have returned an average of 0.67 wt.% MgO (71 grains analysed; range 0.15 to 1.75 wt.%; data from Cossette (1985), Ghisler (1991) and Fergusson & Rowntree (2011)). The combined CaO+MgO has an average of 0.95 wt.% and a range between 0.53 to 1.14 wt.% (data from Cossette (1985) and Ghisler (1991)).

Thorium and uranium is also low with average uranium content of analysed samples around 2.5 ppm U with a range of 0–4.5 ppm and average thorium content being 14.25 ppm with a range of 7.5–19 ppm (data from Reeves (1991) and unpublished GGU data by P.R. Dawes).

Ferguson & Rowntree (2011) finds that 48 % and 50 % of the ilmenite grains are in the size range 0.3 to 1.0 mm for two samples from active beaches and 65 % and 62 % in the size range 0.3 to 1.0 mm for two samples of uplifted beaches. For all samples between 91 % to 94 % of the grains are larger than 0.177 mm.

Figure 13. *Thick raised beach with very rich black sand at Interlak. Photo courtesy: Blue Jay Mining Ltd., 2015.*

Figure 14. *Wide active beach with black sand at mid-tide with thick raised beach in the background. East of Moriusaq. Photo courtesy: Blue Jay Mining Ltd., 2015.*

Resource size:
No certified resource estimate has been made for the ilmenite deposits. Based on arial extent of beaches and on an assumed overall depth of 2 m to bedrock, Appel et al. (1991) estimated a total onshore sand amount of 40 million m^3, equal to 80 million tons. However, the depth to the bedrock could be greater as also some of the exposed raised beaches-faces witness (Figs 12–14).

The TiO_2 grades found in the onshore black sand deposits are considerable lower than those obtained in the active beach zone. The potential tonnage of the active beach-face/swash zone (active beach) it-self is probably limited as only the aerial extent has been explored to some degree. However, current work program carried out by Blue Jay Mining Ltd., examine the possibility of offshore placers in the surf and nearshore zones (wave breaking and wave shoaling) to a water depth of 35 m below present day sea surface (the minimum level of the paleo-sea surface). In this context, the paleo-sea surface level should be considered. The paleo-sea surface have been estimated to be 35 m below present day sea surface; which potentially would leave plenty of room for drowned fossil beach systems.

The possibility for offshore deposits considerably increases the potential for larger tonnages. Also near-shore flat river-delta or flat tidal zones have not been considered for their potential (as traps for heavy minerals) (Figs 10, 11 and 14).

The thickness of the heavy mineral sands and morphology of underlying rocks are unknown; no quantitative or qualitative investigations have been made on the dimensions of black sand deposits in the onshore raised beach-systems or the possible present-day seacovered fossil beach-systems. All examined samples are taken in the summer-thawed layer. All sampling has been done manually; no larger machinery has been used. Hand-held cored auger drilling has not reached deeper than a maximum of 1 m.

3.1.1.1 Mineralogical and chemical compositions of black sand samples, concentrate and ilmenite/magnetite grains

The details from various studies that have analysis of the mineralogy and chemical composition of black sand, heavy mineral concentrate or ilmenite/magnetite grains from Moriussaq are given in the following.

A summary of the mineralogical composition of black sand samples from North Star Bugt (bay north of Thule Airbase, 30 km ESE of Moriussaq) can be found in Ghisler & Thomasen (1972) and Dawes (1989). These are also given in Table 2. Dawes (1989) states that the mineralogical compositions of the black sands from North Star Bugt compare well with black sands from Moriussaq. Some of the samples richest in black minerals have opaque fractions up to 95 %, with more than 70 % absolute weight of ilmenite.

Dawes (1989) also finds that chemical analysis of sand samples from the Moriussaq area confirm field assessments that active beaches contain higher concentrations of titanium; with average analytical TiO_2 of the sand samples being 43 % (which roughly equates to 70 % ilmenite) for the active beach black sand samples (range 41–44 %; 3 samples) and 12 % (which roughly equates to 20 % ilmenite) for the raised beaches black sand samples (range 6–23 %; 13 samples).

Table 2. *Mineralogical composition of black sand samples from North Star Bugt (after Dawes 1989)*

GGU sample no.	13842	141039	141040
Heavy fraction >2.9 wt.%	95 %	84 %	54 %
Opaque % (number of grains)	73 %	68 %	54 %
Heavy fraction percentages of transluscent minerals:			
diopside	68 %	34 %	39 %
augite	+	7 %	3 %
hypersthene	22 %	10 %	6 %
hornblende	7 %	37 %	44 %
epidote	3 %	7 %	8 %
garnet		4 %	+
titanite	+	1 %	
zircon		+	
sillmanite		+	
Relative composition of the opaque fraction (number of grains):			
ilmenite	95 %	88 %	90 %
titanomagnetite	4 %	6 %	3 %
magnetite	+	6 %	6 %
pyrite	+	+	1 %
Density if sand (calculated)	4.5	4.2	3.5
Absolute weight % of ilmenite	74 %	60 %	37 %

+: present in amounts below 1%

Dawes (1989) also investigates the chemical composition of ilmenite grains separated from six samples from Moriussaq. These results are given in Table 3. These grains give an average TiO_2 value of the ilmenite of about 46 % with a total iron around 38.5%. The CaO content is found to be between 0.13 to 0.16 % with a MgO content between 0.66 to 0.92 %. The combined CaO+MgO content is between 0.79 to 1.05%. The vanadium content is moderately elevated between 0.34 to 0.39 %.

Ghisler (1991) also investigated the composition of individual ilmenite minerals from two samples taken from beach environments at Morisuaq (reanalyses of sample 139292 and 243649 that also were investigated by Dawes 1989) as well as from a basaltic sill in the Thule Airbase area. The results are given in Table 4. The analytical results of Ghisler (1991) are comparable with the results of Dawes (1989).

