DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2003/92

A Landsat study of the Pituffik region, North-West Greenland

With a summary of mineral occurrences and potential

Johan D. Krebs, Bjørn Thomassen and Peter R. Dawes

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

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Contents

Maps

Figures

Table

1. Abstract

This Landsat study aims at the delineation of mineral exploration targets in the southern part of Qaanaaq (Thule) municipality, North-West Greenland. It has been carried out by the Geological Survey of Denmark and Greenland being mainly funded by the Bureau of Minerals and Petroleum, Government of Greenland. The study area is centred on Pituffik or Thule Air Base (TAB) and comprises *c*. 4 300 km^2 ice-free land.

The Pituffik region exposes Precambrian rocks: a high-grade Archaean crystalline shield, comprising four major complexes, overlain by the unmetamorphosed mainly Mesoproterozoic Thule Supergroup. This is a multicoloured, continental to shallow marine sequence with one interval of basaltic volcanic rocks. Basic sills are common at several levels.

The crystalline shield hosts a regional iron province with banded iron-formation (BIF). In the Thule Supergroup mineralisation is only known from the Dundas Group where pyrite and minor chalcopyrite are often associated with sill/sediment contacts. Ilmenite placers occur on active and uplifted beaches at several localities, and minor gold has been obtained from panning a river. A summary of mineral potential is: gold and base metals in the shield, lead-zinc in the Thule Supergroup and titanium and gold in placers.

Four images of Landsat 7 ETM data were processed to pin-point localities with mineralisation potential by means of mapping minerals that carry iron oxides (rust zones) and hydroxyl ions (clay alteration). Areas with coincident rust coloration and hydrothermal alteration are considered to have a potential for mineralisation. Two different techniques were used for the processing: (1) standard band ratios and (2) feature-oriented Principal Component Analysis (PCA). The techniques are based on transitions occurring in three compounds abundant in geologic material: iron oxides – Fe-O and Fe^{2+} – indicating iron oxide stained areas, and hydroxyl – OH^- – indicating hydroxyl-bearing minerals. By combining these three data sets, a so-called Crosta image illustrating areas of rust zones, clay alteration and anomalies can be produced. An anomaly is defined as a pixel belonging to the 99.999% fractile in both the hydroxyl and the iron band of both the processed ratio image and PCA data. Twenty-four anomalies are outlined, six in shield lithologies and 18 in the Thule Supergroup, mainly Dundas Group. These are presented with co-ordinates and indicated on a map. Some of the anomalies are also shown as Crosta images.

The Thule Supergroup is coeval with and a correlative of the Bylot Supergroup of neighbouring Baffin Island, Canada, that hosts in carbonates an economic lead-zinc deposit – Nanisivik. For comparison, a Landsat scene over Nanisivik was studied although on it no obvious signs of clay alteration and rust zones, other than formational rust, were observed.

A Landsat survey is a low-cost method to locate exploration targets and as such, it is an important tool in planning field operations. However, as the disappointing results from Nanisivik demonstrate, the method cannot be used to *exclude* the possibilities of finding economic deposits. It is recommended to follow up on all 24 Landsat anomalies with field checks. Highest priorities should be given to those in the shield rocks and in the Thule Supergroup carbonates, followed by the larger anomalies in the Dundas Group.

2. Introduction

This Landsat study carried out in 2003 aims at the delineation of mineral exploration targets in the region between western Melville Bugt and Olrik Fjord (75°50′N–77°10′N, 64°W–72°W), North-West Greenland (Maps 1 & 2). A similar study was carried out in 2001 prior to the field work undertaken during *Qaanaaq 2001* that focussed on the region immediately north of the present study area (Thomassen *et al*. 2002a, b). The 2003 Landsat work is organised by the Geological Survey of Denmark and Greenland (GEUS) and mainly funded by the Bureau of Minerals and Petroleum (BMP), Government of Greenland. The main goal of the initiative is to pin-point areas that could attract the interest of the mining industry.

The investigated region, that is centred on Pituffik or Thule Air Base (TAB) in the Qaanaaq (Thule) municipality, is referred to herein as the Pituffik region. It has an area of c. 17 000 km^2 of which c. 4 300 km^2 is ice-free. The northern part is dominated by 400–800 m high plateaus capped by local ice caps (Map 2). In the south, high dissected terrain occurs on the Kap York peninsula, and to the east the Inland Ice reaches the sea on a broad front where the coast consists for the most part of islands, peninsulas and nunataks. The highest altitude is in the north-east at c. 1130 m. The climate is high arctic and the whole area is underlain by permafrost.

A Landsat scene over the lead-zinc deposit at Nanisivik, Baffin Island, Canada, some 600 km to the south-south-west and exposing comparative geology to Pituffik, is also included in the study.

This report presents the results of the Landsat study together with a review of the region's geology, mineral occurrences and mineral potential. It presents recommendations for follow-up work. Author roles are: J.D.K. processed and interpreted the Landsat scenes; B.Th. structured the paper and compiled geologic and economic geology information; PRD refined the geological descriptions and helped with all-round quality control.

3. Geological setting

The Pituffik region exposes a high-grade Archaean crystalline shield overlain by unmetamorphosed Proterozoic strata of the intracratonic Thule Basin (Map 1). The profound unconformity between these two provinces is well preserved through the region.

North-West Greenland was mapped by the former Geological Survey of Greenland (GGU) between 1971 and 1980, mainly by shoreline investigations with limited helicopter traversing inland. Steensby Land and areas around Pituffik (map 2), exposing large tracts of Thule Basin deposits, were mapped at 1:100 000; other areas, composed mainly of shield rocks are available at 1:200 000 (Dawes 1988). Unpublished maps at these scales form the basis of the Survey's 1:500 000 geological map, Thule, sheet 5 (Dawes 1991). Unless otherwise stated, rock unit names in this report are taken from this map, to which the reader is referred for further geological information.

3.1 Archaean crystalline shield

The existing geochronological information suggests that the crystalline shield of the study region is composed of Archaean rocks that have been subjected to Palaeoproterozoic reactivation. However, some Palaeoproterozoic crust could be present, in one or more of the four map units recognised.

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 (Map 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. 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. It contains at least some rocks that have been derived from the previous unit.

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. The age of the rocks is unknown; some could be Palaeoproterozoic.

3.2 Thule Basin

The Thule Basin developed on the peneplaned surface of the Precambrian shield. It is represented by the Thule Supergroup, a multicoloured, continental, littoral to shallow marine sedimentary succession with one main interval of basaltic volcanic rocks. Basic sills are common at several levels. The study region exposes the south-eastern part of the basin where four groups are recognised (Dawes 1997). The lower three groups are Mesoproterozoic in age; the age of the upper strata (Narssârssuk Group) is uncertain.

The *Nares Strait Group* forms the basal strata exposed in the north-western part of 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 multicoloured 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, peritidal environment in conditions perhaps analogous to modern coastal sabkhas.

3.3 Regional structures

Down-faulted blocks of Thule Supergroup form the western part of the area bordered on the east by generally higher elevation areas of the Precambrian shield. The study area has a distinct WNW–ESE structural grain formed by regional faults and basic dykes. The main WNW-striking dyke swarm that cuts the entire Thule Supergroup is Neoproterozoic (675–630 Ma).

Compared to the gneisses and supracrustal rocks of the Precambrian shield, the Thule Supergroup is little disturbed. The main regional structures are fault blocks, grabens, large-scale flexures, as well as some local folds associated with faults. Prominent faults vary from NW–SE-trending to WNW–ESE-trending. Some faults represent appreciable displacement, for example those juxtaposing the middle to upper strata of the Thule Supergroup with the Precambrian shield. Thus the Narssârssuk Fault that borders the youngest beds of the Supergroup (Narssârssuk Group) on the south represents a downthrow of several kilometres.

4. Mineral exploration

Only limited mineral exploration has been carried out in the Pituffik region and no major mineral occurrences are known. The most publicised occurrence has been the ilmenite placer deposits (Ghisler & Thomsen 1971, 1973; Dawes 1989). A brief historical review of mineral discovery and exploration is given below.

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).

1950: During ship-based geological reconnaissance by the former Geological Survey of Greenland (GGU), ilmenite-rich sand was collected at North Star Bugt (Ghisler & Thomsen 1971).

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 (Stuart 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).

5. Mineral occurrences

The main mineralised localities in the Pituffik region are listed below and indicated by letters **A** to **O** on Map 2. None are of immediate economic interest.

5.1 Archaean crystalline shield

The southern part of the Pituffik region hosts part of the major iron province which stretches from Kap Seddon (*c.* 75° N) in the east along the Melville Bugt coast (Lauge Koch Kyst) to Wolstenholme Ø. It has been suggested that this belt correlates with the iron-rich rocks on northern Baffin Island, Canada, that host the Mary River iron ore deposits (Dawes & Frisch 1981; Jackson 2000). In the study area, the iron province stretches 175 km from Sorte Fjeldvæg west-north-west to De Dødes Fjord and Wolstenholme Ø, as indicated by Dawes (1979, fig. 6; 1991; see localities **G**, **D** and **A**, respectively, on Map 2). Iron in the form of magnetite and lesser hematite occurs both as quartz banded iron-formation (BIF), massive lenses and layers, and disseminated, mainly in pelitic and mafic schists of the Lauge Koch Kyst supracrustal complex. Selected localities exposing magnetite-rich rocks are listed below (**A**–**G**), as well as other minor mineralisation in the shield (**H**–**J**).