Table 3. *Chemical composition of ilmenite grains separated from heavy mineral concentrates of black sands from Moriussaq (Dawes 1989; based on chemical data from the company Qit-Fer et Titane (Cossette, 1985)). The concentrates were produced using a combination of heavy liquid separation (s.g. 2.96 and 4.00) and magnetic separation on the Frantz magnetic separator.*

GGU sample no.	**139273**	**139288**	**139292**	**243624**	**243639**	**243649**
Locality description	Active beach	Active beach	Active beach	Active beach	Active beach	Uplifted beach, 200 m inland
Analytical ilmenite % in the sand:						
% ilmenite	33.0	42.0	60.0	39.0	12.0	14.0
Chemical results of ilmenite grains:						
TiO_2	46.30	46.50	46.50	44.00	46.20	45.50
Fe_{total}	38.80	38.90	38.90	37.60	38.40	38.80
Al_2O_3	0.45	0.43	0.40	0.43	0.40	0.40
CaO	0.14	0.13	0.13	0.13	0.16	0.14
MgO	0.87	0.88	0.92	0.66	0.80	0.86
MnO	0.61	0.62	0.62	0.65	0.64	0.61
SiO_2	0.74	0.74	0.70	0.87	1.50	1.03
Cr_2O_3	0.06	0.06	0.06	0.02	0.03	0.06
V_2O_5	0.39	0.38	0.38	0.34	0.35	0.39
	88.30	88.64	88.61	84.70	88.48	87.79

Table 4. *Chemical composition of ilmenite grains from heavy mineral concentrates of black sand and from rock sample of basaltic sill (Ghisler 1991). No information on how the concentrates were made.*

	Ilmenite mineral grains from concentrates of black sand sample				**Ilmenite mineral grains from rock sample of basaltic sill**		
GGU-Sample no.	**139292** ilmenite from active beach sand at Moriussaq area			**243649** ilmenite from uplifted beach sand; 200 m inland, Moriussaq area	**116624** from basaltic sill rock sample)		
Grain no.	1	2	3	1	1	2	3
	%	%	%	%	%	%	%
Na_2O	0.01	0.00	0.00	0.04	0.02	0.04	0.03
MgO	0.81	0.53	1.13	1.12	0.30	0.79	0.33
Al_2O_3	0.05	0.07	0.02	0.01	0.06	0.16	0.03
SiO_2	0.00	0.04	0.01	0.02	0.00	0.00	0.05
K_2O	0.00	0.000	0.02	0.00	0.00	0.04	0.00
CaO	0.02	0.00	0.00	0.02	0.04	0.06	0.02
TiO_2	46.95	47.34	46.54	46.77	48.89	48.97	48.69
V_2O_5	0.65	0.15	0.55	0.40	0.42	0.46	0.46
Cr_2O_3	0.00	0.08	0.02	0.05	0.00	0.13	0.00
NaO	0.50	0.82	0.46	0.43	0.74	0.98	0.59
FeO	50.11	49.37	50.00	49.46	49.15	47.28	48.77
NiO	0.03	0.00	0.04	0.00	0.00	0.12	0.00
Total	*99.13*	*98.40*	*98.76*	*98.32*	*99.62*	*99.03*	*98.97*

The ilmenite from the beach samples investigated by Ghisler (1991) from Moriussaq contains between 46 to 47 % TiO_2. Ghisler (1991) notes that the TiO_2 content in the rock sample is 2 % higher than in the samples of the black sand whereas the FeO content in the rock samples are c. 1 % lower. In this respect it should be noted that there is 25 km between the beach sand sample locality at Moriussaq and the rock sample locality at Thule Airbase. The ilmenite grains investigated by Ghisler (1991) contain small exsolutions of baddeleyite. It should also be noted that the ilmenite is moderately high in vanadium (0.40

to 0.65 %) and that the CaO and MgO content is very low; between 0 to 0.02 and 0.43 to 0.82 % respectively and combined below 1%.

Based on a small field campaign in 1985 the exploration company Greenex A/S analysed sand samples from the Moriussaq area for their TiO_2, Au, Pt and Pd content (Table 5; Christensen 1985). The black sand samples from uplifted beaches have a resulting average of 11.9 % TiO_2 (range 6.13 to 22.85 % TiO_2; 13 samples) whereas black sands from active beaches yields an average of 32.95 % (range 14.28 % to 43.71 %; 3 samples). It should be noted that Christensen (1985) obtains 30 ppb platinum in two out of 13 heavy sand samples. The analytical work on the heavy mineral sand samples in all other reports has not included analysis for platinum.

Table 5. *Analysis of black sand samples from Moriussaq by Greenex A/S (Christensen 1985).*

Greenex sample no.	Locality description	TiO_2	Platinum ppm
22411	Uplifted beach	19.52	
22412	Uplifted beach	22.95	
22413	Uplifted beach	11.86	
22414	Uplifted beach	8.11	
22415	Uplifted beach	11.00	
22416	Active beach	14.28	
22417	Uplifted beach	6.77	
22418	Active beach	40.86	
22419	Active beach	43.71	
22420	Uplifted beach	21.40	
22421	Uplifted beach	9.64	0.03
22422	Uplifted beach	6.35	
22423	Uplifted beach	6.13	0.03
22424	Uplifted beach	12.33	
22425	Uplifted beach	10.81	
22382	Uplifted beach	8.18	

Note: Unless stated otherwise all samples returned <20 ppb Au, <20 ppb Pt and <20Pd

Figure 15. *Coarse black sand at active beach, Moriusaq. Camera lens cap for scale. Photo courtesy: Jeremy Whybrow, Blue Jay Mining Ltd., 2015.*

Another four samples were in 1994 upon request provided to the company DuPont (Reeves 1997) for testing by X-ray fluorescence and one of the two samples rich in heavy minerals were used to prepare an ilmenite concentrate. The samples were provided to DuPont on the conditions that test results would be shared with GEUS. During the work at DuPont, the researchers at DuPont involved in the investigations either got involved in other projects or left DuPont. However, one of the researchers, J.W. Reeves, continued the work and reported back to GEUS with the results (Reeves 1997).

Out of the four samples two were found to be very high in ilmenite (see results in Table 6) and one of the samples (GGU no. 243630-1) was used to prepare a minus 250 by plus 150 micron size fraction for magnetic separation from which mineral grains then were analysed (Table 7). The most magnetic phase was found to be a titaniferrous magnetite fraction; the intermediate magnetic phase was found to be ilmenite fraction whereas the non-magnetic phase was labelled silicate fraction with no mineral identification.

Reeves (1997) finds the chemical composition of the ilmenite grains (70 grains) to be 45.7 wt.% TiO_2 with a CaO content of 0.2 wt% and MgO content of 0.7 wt.%. The V_2O_5 content is moderately elevated at 0.3 wt.%. According to Reeves (1997) the content of 0.2 wt.% CaO is just barely within chloride grade specification for direct ilmenite chlorinator feed and the TiO_2 grade at 45.7 wt.%, is barely high enough for direct feed. However, Reeves also indicate several favourable things for the ilmenite concentrate. The MgO level is low which would simplify acid leaching. Also, the uranium and thorium content (naturally occurring radionucleides) are low. A high TiO_2 content slag of the Moriussaq ilmenite concentrate could be produced because the level of other oxides is lower than most ilmenite smelted. The concentrate from Moriussaq, at <4 wt.% non-TiO2+Fe2O3 oxides compares according to Reeves (1997) well to other ilmenites that range from 4–10 wt.%. The high grade concentrate of sample 243630-1 were also investigated by elemental mapping by Reeves (1997) to determine if there were any low ilmenite content grains. All were found to be primarily iron and titanium and low in calcium, magnesium, aluminium and silicon. X-ray diffraction also showed only ilmenite. Energy dispersive x-ray analysis (multiple spot EDAX investigations) of 100 grains was used to located calcium in the grains. The calcium was found to be present as 1–10 micron interior inclusions as well as small surface inclusions in the grains and was present in almost 90 % of the grains investigated. The inclusion would, according to Reeves (1997), be removable by attrition gridding.