A. Wolstenholme Ø. A 6–15 m thick magnetite-quartz ‘vein’ was mapped across the island by Davies *et al.* (1963). Written information from W.E. Davies (personal communication 1975) suggests that the occurrence is not a ‘vein’ in a cross-cutting sense but a tract of gneiss rich in magnetite.

B. Magnetitbugt. Several conformable massive magnetite bands up to 3 m thick occur at this locality in folded gneiss with an exposed strike length of 200 m (Davies *et al.* 1963; Dawes 1975; Cooke 1978).

C. West of Freuchen Nunatak (‘Freuchen Gletscher’). A magnetite-quartz ‘vein’ was observed by Davies *et al.* (1963) at two localities south of Pituffik/Thule Air Base. Dawes (1976) reported that iron-rich gneiss and schist occur as several tracts in association with amphibolites and basic schists near the Inland Ice south of the air base. In 1994 Nunaoil investigated the area and found numerous sulphide-bearing rocks located in a supracrustal sequence, as well as BIF with some iron-sulphides along fractures. A float of silicified and carbonatised pyrite-rich pyroclastic rock returned 860 ppb Au (sample 193438; Gowen & Sheppard 1994). Hematite iron-formation float was also noted. Follow-up investigations in 1995 in an east–west-orientated valley west of ‘Freuchen Gletscher’ exposing mafic, felsic and magnetite schists revealed rust zones up to 20 m in width and at least 300 m in strike length. Silicification and dm-wide bands of mylonitised country rock with semi-massive pyrite in lenticular zones, as well as minor quartz veining were noted. Up to 43 ppb Au was recorded in scree sediment at one of the rust zones (Gowen & Kelly 1996).

D. De Dødes Fjord. Magnetite-rich rocks, often as BIF and in places with hematite and sulphides, occur in metasediments on nunataks and semi-nunataks at De Dødes Fjord.

Some of the rocks resemble classical banded ironstones, and the total thickness of iron-rich rocks probably exceeds 40 m (Dawes 1976).

E. Sidebriksfjord. Supracrustal rocks outcropping on nunataks at the head of Sidebriksfjord invariably contain anomalous magnetite. For example, the succession of pelitic schists, amphibolites and ultramafic rocks lying above multiphase gneisses and forming the core of the spectacular synform featured in Dawes (1976, fig. 7) contain iron-formation and magnetite-rich units.

F. Bushnan Ø. On this island, Dawes (1979) reported a succession of quartz-rich gneisses and schists containing several units of magnetite-rich melanocratic gneiss and magnetite-bearing quartzite.

G. Sorte Fjeldvæg. Up to 2 m thick units of well-developed banded ironstones, composed of intercalated discrete bands of quartz and magnetite several millimetres thick, and intercalated with garnet amphibolite and leucocratic gneiss, were reported by Dawes (1979).

H. Ironstone Fjeld. A gossan 200 m in diameter occurs on the south side of the mountain. The gossan area is criss-crossed by small quartz veins which are associated with disseminated mineralisation. The host rock is a granite gneiss with inclusions of biotite schist. A sample returned 0.1 oz Au and 1.56 oz Ag (Stuart Smith & Campbell 1971). Some gneisses are magnetite anomalous.

I. Salve Ø. Copper mineralisation seen as malachite staining is indicated on the geological map of Dawes (1991), with magnetite-rich metasediments on neighbouring islands.

J. Olrik Fjord. Two ultramafic pods (peridotite) in granitic gneiss south of Olrik Fjord host minor sulphide mineralisation. A sample of nearby amphibolite with minor sulphides returned 116 ppm Au and 1204 ppm As (sample 193403; Gowen & Sheppard 1994).

5.2 Thule Basin

All mineralisation presently known in the Thule Supergroup occurs in strata of the Dundas Group that in the study region hosts stratiform pyrite in dark shales and is severely invaded by basaltic sills. In Steensby Land, rust due to sulphide mineralisation (pyrite, chalcopyrite and sphalerite) is common in dolomites and shales where sills and dykes are prominent. The sulphides occur in thin veins in both sediments and dolerites (Dawes 1975; Cooke 1978). Selected localities **K–M** are listed below.

K. Naajat (Naujat). Veinlets and pods of Fe- and Cu-sulphides occur in a swarm of dykes and in adjacent shales, staining the cliffs green (Cooke 1978). A grab sample from a pod of dark carbonate rock returned 1.8% Zn, 0.2% W and 0.03% Cu (sample 193359; Gowen & Sheppard 1994).

L. Moriusaq. Pockets of massive pyrite and magnetite-ilmenite occur in dolomite and shales for 50 m along strike. These are probably derived from an underlying basic sill

(Cooke 1978). Brecciated and vuggy carbonate veins with 1–2% chalcopyrite and pyrite, 1–50 cm wide and up to 5 m long and formed within fractures in sills are widespread. Semi-massive pyrrhotite occurs in a dolerite dyke at Moriusaq harbour and as blocks in the immediate vicinity of the settlement (Gowen & Kelly 1996).

M. Nuulliit (Nûgdlît). Massive pyrite occurs in dolomite beds as pods and lenses up to 15 cm thick. Disseminated pyrite cubes also occur. Traces of copper sulphides causing malachite staining can be associated. The sulphides were probably introduced by one or more of the nearby sills (Cooke 1978).

5.3 Recent placers

N. Steensby Land ilmenite showing. The most promising heavy mineral sands occur on active and uplifted beaches of the Steensby Land ilmenite showing (Dawes 1989). The source of the placer ilmenite is the titanium-rich Steensby Land sill complex. Average grade of the active beaches is *c.* 43% $Ti0_2$; uplifted beaches have a larger tonnage potential but lower titanium values with an average around 12% $Ti0_2$ (Cooke 1978; Dawes 1989). Greenex's 1985 spot sampling of sands around Moriusaq confirmed GGU's results as far as ilmenite; assays for gold, platinium and palladium returned concentrations below 20 ppb, apart from two values of 30 ppb Pt (Christensen 1985).

O. North Star Bugt: The main river draining the wide Quaternary-floored valley in which Pituffik/Thule Air Base is located, has its mouth in North Star Bugt flats that contain black sands. These contain up to 75% weight ilmenite (Ghisler & Thomsen 1971, 1973).

6. Geochemical surveys

Four geochemical surveys have been carried out in the Pituffik region although none of these systematically cover the entire region. Only one significant anomaly is recognised, marked on Map 2 by **P**. The surveys and the anomaly are briefly described below.

1950: GGU collected sand samples at sporadic localities along the coast during geological reconnaissance in 1950. This resulted in detection of ilmenite- and magnitite-rich sands at North Star Bugt (Ghisler & Thomsen 1971).

1992: During *Ujarissiorit* follow-up in 1992, 15 heavy mineral concentrates (HMC samples) were collected around Pituffik and in southern Steensby Land. Three of these were anomalous in gold: Sioqqap Kuua (Siorqap kûa or 'Fox Canyon'), 2710 ppb Au (sample 302419), Narsaarsuk Elv, 174 ppb Au (sample 302417) and Booth Sund north, 123 ppb Au. (Ujarassiorit 1993).

1994–1995: Nunaoil collected stream sediment samples in selected parts of the Pituffik region in 1994 and 1995. The company took large sediment samples for bulk leaching gold analysis (BLEG), as well as standard stream sediment samples. Subsequently, the company rejected the BLEG technique. During the two summers, 92 stream sediment samples were collected. These show modest metal concentrations, viz. max. 43 ppb Au, 258 ppm Cu, 118 ppm Pb, 173 ppm Zn and 1000 ppm Ba (Gowen & Sheppard 1994; Gowen & Kelly 1996).

2001: During *Qaanaaq 2001*, 23 stream sediment samples were collected in an area in Steensby Land in order to try to establish geochemical background concentrations of relevance for the ongoing pollution assessment at Pituffik/Thule Air Base. The maximal gold and base metal concentrations are: 5 ppb Au, 419 ppm Cu, 19 ppm Pb and 181 ppm Zn (Steenfelt 2002).

Anomaly P. Sioqqap Kuua (Siorqap kûa or 'Fox Canyon'). This anomaly, located inside of the air base area, is the most significant geochemical anomaly in the region. Following rumours of placer gold mining by base personnel, the upper and lower course of the stream Sioqqap Kuua was panned for gold by Cooke (1978). Only two very small gold colours were obtained from about 50 pans. Subsequently, a HMC with 2.7 ppm Au was collected during *Ujarassiorit* follow-up (Ujarassiorit 1993), and a stream sediment sample with 14 ppb Au was collected from the drainage area by Nunaoil (sample 193452; Gowen & Sheppard 1994). The gold probably origins from the Thule mixed-gneiss complex, see mineral occurrence **C**.