Table 6. *Chemical composition of black sand samples from Moriussaq in weight percent (for Th and U in ppm; data from Reeves, 1997)*

GGU sample no.	243630-1	243630-4	243628-3	243633-3
Locality description	Active beach	Active beach	[no certain information: probably raised beach sand material]	[no certain information: probably raised beach sand material]
TiO_2	34.9	30.9	4.65	4.08
Fe_2O_3	44.0	39.5	13.2	11.7
Al_2O_3	2.13	3.23	11.2	12.6
CaO	2.83	3.92	9.0	9.69
MgO	2.0	2.6	5.4	5.4
MnO_2	0.44	0.42	0.22	0.21
SiO_2	13.3	18.8	50.4	51.2
ZrO_2	0.08	0.08	0.04	0.03
NbO_5	0.03	0.03	0.01	0.01
Cr_2O_3	0.07	0.06	0.05	0.04
Nd_2O3	0.00	0.00	0.00	0.00
P_2O_5	0.02	0.03	0.27	0.19
V_2O_5	0.23	0.21	0.06	0.05
K_2O	0.08	0.12	0.42	0.42
Th ppm	20	12	19	17
U ppm	0	4	0	3

Table 7. *Chemical composition of ilmenite, magnetite and silicates grains from concentrates of black sand sample 243630-1 (data from Reeves, 1997). The concentrate was made by magnetic separation on a -250 to +150 micron size fraction.*

GGU sample no.	243630-1		
Fraction	Ilmenite	Magnetite	Silicates
Magnetic phase	intermediate magnetic phase	most magnetic phase	non-magnetic phase
Number of grains	70	6	24
TiO_2	45.7	Same	2.2
Fe_2O_3	52.6	Same	12.7
Al_2O_3	0.2		6.2
CaO	0.2		12.5
MgO	0.7		10.8
MnO_2	0.5		0.27
SiO_2	1.3		54.5
ZrO_2	0.1		0.05
NbO_5	0.03		0.01
Cr_2O_3	0.07		0.04
Nd_2O3	0.03		0.01
P_2O_5	0.01		0.14
V_2O_5	0.3		0.15
K_2O	0.0		0.16
Th ppm	17		17
U ppm	16		9

The exploration company Hunter Minerals Pty Ltd. requested in 2010 GEUS to do a small study on four heavy mineral concentrates from four samples of the Moriussaq black sands (Ferguson & Rowntree 2011). The ilmenite-magnetite concentrate was generated from magnetic separation that afterwards was subject to grain size (see also Figs 15-16) and chemical microprobe analysis (60 ilmenite grains and 26 magnetite grains). The size distribution is given in Table 8 whereas the chemical ilmenite and magnetite grain analysis are given in Table 9 and 10.

Ferguson & Rowntree (2011) reports that the above requested study revealed that 60 % of the ilmenite grains were in the size range 0.3 to 1.0 mm (Table 8) and that on average, ilmenite comprised 92 wt. % of the concentrate. Based on the microprobe results averages of 47.65 % TiO_2, 49.57 % FeO and 0.48 % V_2O_5 and 0.63 % MgO is obtained for the ilmenite grains analysed (Table 9). For the titaniferrous magnetite grains averages of 80.62 % FeO, 10.13 % TiO_2, 1.14 % V_2O_5 and 0.11 % CoO is obtained (Table 10).

Table 8. *Size of ilmenite grains in concentrate from black sand samples from Moriussaq (Ferguson & Rowntree 2011). The concentrate was made by magnetic separation.*

	Tyler Mesh	+16	-16 to +32	-32 to +48	-48 to +60	-60 to +80	-80 to +100	-100 to +200	-200
	Tyler mesh converted to millimetre	>1 mm	1–0.5 mm	0.5–0.3 mm	0.3–0.25 mm	0.25–0.177 mm	0.177–0.149 mm	0.149–0.074 mm	<0.074 mm
Ilmenite concentrate sample no.	Locality description								
243649	Uplifted beach	5 %	31 %	29 %	14 %	15 %	4 %	2 %	0 %
243639	Uplifted beach	9 %	26 %	27 %	15 %	14 %	5 %	3 %	0 %
139288	Active beach	7 %	20 %	23 %	18 %	25 %	5 %	1 %	0 %
243624	Active beach	5 %	17 %	26 %	19 %	26 %	5 %	2%	0 %

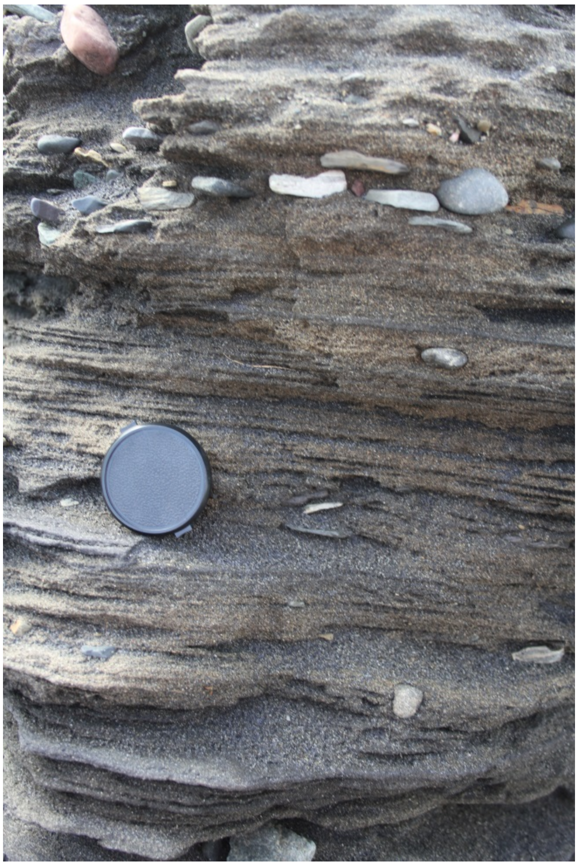

Figure 16. *Internal layering with black sand horizon. Camera lens cap for scale. Photo courtesy: Blue Jay Mining Ltd., 2015.*

Table 9. *Chemical composition of ilmenite grains (60 individual grains) from magnetic generated ilmenite concentrate of four different black sand samples from Moriussaq (Ferguson & Rowntree 2011)*

Sample_grain_no	Al_2O_3	MnO	FeO	TiO_2	MgO	NiO	SiO_2	Cr_2O_3	V_2O_3	Total
139284_ilmenite-1	0.04	0.49	49.75	46.89	0.78	0.01	0.04	0.08	0.49	98.58
139284_ilmenite-2	0.03	0.42	49.82	46.94	0.56	0.00	0.05	0.03	0.49	98.34
139284_ilmenite-3	0.01	0.53	49.54	47.83	0.45	0.01	0.06	0.02	0.48	98.92
139284_ilmenite-4	0.02	0.63	49.20	48.98	0.24	0.00	0.04	0.02	0.43	99.57
139284_ilmenite-5	0.02	0.45	50.18	47.45	0.44	0.01	0.05	0.01	0.56	99.18
139284_ilmenite-6	0.02	0.46	50.26	47.19	0.56	0.01	0.04	0.00	0.49	99.05
139284_ilmenite-7	0.03	0.76	48.79	48.69	0.17	0.01	0.04	0.00	0.41	98.89
139284_ilmenite-8	0.03	0.44	49.52	47.73	0.77	0.01	0.04	0.01	0.49	99.05
139284_ilmenite-9	0.03	0.43	50.41	46.69	0.79	0.02	0.04	0.10	0.50	99.00
139284_ilmenite-10	0.01	0.57	49.00	48.73	0.25	0.00	0.03	-0.01	0.42	99.00
139284_ilmenite-11	0.02	0.49	49.02	48.79	0.38	0.00	0.02	0.00	0.42	99.15
139284_ilmenite-12	0.04	0.49	49.09	48.65	0.27	0.00	0.02	0.00	0.41	98.97
139284_ilmenite-13	0.04	0.44	49.21	47.95	0.68	0.02	0.02	0.01	0.49	98.86
139284_ilmenite-14	0.03	0.47	49.50	47.79	0.61	0.02	0.02	0.01	0.54	98.98
139284_ilmenite-15	0.03	0.43	49.81	48.01	0.68	0.01	0.03	0.01	0.52	99.53
243624_ilmenite-1	0.05	0.45	49.34	48.69	0.54	0.00	0.01	0.02	0.42	99.52
243624_ilmenite-2	0.04	0.49	49.45	47.91	0.41	0.01	0.02	0.00	0.44	98.78
243624_ilmenite-3	0.04	0.46	49.62	47.54	0.94	0.02	0.01	0.07	0.52	99.23
243624_ilmenite-4	0.05	0.43	49.59	46.98	1.22	0.01	0.01	0.11	0.55	98.94
243624_ilmenite-5	0.04	0.44	50.01	47.29	0.94	0.01	0.01	0.08	0.51	99.33
243624_ilmenite-6	0.02	0.56	49.87	47.76	0.40	0.01	0.02	0.04	0.49	99.18
243624_ilmenite-7	0.03	0.53	49.62	48.81	0.17	0.01	0.00	0.00	0.46	99.63
243624_ilmenite-8	0.04	0.39	50.16	46.82	0.98	0.00	0.00	0.11	0.53	99.04
243624_ilmenite-9	0.02	0.48	49.27	48.03	0.52	0.01	0.02	0.04	0.48	98.88
243624_ilmenite-10	0.02	0.48	49.08	48.41	0.60	0.00	0.02	0.00	0.41	99.03
243624_ilmenite-11	0.03	0.48	49.69	48.04	0.61	0.02	0.02	0.01	0.54	99.43
243624_ilmenite-12	0.04	0.46	49.59	47.58	0.84	0.00	0.01	0.06	0.46	99.05
243624_ilmenite-13	0.03	0.46	49.57	48.21	0.60	0.01	0.03	0.06	0.45	99.41
243624_ilmenite-14	0.04	0.48	50.32	47.37	0.53	0.01	0.02	0.10	0.51	99.39
243624_ilmenite-15	0.05	0.81	49.47	48.22	0.18	0.00	0.01	0.06	0.47	99.28
243639_ilmenite-1	0.03	0.54	49.91	47.19	0.52	0.02	0.03	0.00	0.50	98.75
243639_ilmenite-2	0.03	0.51	50.22	47.15	0.66	0.02	0.03	0.01	0.52	99.13
243639_ilmenite-3	0.03	0.39	49.33	46.63	1.22	0.01	0.05	0.09	0.56	98.32
243639_ilmenite-4	0.04	0.42	50.39	46.44	1.27	0.02	0.04	0.13	0.50	99.25
243639_ilmenite-5	0.05	0.37	49.18	47.65	1.75	0.01	0.04	0.12	0.58	99.74
243639_ilmenite-6	0.03	0.42	50.05	46.92	0.95	0.01	0.05	0.10	0.48	99.02
243639_ilmenite-7	0.04	0.50	48.99	47.97	0.70	0.01	0.04	0.00	0.46	98.72
243639_ilmenite-8	0.02	0.46	49.91	47.21	0.62	0.01	0.05	0.01	0.48	98.78
243639_ilmenite-9	0.02	0.46	49.84	47.46	0.54	0.01	0.06	0.08	0.49	98.96
243639_ilmenite-10	0.03	0.51	49.70	47.64	0.72	0.01	0.04	0.05	0.43	99.14
243639_ilmenite-11	0.03	0.53	47.21	48.35	0.61	0.02	0.03	0.05	0.42	97.24
243639_ilmenite-12	0.03	0.43	49.64	47.83	0.27	0.00	0.04	0.01	0.45	98.69
243639_ilmenite-13	0.03	0.46	49.57	47.04	0.72	0.00	0.02	0.07	0.51	98.43
243639_ilmenite-14	0.03	0.38	49.66	46.80	0.96	0.02	0.04	0.06	0.55	98.50
243639_ilmenite-15	0.04	0.37	49.49	46.75	0.97	0.02	0.05	0.09	0.54	98.32
243649_ilmenite-1	0.04	0.57	49.97	47.59	0.50	0.01	0.01	0.01	0.49	99.18
243649_ilmenite-2	0.03	0.47	50.19	47.58	0.54	0.02	0.03	0.02	0.48	99.35
243649_ilmenite-3	0.03	0.53	49.32	48.55	0.15	0.00	0.03	0.01	0.43	99.05
243649_ilmenite-4	0.04	0.48	49.96	47.80	0.48	0.01	0.02	0.03	0.46	99.27
243649_ilmenite-5_rim	0.03	0.52	49.11	48.16	0.56	0.01	0.02	0.01	0.46	98.87
243649_ilmenite-5_core	0.04	0.53	49.45	48.24	0.59	0.01	0.03	0.00	0.46	99.34
243649_ilmenite-7	0.04	0.46	50.20	47.21	0.64	0.02	0.06	0.09	0.50	99.21
243649_ilmenite-7	0.03	0.41	49.94	46.89	0.82	0.02	0.03	0.08	0.53	98.76
243649_ilmenite-8	0.04	0.40	50.07	46.40	0.77	0.01	0.02	0.11	0.50	98.32
243649_ilmenite-9	0.03	0.43	49.02	47.22	1.01	0.01	0.05	0.00	0.47	98.23
243649_ilmenite-10	0.03	0.45	48.62	48.43	0.27	0.01	0.03	0.00	0.41	98.25
243649_ilmenite-11	0.03	0.50	48.96	47.49	0.46	0.02	0.04	0.00	0.46	97.95
243649_ilmenite-12	0.04	0.45	49.47	47.42	0.68	0.00	0.07	0.01	0.49	98.62
243649_ilmenite-13	0.03	0.61	49.39	47.71	0.23	0.00	0.03	0.00	0.43	98.44
243649_ilmenite-14	0.03	0.45	50.01	47.68	0.55	0.01	0.03	0.01	0.48	99.24
243649_ilmenite-15	0.03	0.43	49.54	47.33	0.89	0.02	0.03	0.03	0.51	98.81
Average	*0.03*	*0.48*	*49.57*	*47.65*	*0.63*	*0.01*	*0.03*	*0.04*	*0.48*	*98.94*
Standard deviation	*0.01*	*0.08*	*0.52*	*0.64*	*0.30*	*0.01*	*0.02*	*0.04*	*0.04*	*0.44*
Minimum	*0.01*	*0.37*	*47.21*	*46.40*	*0.15*	*0.00*	*0.00*	*0.00*	*0.41*	*97.24*
Maximum	*0.05*	*0.81*	*50.41*	*48.98*	*1.75*	*0.02*	*0.07*	*0.13*	*0.58*	*99.74*