7. Nanisivik lead-zinc deposit

The Precambrian geology of the Pituffik area shows many similarities to that in areas of adjacent Canada. For example, the Borden Basin of Baffin Island and the Thule Basin of Greenland are coeval depocentres. The upper part of the Thule Supergroup has a comparable lithology, age and structural setting to part of the Bylot Supergroup of the Borden Basin that hosts the economic lead-zinc deposit of Nanisivik. For this reason, a Landsat scene covering the area of Nanisivik mine has been consulted as part of this study. As background, a short description of the mined deposit is also given here.

The Nanisivik mine is located on Borden Peninsula, northern Baffin Island, about 750 km north of the Arctic Circle and some 600 km from our study area. The lead-zinc deposit has been described as a classical Mississippi Valley type deposit hosted by Mesoproterozoic carbonates. It has been presumed to be of Precambrian age (Olson 1984; Sutherland & Dumka 1995) but recent studies have suggested an Ordovician age (Sherlock *et al.* 2003; see below). The following summary of the current status as seen by the staff of the Geoscience Office, Iqaluit, Nunavut, Canada, has been obtained from Ross L. Sherlock (personal communication 2003).

The mine was in operation from 1976 to the fall of 2002, producing about 19 million tonnes of ore grading 8.7% Zn, 0.69% Pb and 41 g/t Ag. These base metal ores were produced from sulphide bodies that collectively total over 100 million tonnes of pyrite. The Mesoproterozoic Bylot Supergroup that hosts the mined deposit rests unconformably on the Archaean to Proterozoic Rae Province basement complex of granites and gneisses, part of the Mary River Group. The sulphides at Nanisivik are hosted in petroliferous dolostones of the Society Cliffs Formation (coeval with the Narssârssuk Group of Greenland). Three subdivisions of the host formation have been identified and known sulphide deposits are hosted exclusively by the middle and upper subdivisions. A series of long-lived east–west-trending normal faults, some of which are syn-sedimentary, divide the Nanisivik area into a series of horst and grabens. The strata have also been folded into broad, open north–south-trending folds. All known sulphide bodies are associated with normal faults particularly where they cut antiform fold axes.

Recent mapping and dating of alteration minerals indicate a mid-Ordovician age (461 Ma) for the mineralisation (Sherlock *et al.* 2003). Such an age is problematic in terms of identifying regional events to drive a hydrothermal system of the magnitude required to produce Nanisivik. Localised uplift revealed by a disconformity may have been sufficient to initiate a gravity-driven fluid flow system. The local structural and stratigraphic framework, including antiform hinges, gas-water interfaces and normal faults are considered significant in controlling sulphide deposition.

8. Mineral potential

The Pituffik region is envisaged to host potential for several types of mineralisation. These are listed below using mainly the terminology of Eckstrand *et al.* (1995).

8.1 Archeaen crystalline shield

1. Banded iron-formations in the Lauge Koch Kyst supracrustal complex. Although interesting size and grade have not been reported, the occurrence of a major iron ore deposit of Mary River type cannot be discounted.

2. Volcanic-associated massive Cu-Pb-Zn sulphides (VMS). The metavolcanics of the Lauge Koch Kyst supracrustal complex, in particular, host a potential for this type of mineralisation.

3. Magmatic Ni-Cu-PGE occurrences could be associated with the mafic plutonic rocks of the Kap York meta-igneous complex.

4. Structurally-hosted gold could occur within the supracrustal sequences: one promising target must be in association with iron-formations in the Lauge Koch Kyst supracrustal complex.

8.2 Thule Basin

5. Nanisivik (MVT) type Pb-Zn mineralisation might be expected in dolomites of the Narssârssuk Group. At Nanisivik, pyrite-dominated Pb-Zn mineralisation is fault controlled and hosted in karstic features within dolomites and dolostones.

6. SEDEX type Pb-Zn mineralisation could occur in the argillaceous lithologies of the Dundas Group, from where stratiform pyrite is known.

7. Redbed type copper mineralisation might occur in sandstones and shales of the Baffin Bay Group, as known in the Qaanaaq region to the north.

8. Unconformity-associated U(-Ni-Co-Au). The well-preserved unconformity at the base of the Thule Supergroup provides a target for this type of mineralisation.

9. Skarn mineralisation could be associated with the abundant sills and dykes of the Dundas Group, especially the Steensby Land sill complex. Given the mafic character of the intrusions, iron and gold skarns are the most likely types.

10. Magmatic Ni-Cu-PGE mineralisation might be expected in association with the sills of the Dundas Group.

11. On the Brodeur Peninsula, northern Baffin Island, diamond-bearing kimberlite pipes are hosted by Ordovician sediments. Although no Palaeozoic cover rocks have survived in the Pituffik region, similar kimberlites could pierce the Thule Basin strata.

8.3 Placers

12. Ilmenite (platinum). An ilmenite potential has been demonstrated in active and raised beaches especially along the Moriusaq coast, and an additional platinum contribution has been indicated.

13. Gold. Panning of gold from an unknown source in Sioqqap Kuua indicates a placer potential in this water course.

9. Remote sensing study

Part of *Qaanaaq 2001* was a pre-season remote-sensing study aimed at delineating areas of potential economic interest (Thomassen *et al.* 2002b). It was based on four images of Landsat 7 ETM data with a 30 x 30 m pixel size recorded during the season of minimum snow cover (5 and 24 July 1999). The idea was to determine localities with best mineralisation potential by means of mapping minerals that carry iron oxides (rust zones) and hydroxyl ions (clay alteration or argillic alteration). In principle, areas with coincident rust coloration and hydrothermal alteration are those considered to have most potential for mineralisation.

The 2001 study outlined 28 anomalies that became targets for field checks. They gave a first impression of the regional distribution of rust zones and hydrothermal alteration: 13 of the anomalies were in shield lithologies and 15 in the Thule Supergroup, mainly Dundas Group. Most anomalies were visited during the field work and this showed that 17 anomalies are related to mineralisation and/or hydrothermal alteration with the remainder stemming from formational responses. It also turned out that all areas of alteration and/or rust coloration observed during the field work were indeed registered in the processed Landsat data.

For the Pituffik remote-sensing project reported on here, the same four Landsat scenes and the same processing technique as used for the 2001 project were chosen. However, this time visual geological interpretation and selection of the automatically generated anomalies were undertaken. Therefore, the description of the processing steps is similar to that given in Thomassen *et al.* (2002b). The advantage of using the same procedure was that the knowledge of the image/field interaction obtained in 2001 could be used to aid the visual geological selection of the anomalies found by the automated analysis. Thus, anomalies known to be caused by formational rust, overburden, etc. could be avoided. The automated analysis was improved by the fact that the data were processed on newer software that could handle floating point values thus allowing a narrower range to be defined in the statistics.

9.1 Pre-processing

Before actual treatment it was necessary to pre-process the data for the effects of surface cover, image defects, line dropouts, badly illuminated pixels, correction of sensor variation gain and offset. Five different types of surface characterise the study area: exposed bedrock, scree, fresh water lakes and streams, seawater, and snow and ice. Since only the first two types are relevant to the study, the others were omitted before processing took place by the construction of masks. Areas in shadow were also omitted.

As no ground truth was available for the construction of the masks, they were constructed using known biophysical properties and published spectral data. The spectral signature of the undesired surface served as input for a box classification characterised by its value in different bands each dependent on the physical properties of the surface. The classification procedure had to be simple to ensure that it was applicable to all data sets with only minor adjustments though they were recorded at some temporal intervals. The contrast between noise and areas of interest was assumed to be large and therefore a simple procedure could be used without leading to unacceptable data loss. The band and DN (digital number) cut-off value used for the box classification were mostly determined from profiles across the feature/surface cover of interest.

9.2 Processing

Two techniques were used for the processing of the data: (1) standard band ratios and (2) feature-oriented Principal Component Analysis (PCA).

(1) Standard ratios. The standard ratios maximise the lithologic information. This relation has been confirmed both empirically and physically. Crippen (1989) presented the arguments for the selection of the standard band ratios TM3/TM1 + TM4/TM5 and TM5/TM7 for the mapping of iron oxides and hydroxyl carrying minerals, respectively. The selection of the bands contributing to the various ratios is based on transitions occurring in three compounds abundant in geologic material.

Iron oxides Fe-O. The Fe-O charge transfer transition occurs as a broad absorption band below 550 nm (Hunt 1977). This feature, situated in TM band 1 (blue-green) together with the high reflection in TM band 3 (red), is typical for iron oxide rusty colour. This will cause iron oxide stained areas to score high values in a TM3/TM1 ratio image.

Iron oxides Fe^{2+}. Iron Fe^{2+} crystal field transitions for the ion in various forms of distorted octahedral sites with six-fold co-ordination occur as absorption bands in the region from 750–1500 nm (Hunt 1977). These features situated in TM band 4 (near infra red – NIR) can be used to detect iron oxides using the TM4/TM5 as most minerals reflect well in TM band 5 (short wave infra red – SWIR). This ratio will score high and low values depending on whether these oxides are present or not. The iron in augite will also be detected by this ratio; however, this is of limited importance, as iron oxide surface coating will cloak this weak contribution

Hydroxyl OH^-. Hydroxyl OH^- has only one fundamental stretching mode located near 2750 nm with the exact location depending on what the group is directly attached to and the site it occupies. These features fall outside the spectral capability of the Landsat TM. However, the overtones all lie in the 2200–2400 nm range well within TM7 (SWIR). Using the fact that most minerals reflect well in TM band 5 (SWIR), the ratio TM5/TM7 will score high values where hydroxyl-bearing minerals are present.