Sample description: no. 139288 is from active beach at Moriussaq; no. 243624 is from active beach SE of Moriussaq, no. 243639 is from an uplifted beach 4 km SE of Moriussaq, no. 243649 is from an uplifted beach at Moriussaq. Note: in the appendix I of Ferguson (2010) regarding sample no. 139284 - by comparing with notes by P.R. Dawes this seems to be an error; so that the correct sample no. is 139288. Note; the here calculated statistics are slightly different from the ones summaries by Fergusson (2010); the above calculations are made on the microprobe data provided by the Appendix I in Fergusson (2010).

Table 10. *Chemical composition of magnetite grains (60 individual grains) from magnetic generated ilmenite concentrate of four different black sand samples from Moriussaq (Ferguson & Rowntree 2011)*

Sample_grain_no	Al_2O_3	MnO	FeO	TiO_2	MgO	NiO	SiO_2	Cr_2O_3	V_2O_3	CoO	Total
B42624_magnetite-1	1.11	0.27	79.69	11.58	0.15	0.01	0.06	0.03	0.99	0.12	93.99
B42624_magnetite-2	0.76	0.24	81.74	9.74	0.14	0.02	0.03	0.04	1.23	0.10	94.05
B42624_magnetite-3	1.11	0.27	80.34	11.49	0.10	0.01	0.01	0.02	0.78	0.11	94.24
B42624_magnetite-4	1.11	0.27	79.52	11.66	0.15	0.00	0.04	0.04	1.07	0.09	93.96
B42624_magnetite-5	0.73	0.23	82.55	8.42	0.08	0.03	0.02	0.05	1.48	0.10	93.68
B42624_magnetite-6	1.17	0.25	82.86	7.09	0.20	0.04	0.03	0.05	1.24	0.12	93.04
243649_magnetite-1	0.95	0.41	75.33	17.98	0.02	0.02	0.03	0.02	0.84	0.07	95.67
243649_magnetite-2	0.91	0.20	81.21	8.46	0.11	0.05	0.03	0.16	1.35	0.11	92.59
243649_magnetite-4	0.84	0.17	83.87	6.64	0.19	0.05	0.02	0.04	1.09	0.14	93.05
243649_magnetite-5	1.02	0.20	83.61	6.66	0.14	0.04	0.03	0.18	1.20	0.08	93.18
243649_magnetite-7	1.07	0.39	73.36	18.13	0.11	0.06	0.05	0.02	0.70	0.10	94.00
243639_magnetite-1	0.67	0.21	85.03	5.37	0.09	0.02	0.01	0.05	1.54	0.15	93.15
243639_magnetite-2	0.90	0.26	79.97	11.06	0.12	0.01	0.03	0.03	0.99	0.11	93.47
243639_magnetite-4	2.04	0.20	82.27	8.97	0.33	0.03	0.01	0.04	1.09	0.09	95.07
243639_magnetite-5	1.20	0.15	84.33	6.71	0.28	0.05	0.02	0.08	1.42	0.10	94.34
243639_magnetite-6	0.75	0.32	80.64	10.82	0.01	0.02	0.02	0.04	1.28	0.10	93.99
243639_magnetite-7	0.65	0.29	80.12	11.51	0.03	0.01	0.05	0.04	0.90	0.11	93.71
243639_magnetite-8	1.74	0.19	82.90	6.45	0.32	0.04	0.03	0.04	1.21	0.12	93.04
B9268_magnetite-1	0.80	0.17	81.96	7.35	0.19	0.04	0.04	0.23	1.84	0.12	92.74
B9268_magnetite-2	1.48	0.25	81.42	8.57	0.26	0.03	0.02	0.05	1.12	0.09	93.28
B9268_magnetite-3	1.92	0.32	72.38	17.87	0.45	0.06	0.02	0.08	0.75	0.12	93.98
B9268_magnetite-4	0.94	0.29	80.31	9.91	0.05	0.01	0.04	0.04	1.16	0.10	92.85
B9268_magnetite-5	0.65	0.27	81.45	9.01	0.04	0.02	0.03	0.05	1.37	0.09	92.98
B9268_magnetite-6	0.83	0.33	79.07	12.50	0.07	0.01	0.03	0.02	0.65	0.10	93.60
B9268_magnetite-6	2.12	0.38	76.81	12.49	0.47	0.07	0.23	0.21	1.05	0.13	93.96
B9268_magnetite-7	1.38	0.16	82.91	6.48	0.18	0.04	0.01	0.37	1.42	0.12	93.08
B9268_magnetite-8	0.82	0.25	81.11	10.56	0.03	0.01	0.03	0.04	1.09	0.10	94.04
Average	1.10	0.26	80.62	10.13	0.16	0.03	0.04	0.08	1.14	0.11	93.66
Standard deviation	0.41	0.07	3.03	3.44	0.12	0.02	0.04	0.08	0.27	0.02	0.69
Minimum	0.65	0.15	72.38	5.37	0.01	0.00	0.01	0.02	0.65	0.07	92.59
Maximum	2.12	0.41	85.03	18.13	0.47	0.07	0.23	0.37	1.84	0.15	95.67

Sample numbers and description: The by Fergusson (2010) in Appendix II given sample no. B42624 is interpreted to represent B-sample of GGU sample no. 243624. The by Fergusson (2010) in Appendix II given sample no. B9268 is interpreted to represent GGU sample no. 139288. GGU sample no. 139288 is from active beach at Moriussaq; no. 243624 is from active beach SE of Moriussaq, no. 243639 is from an uplifted beach 4 km SE of Moriussaq, no. 243649 is from an uplifted beach at Moriussaq. Note; the here calculated statistics are slightly different from the ones summaries by Fergusson (2010); the above calculations are made on the microprobe data provided by the Appendix I in Fergusson (2010).