(2) Feature-oriented Principal Component Analysis (PCA). This process is also called the Crosta technique after its originator (Crosta & McMoore 1989). It bears a slight resemblance to the band ratio technique. The band selection process is the same as the one used for the standard ratio technique TM3 vs. TM1 and TM4 vs. TM5 for the mapping of iron oxides, and TM5 vs. TM7 for hydroxyl mapping. The idea is again to find areas where a high reflection in TM5, linked with a low reflection in TM4, indicate the presence of Fe-O, areas where high reflection in TM5, linked with a low reflection in TM1, indicate the presence of Fe^{2+}, and areas where high reflection in TM5, linked with a low reflection in TM7, indicate the presence of hydroxyl.

The aim is to select the input bands to the PCA in such a way that areas where the above is fulfilled will appear as abnormal values. As input 2, combinations of four bands each, are used TM1, TM3, TM4 and TM5 for the mapping of iron oxides, and TM1, TM3, TM5 and TM7 for hydroxyl mapping (Loughlin 1991a). The reason for only conducting PCA on four bands instead of all six is to assure that certain materials will not be mapped, and to increase the likelihood that others will be unequivocally mapped into only one of the principal component images (Loughlin 1991b). To locate where the information of the different input TM bands goes, the values of the eigenvector loading for the input bands is needed. This loading is directly read from the eigenvalue matrix. By combining these three data sets in a RGB (red, green, blue) display as hydroxyl, iron, and hydroxyl + iron, areas with hydrothermal alteration will be green, those with iron oxide staining red, and areas with both, bright white. This image is called the Crosta image.

9.3 Geometric rectification

The Landsat data of the study area were rectified using a second-order model and ground control points selected from 1:250 000 topograpic data (G/250 Vector, Kort & Matrikelstyrelsen, Copenhagen).

9.4 Anomalies

For the automatic analysis, an anomaly was defined as a pixel belonging to the uppermost 10 ppm (99.999% fractile) in both the hydroxyl and the iron band of both the processed Crosta and ratio image data. If the pixel located by these criteria occurred together with two or more adjoining pixels from the same fractile, it was registered as an anomaly. After the automatic analysis, the images were interpreted manually, utilising the experience gathered in 2001. A minute variation occurred in comparison to the results obtained in 2001, caused by the use of floating point values for statistic calculations with the new software. All anomalies that could be related to formational rust etc. were removed. A selection between the remaining anomalies was made, on the basis of the geological units and the lineaments known/interpreted from aerial photographs. Lineaments, where near-anomalies were detected by the automated analysis, were added. The Crosta and ratio data was burnt on DVD and stored at GEUS.

9.5 Results

A rough distinction between the major lithological units is apparent in the image data, with especially the Dundas Group showing up as being iron-oxide stained. This means that isolated exposures of the Dundas Group were automatically registered as anomalies but these were removed from the list of valid anomalies. A total of 24 anomalies have been approved:

they are numbered and listed with co-ordinates in Table 1, and depicted on Map 3. Six of the anomalies are in shield lithologies with 18 in the Thule Supergroup.

It should be stressed that due to snow cover and the narrow stretches of ice-free land that form the Lauge Koch Kyst, no anomalies could be distinguished east of the Kap York peninsula. Thus, this study in no way assesses fully the potential for mineral anomalies in two of the region's geological provinces, viz. the Melville Bugt orthogneiss complex and the Lauge Koch Kyst supracrustal complex (see later).

Five of the anomalies are shown as Crosta images in Figures 1–4 in which anomalous concentrations of hydroxyl, hydroxyl + iron-oxide and iron-oxide, respectively, are displayed brightly in RGB colour space: red, areas of extensive iron-oxide coloration; green, areas rich in hydroxyl-bearing minerals; white, areas where both iron-oxides and hydroxyl-rich minerals are present. Therefore, all the pertinent anomalies are white. The anomalies are commented on in the following.

Thule mixed-gneiss complex. Two anomalies occur in this unit south of Pituffik. Anomaly no. **1** south-east of Magnetitbugt (Figure 1), consists of two intersecting lineaments hosting dolerite dykes. A WNW-striking dyke of Neoproterozoic age cuts a NNE-striking dyke of uncertain age. Iron-formation is known from the same area, see mineral occurrence **B**. Anomaly no. **1** constitutes an interesting exploration target for structurally hosted gold, especially the actual dyke intersection. Anomaly no. **2**, north-west of Pituffik Gletscher (Figure 2), consists of one distinct oval spot and other less distinct patches of uncertain significance (perhaps representing loose deposits) along a NNE-striking valley near mineral occurrence **C**.

Kap York meta-igneous complex. This unit hosts two anomalies, nos. **3** and **4**, with no. **3** being shown in Figure 3. They are both WNW-orientated linear features in little known gabbroid rocks that could have a potential for gold.

Melville Bugt orthogneiss complex. As mentioned on the previous page, no results could be obtained from the area east of Kap York peninsula that exposes this complex.

Lauge Koch Kyst supracrustal complex. The two anomalies delineated in this unit both correspond to known mineralisation. In the area west of Freuchen Nunatak, anomaly no. **5** (Figure 2) constitutes a NW-striking band probably related to supracrustal rocks, and to the sulphide-bearing iron-formation designated mineral occurrence **C** in this report. A gold potential is indicated, and this type of geological environment is believed to be the source of the secondary gold occurring in the sands of Sioqqap Kuua (geochemical anomaly **P**). Anomaly no. **6**, on a nunatak west of De Dødes Fjord, probably stems from the iron-formation described as mineral occurrence **D**. The anomaly potential of the supracrustals along the Lauge Koch Kyst to the east of this is unknown (see earlier).

Baffin Bay Group. Of the three anomalies in this unit, especially anomaly no. **9** on Wolstenholme Ø is noteworthy. It is located at the faulted contact between rocks of the Baffin Bay Group and the Thule mixed-gneiss complex with its iron-formation (mineral occurrence **A**) and a basic dyke. This locality should be checked for gold and uranium.

Dundas Group. With 14 anomalies (nos. **10–23**), this Group dominates in the Landsat study, even though localities judged to represent small outliers have been excluded. Most of the anomalies are associated with dykes and sills of the Steensby Land sill complex, and it is demonstrated that the known sulphide mineralisation associated with these rocks is easily picked up by the applied technique. The largest anomalies (nos. **11**, **12**, **13**, **15, 19** and **23**) should be given preference as follow-up targets with a view to skarn mineralisation and magmatic sulphide concentrations.

Narssârssuk Group. One distinct anomaly (no. **24**) exists in the Aorfêrneq Formation of this Group (Figure 4). The Formation consists of dolostone, limestone, arenaceous carbonates, evaporite and breccia with some chert, excellent host rocks for MVT/Nanisivik type lead-zinc deposits. Moreover, these rocks are lithologically comparable and time equivalents to strata of the Society Cliffs Formation of Baffin Island that, as described earlier, hosts the Nanisivik deposit. Therefore, it is extremely relevant to check out this anomaly in the field.

Table 1. *Landsat anomalies in the Pituffik region*

No.	Lat.	Long.	Geological unit	Shape	Size in m	Comments	Mineral occur.
1	76.36857	69.47736	Thule mixed-gneiss complex	Linear	60x2000	Intersecting dykes	**B**
2	76.32151	68.66644	Thule mixed-gneiss complex	Oval	300x800		**C**
3	76.04063	67.63032	Kap York meta-igneous complex	Linear	30x500	WNW-orientated	
4	75.95172	66.85588	Kap York meta-igneous complex	Linear	30x200	WNW-orientated	
5	76.36500	68.55084	Lauge Koch Kyst supracrustal complex	Linear	200x2000	WNW-orientated	**C**, (**P**)
6	76.2226	67.72880	Lauge Koch Kyst supracrustal complex	Spot	Ø150–200		**D**
7	77.05029	69.24686	Baffin Bay Group	Oval	100x500	At glacier margin	
8	77.13581	68.02762	Baffin Bay Group	Diffuse	?		
9	76.41814	69.93829	Baffin Bay Group	Diffuse	200x800	Dyke/base-ment contact	**A**
10	77.02702	71.11136	Dundas Group	Diffuse	?	At sill/dyke	
11	77.03316	70.86590	Dundas Group	Oval	100x500	NNW-orient., at sill/dyke	
12	76.95588	70.68222	Dundas Group	Semi-circle	100x1000		
13	76.90973	70.02655	Dundas Group	Oval	300x600		
14	77.12303	68.11805	Dundas Group	Diffuse	?	Near Baffin Bay Group	
15	76.83211	69.86856	Dundas Group	Oblong	100x400	Sill	
16	76.80628	69.69303	Dundas Group	Spot	100x150	Overburden	
17	76.80201	69.65592	Dundas Group	Spot	100x100	Sill	
18	76.77515	69.54481	Dundas Group	Linear	100x100	Sill/dyke	
19	76.76285	69.39169	Dundas Group	Oval	100x500	WNW-striking dyke	
20	76.70072	69.07641	Dundas Group	Spot	Ø100	Dyke	
21	76.67389	68.55517	Dundas Group	Diffuse	?	Sill	**K**
22	76.57876	68.62978	Dundas Group	Spot	Ø150		
23	76.53523	68.23946	Dundas Group	Semi-circle	150x1000	Sill	
24	76.50070	68.84294	Aorfêrneq Formation, Narssârssuk Group	Oblong	200x1000	E–W-ori-entated	

9.6 Nanisivik

A Landsat scene from 2 August 2000 covering the Nanisivik Mine area, north-western Baffin Island, Canada, was processed in the same manner as the Greenland scenes (Figure 5). This was to test with a view to Greenland analogies whether or not this lead-zinc deposit would be registered as a Landsat anomaly.

As the main wallrock alteration associated with the Nanisivik ores appears to be recrystalisation of the host dolostone (Olson 1984), no Landsat detection of clay alteration could be expected. On the other hand, Olson reports that massive hematite deposits are overlain by outliers of red-weathering sandstone (Gallery Formation) and that goethitic and limonitic gossans are locally common near pyritic sulphide bodies. These should be recorded in the Landsat data.

It turns out that on the Landsat scene there are no obvious signs of hydrothermal alteration and – more surprisingly – no rust zones other than formational rust, see Figure 5. Thus it appears that the formational rust of the Gallery Formation completely masks the sulphide-generated rust. This means that the deposit would not have been found during an exploration campaign relying solely on this technique.

According to the genetic model for Nanisivik proposed by Ross L. Sherlock (personal communication 2003), hydrothermal fluids migrated vertically and interacted with hydrocarbons trapped by antiformal structures to precipitate metals. But, given the geometry of the local geology, the fluids did not interact with the sedimentary rocks overlying the deposit as these pore spaces were occupied by hydrocarbon gas. Thus, rocks in the hangingwall of the deposit have not been exposed to the hydrothermal fluids and they will not generate a Landsat image anomaly. This is in contrast to the footwall deposit where altered rocks which may show up on Landsat occur. However, the structure at Nanisivik determines that the footwall to the deposit does not outcrop and thus an alteration signature cannot be expected from satellite images.

10. Conclusions and recommendations

Although no economic mineral occurrences are known, the little-explored Pituffik region has a potential for a range of metals, in particular gold and base metals in the shield, lead-zinc in the Thule Basin and titanium and gold in recent placers.

In a way, the study of Landsat images can be compared to visual inspection for rust zones by systematic helicopter flights over a well-exposed area. The Landsat survey is, however, much cheaper and can be performed prior to field work and can thus help in selecting exploration targets. A more refined response would be gained from hyperspectral measurements which would, however, require an airborne survey, as such data are not yet available from satellites. The importance of field work to judge the significance of the obtained anomalies cannot be overstated. It should also be stressed that the method cannot be used to exclude the possibilities of finding economic deposits in an area, as the negative results from Nanisivik clearly demonstrate.

The present Landsat study has delineated 24 anomalies with mineralisation potential, and a field check of these is an important component in any future exploration in the region. In this context one should not forget that the region east of the Kap York peninsula that includes Ironstone Fjeld and the eastern part of the regional iron province, is still lacking in processed data since the quality of the available Landsat data was substandard.

It is recommended that follow-up field work on all 24 Landsat anomalies be undertaken. Highest priorities should be given to those in the shield lithologies (nos. **1**, **2**, **3**, **4**, **5** and **9**) and in the Narssârssuk Group (no. **24**), followed by the larger anomalies in the Dundas Group (nos. **11**, **12**, **13**, **15, 19** and **23**).