Hunter Minerals Pty Ltd. conducted a small field campaign in 2011 in the Moriussaq area and collected 136 samples (weight range between 0.12 to 1.959 kg; Ferguson & Rowntree 2011). The chemical analyses from these samples have not been handed in to the authorities and are not available.

3.2 Iron-sulphide

Pyrite-mineralisation with traces of chalcopyrite, pyrrhotite and sphalerite occur at three localities within rusty shales and subordinate dolomites of the Dundas Group sediments and the Steensby Land sill complex near the mouth of Granville Fjord (Dawes 1975, Cooke 1978; Gowen & Sheppard 1994; Thomassen & Tukiainen 2009; Rosa et al. 2013). Massive pyrite pods and lenses are up to 15 cm thick and occur in carbonate rocks, with disseminated pyrite cubes in the adjacent shales. Pyrite-rich sulphide veinlets penetrate both sediment and dolerite (Dawes 2006). The sulphide mineralisation is typically found at the base of the sills.

Thomassen & Tukiainen (2009) carried out prospecting in the above mentioned areas, on the north-eastern coast of Booth Sund. Their work confirms the presence of iron-sulphide mineralisation as the above mentioned. In addition, a lose moraine boulder of brecciated dolerite cemented by quartz, pyrite and chalcopyrite, returned 6190 ppm Cu and 5160 ppb Au.

3.3 Copper

Copper mineralisation has been observed within sediments of the Thule Supergroup as well as within basement gneiss and metasedimentary rock complexes.

Sedimentary-hosted 'Redbed' type copper mineralisation is present at three formations of the Thule Supergroup (Stensgaard et al. 2011). In general, redbed sedimentary successions constitute a major part of many of the stratigraphic groups of the Thule Supergroup. Also indications of extensive fluid/brine activity are present. A potential for the reduced-facies sediment-hosted type copper mineralisation (Kupferschiefer type) could also be present but has not been observed in the Thule region yet.

Quartzite-hosted and amphibolite-hosted copper mineralisation has been found within the basement of the Prudhoe Land supracrustal complex (Thomassen & Krebs 2004), and within paragneiss in the Thule mixed gneiss complex (Thomassen et al 2002).

3.4 Banded iron formation

Localities with banded iron formation are found within the Thule mixed-gneiss, the Lauge Koch Kyst supracrustal units and the Melville Bugt orthogneiss complexes of the Precambrian shield. This represents a more than 400 km long WNW-ESE-trending belt that altogether is referred to as the 'Thule Iron Province'. The province has been regarded as being correlative to the Algoma-type iron deposits of the Mary River Group of the Commiittee Fold Belt of the northern Baffin Island and the adjacent Melville Peninsula (Dawes 2006).

3.5 Other mineral resource potential

A potential for orogenic gold, sedimentary exhalative gold associated with the banded iron formations and sedimentary-exhalative copper and lead-zinc could be present within the Archaean shield in the Thule region (Dawes 2006; Sørensen et al. 2013). There is also a potential for fault-related mineralisation within the regional faults that cut both the Archaean shield and the Thule Basin.

The Dundas and Narssârssuk groups of the Thule Supergroup within the Meso- to Neoproterozoic Thule Basin hold a potential for sediment-hosted zinc deposits (Sørensen et al. 2013). Both sediment-hosted stratiform-type and Mississippi Valley-type are known from similar sedimentary basins in northern Canada including the former Nanisivik Lead-Zinc Mine. In addition, rift basins containing thick continental clastic sediments and with well-preserved unconformities above the crystalline basement hold a potential for unconformity type uranium mineralisation (Dawes 2006).

4. History – geology expeditions and exploration

4.1 Black sands in the Thule region

The main stages in the discovery and field investigation of the Thule black sand province are summarised below.

- 1916: Lauge Koch reports “iron sand” on the north side of Wolstenholme Fjord, Steensby Land. His sample was later found to be ilmenite-rich (*c.* 90% ilmenite, Ghisler & Thomsen, 1973)

- 1950: GGU carried out routine collection of sand samples during regional geological reconnaissance between Savigsivik and Olrik Fjord. Heavy fractions of sands reported on by Ghisler & Thomsen (1971) establish the presence of ilmenite-rich sands at North Star Bugt (present site of Thule Air Base). Occurrences of sands rich in magnetite noted elsewhere in the district.

- 1971: GGU resampled the North Star Bugt locality and confirms black sands with up to 75% weight ilmenite (Ghisler & Thomsen, 1973).

- 1974: GGU carries out reconnaissance mapping determining the regional extent of black sand occurrences along the coast of Steensby Land (Kap Parry – Wolstensholme Fjord); spot sampling of active beach at Moriusaq (Dawes, 1975).

- 1975: GGU sampling programme of active beaches at North Star Bugt, Moriusaq and Granville Bugt (Dawes, 1976)

- 1977: GGU traverse investigation, including sampling, and magnetic/electromagnetic measurements of the Steensby Land showing from active beach across uplifted plain to bedrock scarp. Samples taken in hand-dug pits and limited to 0.5-1 m. The surface sampling showed no obvious correlation with the magnetic or EM observations (Cooke, 1978).

- 1978: GGU extended the Thule black sand province both north and south with discoveries of heavy mineral sands at 76°N and 78°N (Dawes, 1979).

- 1985: Greenex A/S was granted an exploration license (20.05.1985). In the summer of 1985, spot sampling of sands around Moriusaq in rough pits (Christensen 1985). GGU´s results were confirmed for ilmenite; assays for gold, platinum and palladium give low values, however, notable is a maximum of 30 ppb platinum. The license was relinquished on 31.12.1986.

- 1985–86: QIT-Fer et Titane Inc. was granted an exploration license (30.05.1985). Temporary closure of Thule Air Base summer 1985 prevented planned field work. (Cossette 1985). License expired 31.12.1986.

- 2009: During GEUS reconnaissance work along the coast from Melvillebugt to Baffin Island C. Knudsen made a short one-day stop at Moriusaq where sampling was carried out on the raised beaches.

- 2010: Hunter Minerals Pty Ltd. was granted an exploration license (no. 2010/22) at Moriussaq/Steensby Land. A small field campaign from August 26 to September 2 was undertaken by four persons. Most sampling was done using a shovel and pick. A lightweight hand-operated auger drill was also used with limited success because of pebbles and boulders obstructing the drilling. Laboratory work included microprobe analysis of ilmenite and magnetite grains from concentrate. License was later relinquished.