11. Acknowledgements

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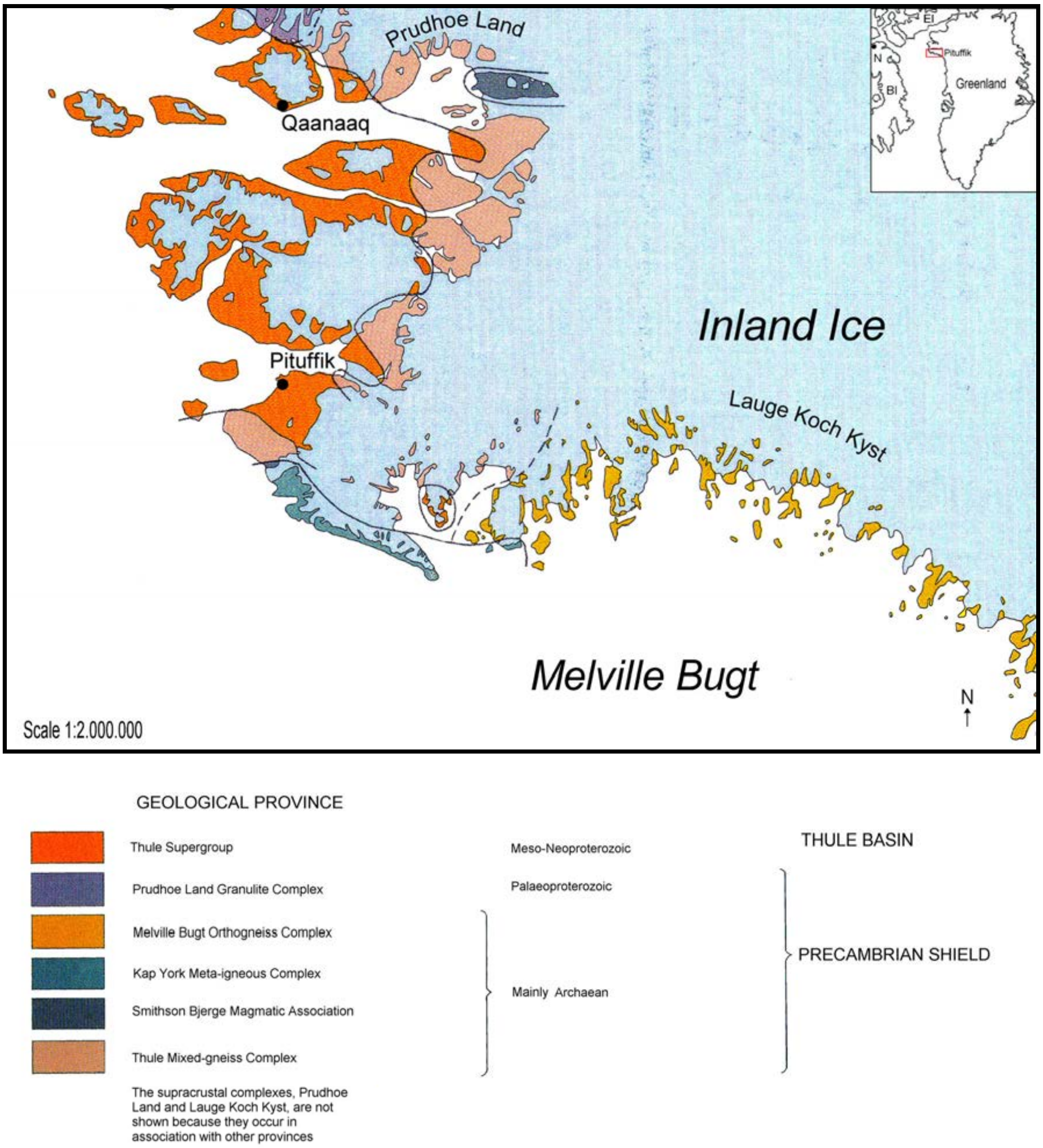
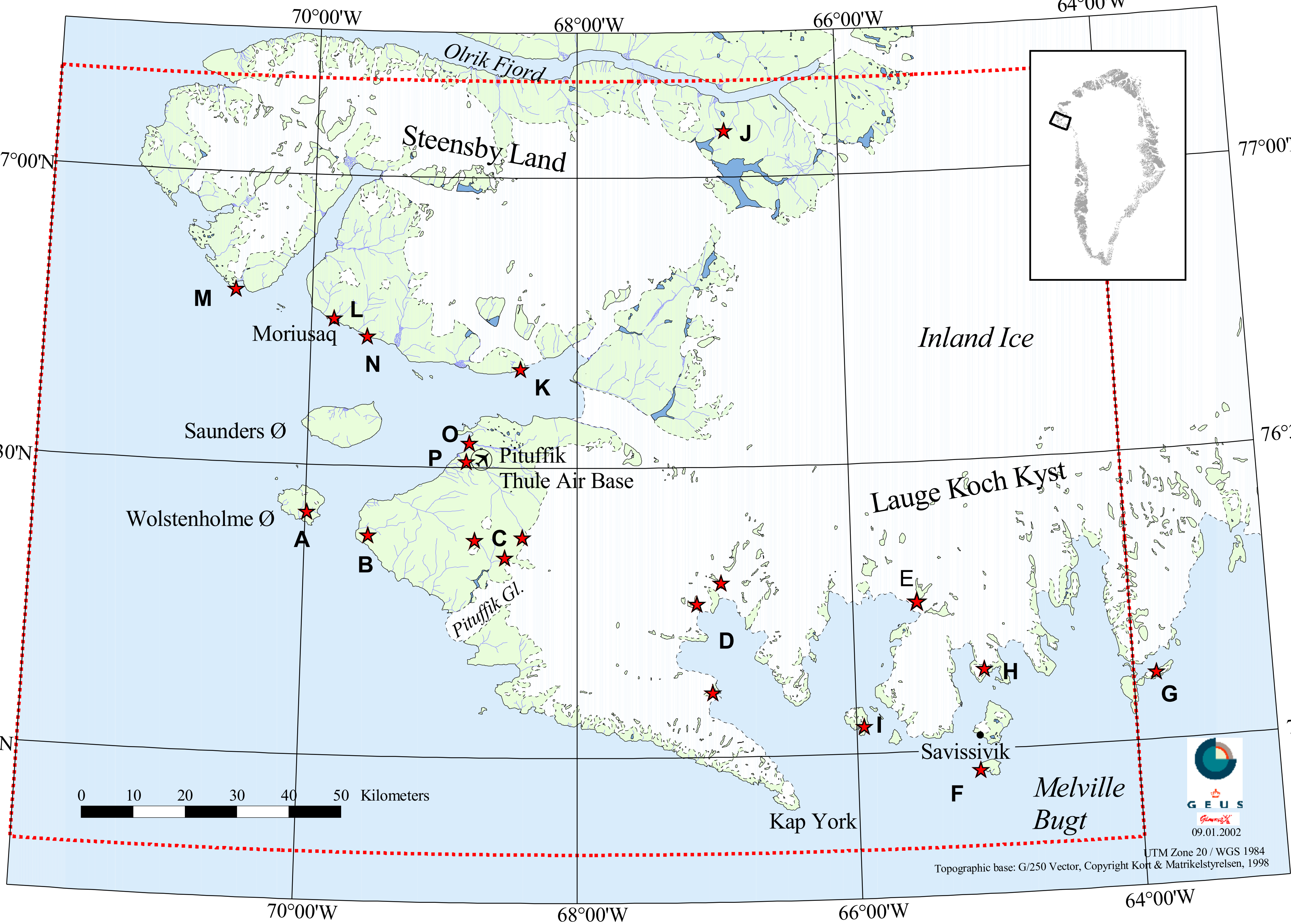
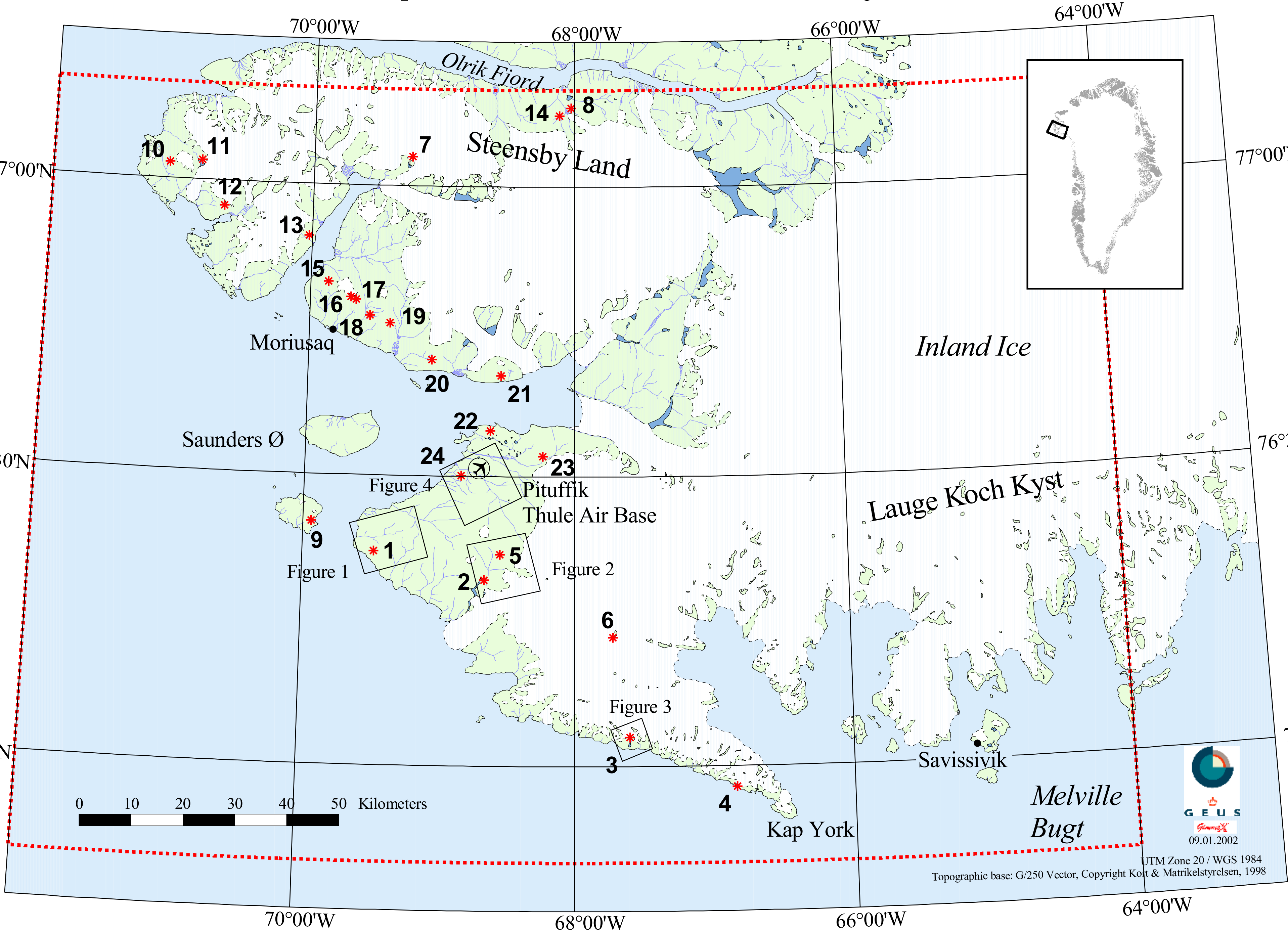


Map 1. *Main geological provinces of the Pituffik region, slightly modified from Dawes (1991). Inset map: Bl, Baffin Island; N, Nanisivik; El, Ellesmere Island.*

Map 2. Mineral occurrences and anomalies in the Pituffik region



Map 3. Landsat anomalies in the Pituffik region



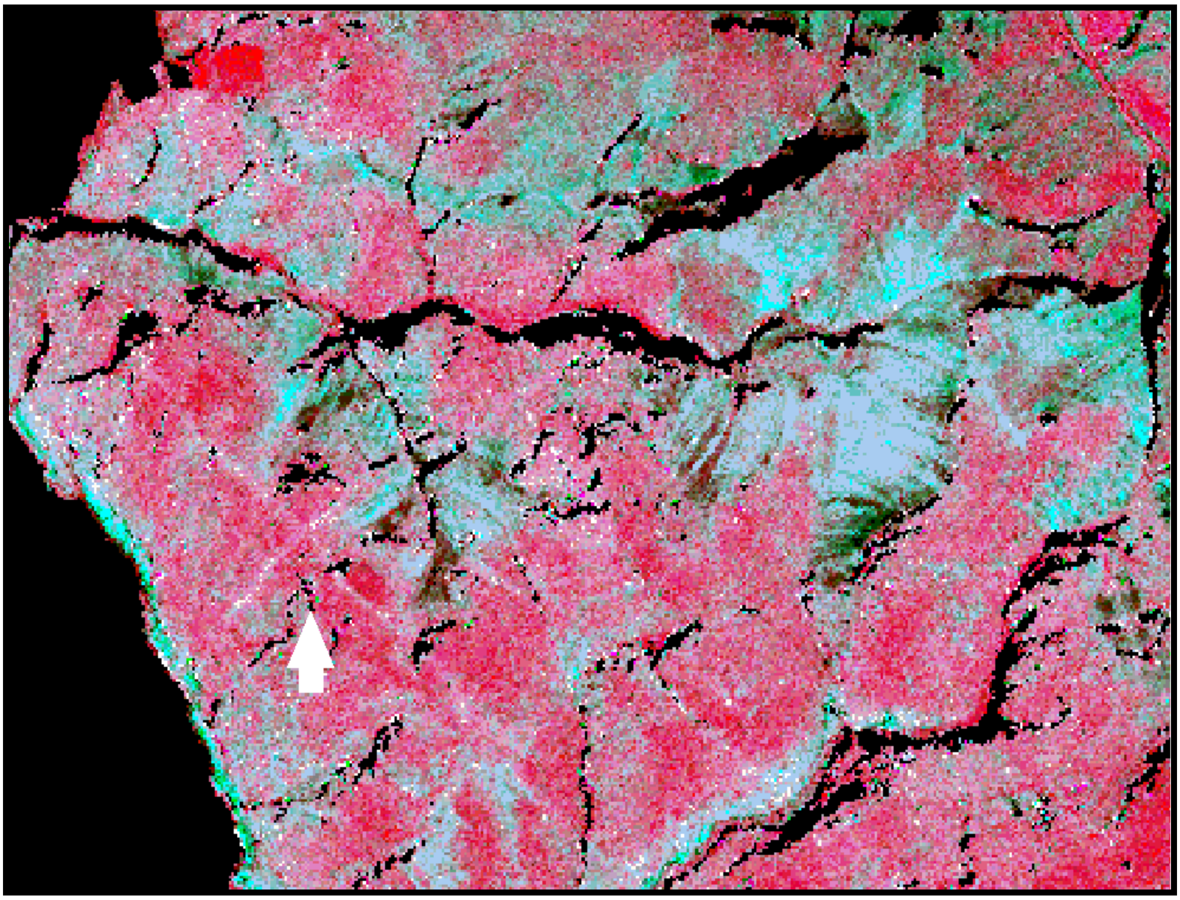


Figure 1. *NW-orientated, c. 10 x 12 km Crosta image of the Magnetitbugt area with Magnetitbugt in upper left corner. Arrow indicates Landsat anomaly no.* ***1****: two intersecting, linear structures hosting basic dykes (white) in the Thule mixed-gneiss complex. For location, see Map 3.*