- 2015: Blue Jay Mining Ltd. was granted an exploration license (no. 2015/08) and is currently holding the license.
    - Blue Jay Mining Ltd. visited the area early August 2015. Reconnaissance and a small sampling program were carried out.
    - GEUS, sub-contracted by Blue Jay Mining Ltd., carried out a geophysical boat-operated bathymetry survey together with an initial off-shore grab-sampling, tidal-zone-sampling and onshore-sampling program in mid-to late August 2015. This work also included initial observations on the coastal and beach/raised beach morphology as well as a helicopter-supported acquirement of oriented oblique high-resolution photos that can be used in a photogrammetry study of the coastal morphology. Results from the work are still pending. The sub-contracted work also included a review study of previous findings and activities at Morisusaq (this report).

4.2 Other exploration activities in the Thule region

Other exploration activity, not focusing on the heavy mineral sands, in the Thule region include (extract from Thomassen 2007):

- 19th century: The early expeditions to the region in the late 19th century found that the eskimos used pyrite from Steensby Land as ‘firestone’. A main locality at Nuulliit (Nûgdlît) was described by Peary (1898, vol. 2, p. 219).

- Pre-war: Early expeditions reported pyrite, arsenopyrite and iron-sand (ilmenite-rich) from southern Steensby Land (Koch 1920) and boulders of hematite from Kap York (Bøggild 1953).

- 1952: GGU reconnaissance noted iron ore north of Bushnan Ø and near Parker Snow Bugt (Bøggild 1953).

- 1953: Geologists of the U.S. Geological Survey working around Thule Air Base noted a magnetite ‘vein’ at four localities from Wolstenholme Ø to the margin of the Inland Ice (Davies et al. 1963).

- 1969: The commercial company Greenarctic Consortium investigated a rust zone at Ironstone Fjeld, Lauge Koch Kyst, during regional reconnaissance (Smith & Campbell 1971).

- 1971–80: During regional mapping by GGU, a number of mineralised localities were recorded (e.g. Dawes 1975, 1976, 1979; Dawes & Frisch 1881). Main localities are indicated on the 1:500,000 map sheet (Dawes 1991).

- 1974: Cominco Ltd. followed up on "previously reported" Au (and Pb-Zn) showings at Ironstone Fjeld with no results. Finding of Naajat (Naujat) Cu-showing (Gill 1975).

- 1975 and 1977: Selected mineral occurrences found during the regional mapping mentioned above became the focus of GGU investigations (Cooke 1978).

- 1985: Greenex A/S investigated ilmenite placers in Steensby Land (Christensen 1985).

- 1989–2002: Several mineralised rock samples from the region collected by Greenlandic residents were submitted to the Greenland mineral hunt programme, Ujarassiorit (Dunnells 1995; Olsen 2002).

- 1992: Ujarassiorit follow-up programme carried out by Nunaoil A/S (Ujarassiorit 1993).

- 1994–1995: Nunaoil A/S explored the region and reported a number of mineral indications (Gowen & Sheppard 1994; Gowen & Kelly 1996).

- 2001: During GEUS/BMP's project Qaanaaq 2001, one day was spent collecting stream sediment samples by helicopter in a test area in southern Steensby Land (Steenfelt 2002).

- 2003: A remote sensing study based on Landsat 7 scenes was carried out by GEUS. Twenty-four anomalies with mineralisation potential were outlined: six in lithologies of the Archean shield and 18 in the Thule Supergroup (mainly Dundas Group; Krebs et al. 2003).

5. Geological Maps

Dawes, P.R. 1991: **1:500,000** Geological of Greenland 1:500 000, Thule, Sheet 5. Copenhagen: Geological Survey of Greenland.

Dawes, P.R. 1988: **1:100,000 + 1:200,000** Geological map of the Thule district, North-West Greenland. Sheets 1–6 at 1:000 000 and 7–11 at 1:200 000. Copenhagen: Geological Survey of Greenland. Sheet 3 Hvalsund, Sheet 5 Granville Fjord and Sheet 6 Bylot Sund cover the Moriusaq black sand deposit. These 11 sheets form the mapping base behind the published 1:500 000 map Thule, Sheet 5.

Dawes, P.R. 2014: **1:100,000 + 1:200,000** - All 11 map of Dawes (1988) Geological map of the Thule district, North-West Greenland map sheets (Geological map of the Thule district, North-West Greenland. Sheets 1–6 at 1:000 000 and 7–11 at 1:200 000) are now currently being digitalised and are in the process of being made available in digital GIS format. Draft versions can be obtained through GEUS.

Bathymetric chart of the Arctic Ocean – IBCAO grid (version 3.0, http://www.ibcao.org)

6. Literature

6.1 Thule black sand province

Cooke H.R. 1978: Mineral reconnaissance of the Thule district, North-West Greenland. Rapport Grønlands Geologiske Undersøgelse **90**, 17–22.

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Dawes, P.R. 1989: The Thule black sand province, North-West Greenland. Open File Series Grønlands Geologiske Undersøgelse **89**/4, 17 pp.

Appel, P.W.U., Dawes, P.R. Garde, A.A. Kalvig, P., Ghisler, M. & Schønwandt, H.K 1991 (GGU/MDI) 1991: Small-scale mining, Case 19, Moriusaq ilmenite sand. In: Potential small-scale mining projects in West Greenland, p. 21–23. Report produced by GGU and Mineral Development International A/S for Grønlands Baseselskab A/S.

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Ghisler, M. & Thomsen, B. 1972: Short note on the ilmenite sands from the Thule district, North Greenland. Unpublished GGU report, 3 pp. Copenhagen: Geological Survey of Greenland.

Ghisler, M. & Thomsen, B. 1973: Nyt vidnesbyrd om forekomster af ilmenitesand i Thule district, Nordgrønland. Unpublished GGU report, 3 pp. Copenhagen: Geological Survey of Greenland.

Christensen, K. 1985: Greenex’ prospektering 1985. Internal Greenex company report, Copenhagen, 22 pp. (In archives of Geological Survey of Denmark and Greenland, GEUS Report File 20058)

6.2 Regional geology

Dawes, P.R. 1975: Reconnaissance of the Thule Group and underlying basement rocks between Inglefield Bredning and Melville Bugt, western North Greenland. Rapport Grønlands Geologiske Undersøgelse **75**, 34–38.

Dawes, P.R. 1976: 1:500,000 mapping of the Thule district, North–West Greenland. Rapport Grønlands Geologiske Undersøgelse **80**, 23–28.

Dawes, P.R. 1979: Field investigations in the Precambrian terrain of the Thule district, North-West Greenland. Rapport Grønlands Geologiske Undersøgelse **95**, 14–22.

Dawes, P.R. 1997: The Proterozoic Thule Supergroup, Greenland and Canada: history, lithostratigraphy and development. Geology of Greenland Bulletin **174**, 150 pp. + references therein.