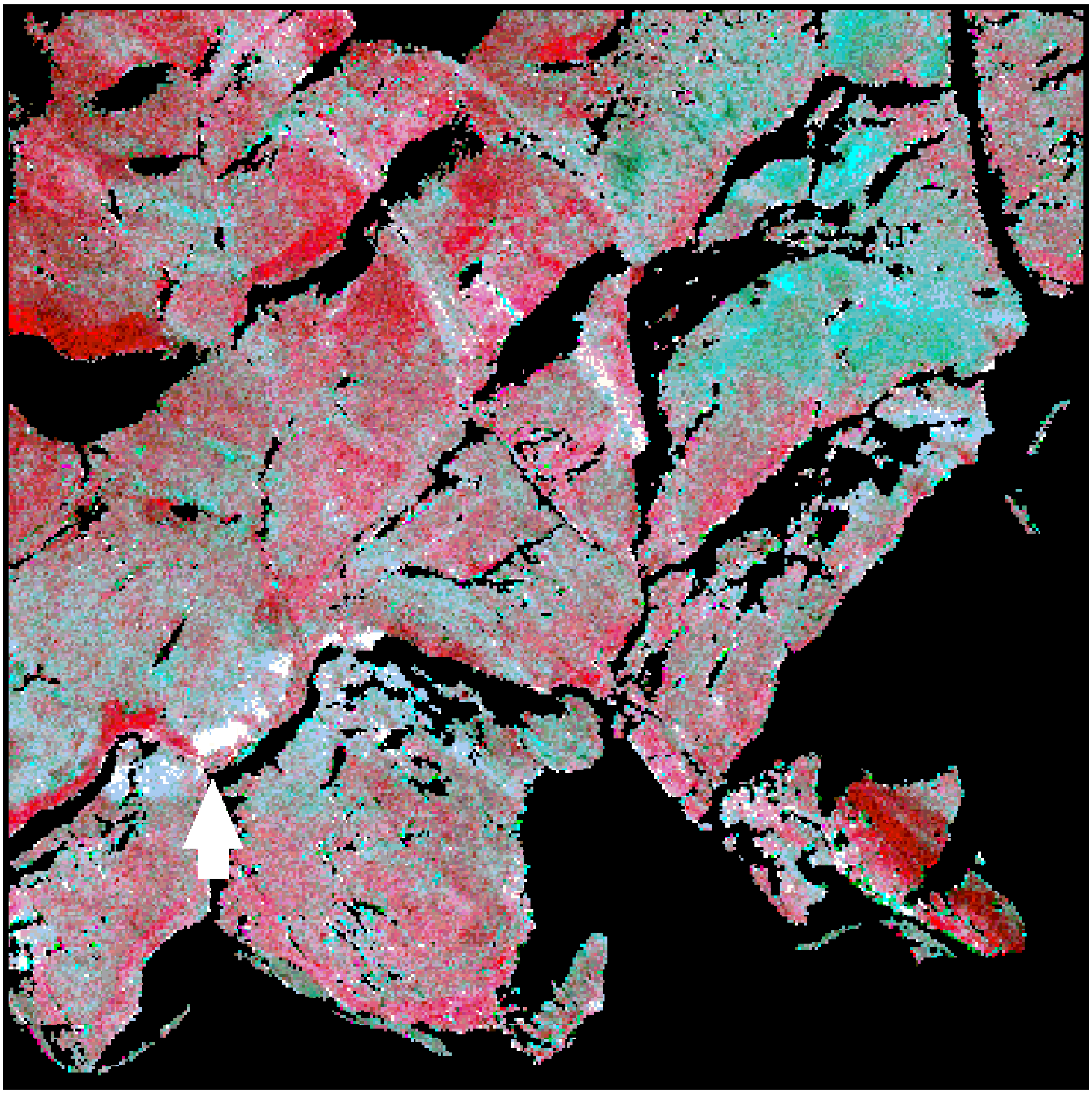


Figure 2. *NNW-orientated, c. 12 x 12 km Crosta image of the Freuchen Nunatak area, with Freuchen Nunatak in the south-eastern corner. 'Freuchen Gletscher' is in the lower centre and part of Pituffik Gletscher south of the arrow. The arrow marks anomaly no.* ***2****, one large and several smaller anomalous areas (white) on the west side of a valley in the Thule mixed-gneiss complex. Anomaly no.* ***5*** *appears in the upper, central part of the picture as a NW-striking white belt, probably in rocks of the Lauge Koch Kyst supracrustal complex. To the north-west of this, thinner NW-orientated whitish lines probably correspond to basic dykes. The bedrock outcrops of Freuchen Nunatak showing dark red colours reflect the redbeds of the Baffin Bay Group, Thule Supergroup. For location, see Map 3.*

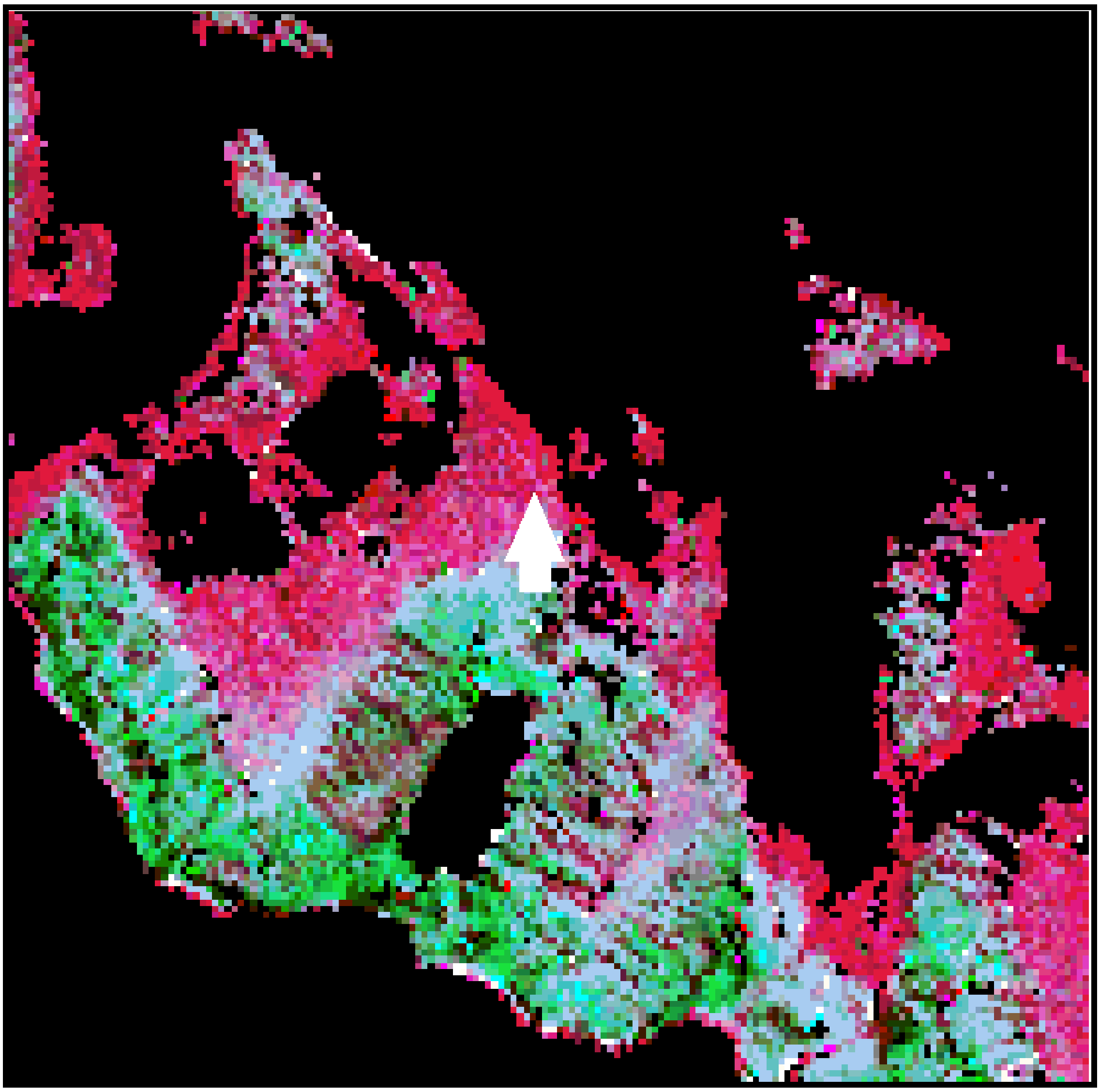


Figure 3. *NNW-orientated, c. 6 x 6 km Crosta image of part of Crimson Cliffs, Kap York peninsula. The arrow marks Landsat anomaly no.* ***3,*** *a WNW-orientated linear structure in the Kap York meta-igneous complex. For location, see Map 3.*