Dawes, P.R. 2006: Explanatory notes to the geological map of Greenland, 1:500 000, Thule, Sheet 5. Geological Survey of Denmark and Greenland Map Series **2**, 97 pp + Sheet 5. + references therein. [Comprises a summary of the bedrock (Precambrian) geology and Quaternary deposits, including the mineralisations shown on the map and black sand beach deposits.]

Nutman, A.P. 1984: Precambrian gneisses and intrusive anorthosite of Smithson Bjerge, Thule district, North-West Greenland. Rapport Grønlands Geologiske Undersøgelse **119**, 31 pp. + map. [Only detailed mapping carried out in the Thule district. Manuscript map in Survey archives is at 1:20 000.]

6.3 Regional isotopic age-dating

Nutman, A.P., Dawes, P.R., Kalsbeek, F. & Hamilton, M.A. 2008: Palaeoproterozoic and Archaen gneiss complexes in northern Greenland: Palaeoproterozoic terrane assembly in the High Arctic. Precambrian Research **161**, 419–45. + references therein.

6.4 Regional mineralisation (incl. placer deposits)

Thomassen, B., Krebs, J.D. & Dawes, P.R. 2002: Qaanaaq 2001: mineral exploration in the Olrik Fjord – Kap Alexander region, North-West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2002**/**86**, 72 pp. + map.

Thomassen, B. & Krebs, J.D. 2004: Mineral exploration of selected targets in the Qaanaaq region, North-West Greenland: follow-up on Qaanaaq 2001. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2004**/**42**, 38 pp. + tables.

Thomassen, B. 2008: The Thule Iron Province, North-West Greenland. A compilation of data. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2008**/**61**, 28 pp. + CD-ROM.

Thomassen, B. & Tukiainen, T. 2009: Pituffik 2007: mineral reconnaissance in the Pituffik region, North-West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2009**/**39**, 116 pp. incl. figs, maps and tables.

6.5 Geochemistry (stream-sediments)

Steenfelt, A. 2002: Geochemistry of southern Steensby Land, North-West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2002**/**56**, 25 pp. Covers the Moriusaq black sands.

Steenfelt, A., Dawes, P.R., Krebs, J.D., Mosberg, E. & Thomassen, B. 2002: Geochemical mapping of the Qaanaaq region, 77°10' to 78°10'N, North-West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2002**/**65**, 29 pp. + 48 maps.

6.6 Satellite remote sensing

Krebs, J.D., Thomassen, B. & Dawes, P.R. 2003: A Landsat study of the Pituffik region, North-West Greenland. With a summary of mineral occurrences and potential. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003**/**92**, 37 pp. incl. maps and figs.

7 Samples; black sand

Samples of the Thule black sands in the GEUS archives are listed below, with the collector and the year of collection.

7.1 Sand unprocessed

GGU Sample no.	Collector	Year	Description
13642	B. Thomsen	1950	Active beach Pituffik
141039	P.R. Dawes	1971	Active beach Pituffik
141040	P.R. Dawes	1971	Active beach Pituffik
166674	P.R. Dawes	1974	Active beach Moriusaq
166675	P.R. Dawes	1974	Active beach Moriusaq
212654	P.R. Dawes	1975	Active beach Siorapaluk, Prudhoe Land
139261–65; 70–84, 86–98	H.R. Cooke	1975	Pituffik/Moriussaq, active and uplifted beaches
243624–700; 243725–34	H.R. Cooke	1977	Regional incl. Pituffik/Moriussaq, active/uplifted beaches
243430	P.R. Dawes	1978	Active beach north of Radcliffe Pynt, northern Prudhoe Land.
243267	P.R. Dawes	1978	Active beach Kap Edvard Holm, Melville Bugt
473867	C. Knudsen	2009	Moriusaq, raised beaches, profile in the uppermost terrace (near hills)
473868	C. Knudsen	2009	As 473867
473869	C. Knudsen	2009	As 473867
473870	C. Knudsen	2009	As 473867
492488	C. Knudsen	2009	Moriusaq, raised beaches, prof. in the lowermost terrace at the beach
492490	C. Knudsen	2009	Moriusaq, ca. 5 m above sea level, ca. 50 x 500 x 2 m
492491	C. Knudsen	2009	Moriusaq, flat surface terrace cut by stream
492492	C. Knudsen	2009	Moriusaq, prof. in the uppermost alluvial fan; stone layer beneath.
492493	C. Knudsen	2009	Moriusaq, profile
492494	C. Knudsen	2009	Moriusaq
492495	C. Knudsen	2009	Profile ca. 200 m from beach. Cut out by small stream
492496	C. Knudsen	2009	[no notes]
492497	C. Knudsen	2009	[no notes]
492498	C. Knudsen	2009	Fabric parallel to layering
492499	C. Knudsen	2009	[no notes]
473865	C. Knudsen	2009	Auger drill hole
473860	C. Knudsen	2009	Auger drill hole
473866	C. Knudsen	2009	Auger drill hole
473862	C. Knudsen	2009	Auger drill hole
473863	C. Knudsen	2009	Auger drill hole
473864	C. Knudsen	2009	Auger drill hole
473861	C. Knudsen	2009	Auger drill hole

7.2 Heavy mineral concentrates

GGU 13642	B. Thomsen 1950, active beach Pituffik
GGU 166674	P.R. Dawes 1974, active beach Moriusaq
GGU 166675	P.R. Dawes 1974, active beach Moriusaq
GGU 139273	H.R. Cooke 1975, 0–20 cm active beach Moriusaq
GGU 139288	H.R. Cooke 1975, 0–20 cm active beach Moriusaq
GGU 139292	H.R. Cooke 1975, 30 cm active beach Moriusaq
GGU 243624	H.R. Cooke 1977, 60 cm active beach SE of Moriusaq
GGU 243639	H.R. Cooke 1977, 30 cm uplifted beach, 4 km SE of Moriusaq
GGU 243649	H.R. Cooke 1977, 20 cm, uplifted beach at Moriusaq

8. References

Appel, P.W.U., Dawes, P.R.. Garde, A.A. Kalvig, P., Ghisler, M. & Schønwandt, H.K 1991: Potential small scale mining projects in West Greenland. Unpublished report produced by GGU and Mineral Development International A/S for Grønlands Baseselskab A/S, 62 pp.

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Davies, W.E., Krinsley, D.B. & Nicol, A.H. 1963: Geology of the North Star Bugt area, northwest Greenland. Meddelelser om Grønland **162**, 12, 68 pp.

Dawes, P.R. 1975: Reconnaissance of the Thule Group and underlying basement rocks between Inglefield Bredning and Melville Bugt, western North Greenland. Rapport Grønlands Geologiske Undersøgelse **75**, 34-38.

Dawes, P.R. 1976: 1:500.000 mapping of the Thule district, North-West Greenland. Rapport Grønlands Geologiske Undersøgelse **80**, 23-28.

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