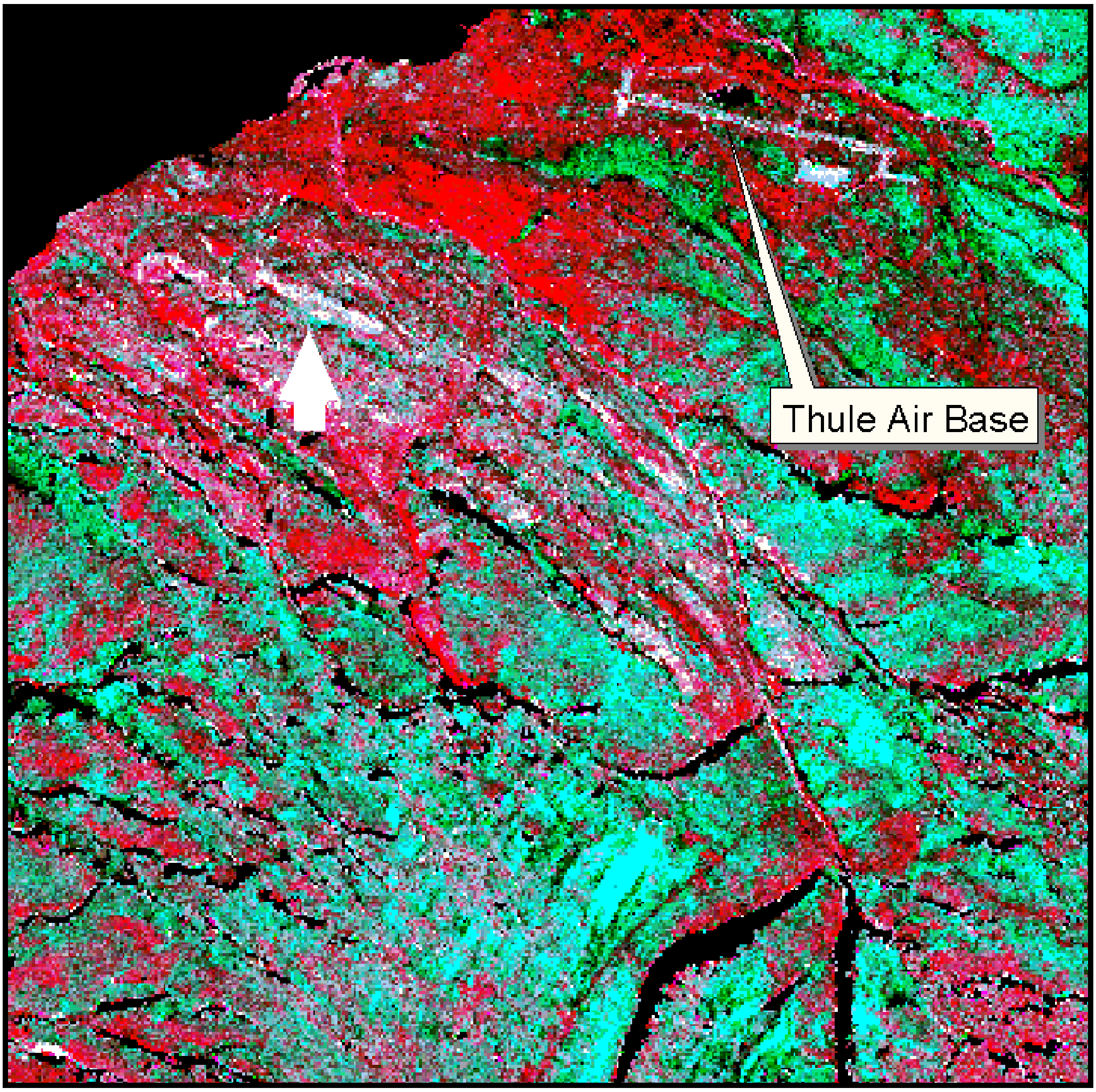


Figure 4. *NNW-orientated, c. 12 x 12 km Crosta image of the Pituffik area with the Thule Air Base runway standing out. The river Sioqqap Kuua ('Fox Canyon' - anomaly* ***P*** *refered to in the text) drains into the one prominent delta shown. The arrow indicates Landsat anomaly no.* ***24****, an almost E–W-orientated oblong structure (white) of unknown origin in the Narssârssuk Group carbonate rocks. A number of other, less distinct alteration zones in the carbonates are also visible. For location, see Map 4.*

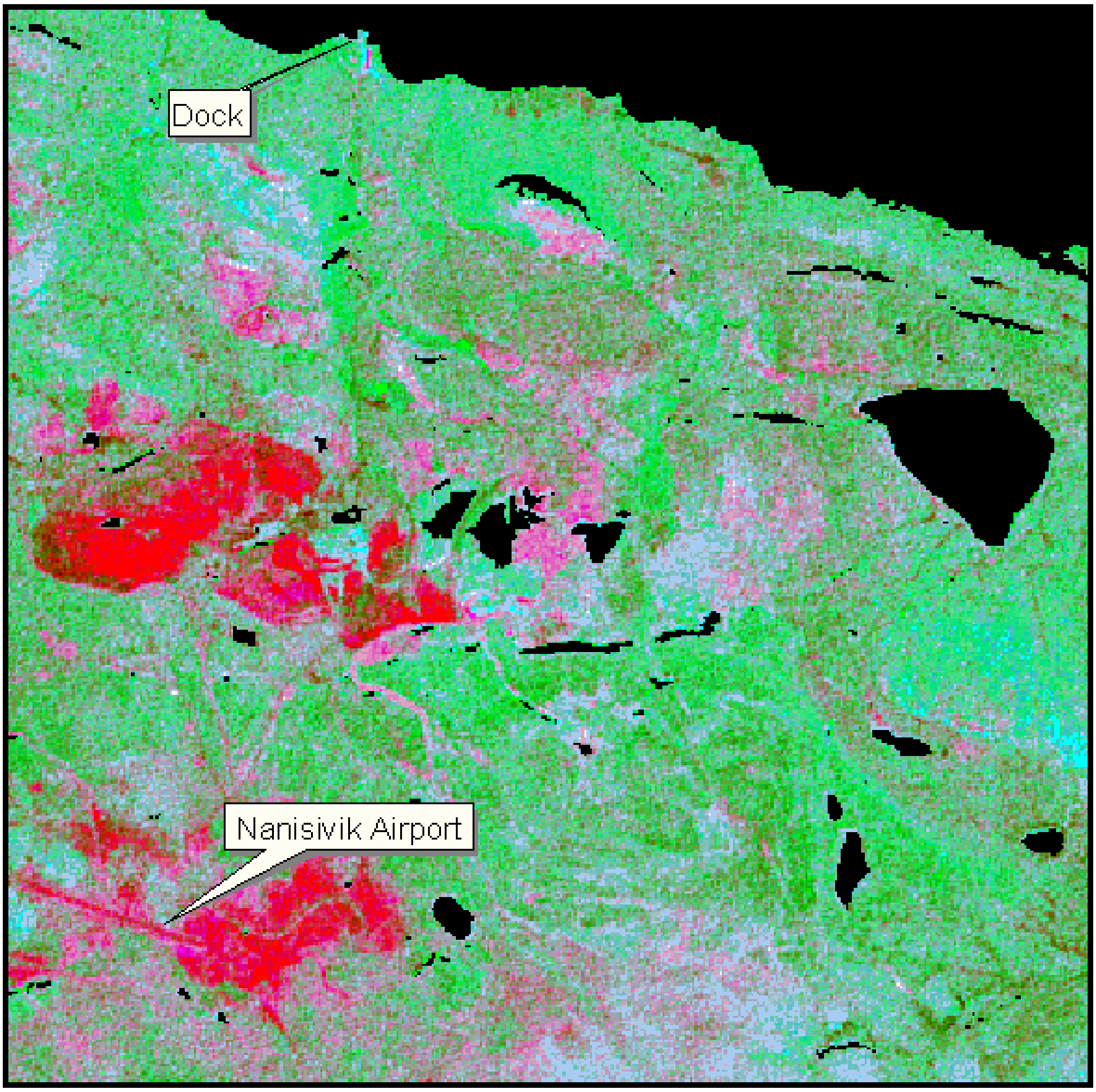


Figure 5. *N–S-orientated, c. 12 x 12 km Crosta image of the Nanisivik area with Strath-cona Sound in the north. The main ore zones situated WNW of the large, triangular lake (Kuhulu Lake) are not evident. The large, oval-shaped red area in the western part of the image reflects the redbed sandstones of the Gallery Formation.*