DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2011/143

Zinc potential in North Greenland

Kristine Thrane, Agnete Steenfelt & Per Kalvig

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MINISTRY OF CLIMATE AND ENERGY

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G E U S

Contents

Abstract

Traces and showings of zinc mineralisation are numerous in Greenland, especially in the Palaeozoic Franklinian Basin, which extends for more than 800 km E-W through North Greenland. Reconnaissance mineral exploration in the 1990s demonstrated widespread zinc mineralisation and the basin is believed to host a high potential for sedimentary zinc deposits. Over the years, much information has been acquired, but this is the first time the results have been compiled in the context of evaluating the zinc potential over the entire area of North Greenland.

This report deals with the compilation of existing and newly-acquired geochemical stream sediment data together with an assessment of their quality and comparability. Analytical data for Zn, Cu, Ba, Sr, Ca and K are made consistent and presented on geochemical maps. The distribution patterns displayed by the maps are discussed.

The compilation of all the results show that the large structures in North Greenland (e.g. the Permin Land flexture, the Nyboe Land fault zone and the Navarana fault) are significant in localising zinc mineralisations. Three new sites of high Zn values along these structures are recognised in this study; northernmost Wulff Land on the Nyboe Land fault zone, western Hall Land and northern Washington Land on the Permin Land flexure.

Two pronounced clusters of stream sediment Zn anomalies warrant further inspection, the one in Inglefield Land and the other in southern Johannes V. Jensen Land between Citronen Fjord and Navarana Fjord. Our evidence collected thus far suggests that Inglefield Land with its Cu-Zn association has potential for massive volcanogenic sulphide deposits. Less information is available for the anomalies in Johannes V. Jensen Land. Since most of the anomalous samples are from streams draining the Amundsen Land Group, the host formation of the Citronen Fjord deposit, a sedex type of occurrence somewhere in that area is a possible source that should be pursued.

In summary, the compilation of data in this report makes clear that favourable conditions have existed in extensive areas of North Greenland for the formation of several types of Zn deposits.

Introduction

Traces and showings of zinc mineralisation are numerous in the Palaeozoic Franklinian Basin, which extends for more than 2,500 km E-W through the Canadian Arctic Islands and northern Greenland. Reconnaissance mineral exploration in the 1990´s demonstrated widespread zinc mineralisation and the basin is considered a high potential for sedimentary zinc deposits. A global increasing demand for base metals has encouraged the mineral industry to search for metals in remote areas. To facilitate such endavours, the Bureau of Minerals and Petroleum (BMP) and the Geological Survey of Denmark and Greenland (GEUS) hereby present an assesment of the zinc potential of North Greenland. Over the years, much information has been acquired, but this is the first time it has been compiled in the context of evaluating the zinc potential over the entire area.

This report provides an introduction to the geology of North Greenland and a documentation of work undertaken during 2011 to compile and improve available geo-information related to the zinc potential of North Greenland. The main activities of 2011 have included:

1) Compilation of geochemical stream sediment data, assessment of their quality and comparability, and acquisition of new analytical data
2) Compilation of information about zinc occurrences
3) Compilation of analytical Zn data for GEUS rock samples
4) Presentation of results in this report and in GIS format on GEUS' website

An overview of the content of the Zn data package on GEUS' website is given in Appendix 1 and geochemical maps of Zn, Ba, Cu, Sr, Ca and K in Appendix 2.

The result of our compilation has emphasised that the Franklinian Basin of North Greenland has a great potential of hosting more sedimentary exhalative (Sedex) and Mississippi Valey Type (MVT) zinc deposits than has been found until now.

Geology of North Greenland

This report covers North Greenland from Inglefield Land in the west to Lambert Land in the east (Figure 1). The Precambrian Greenland crystalline shield, which makes up most of Greenland, outcrops only locally in North Greenland at the margin of the Inland Ice near Victoria Fjord, in Kronprins Christian Land, Lambert Land and more pronounced in Inglefield Land.

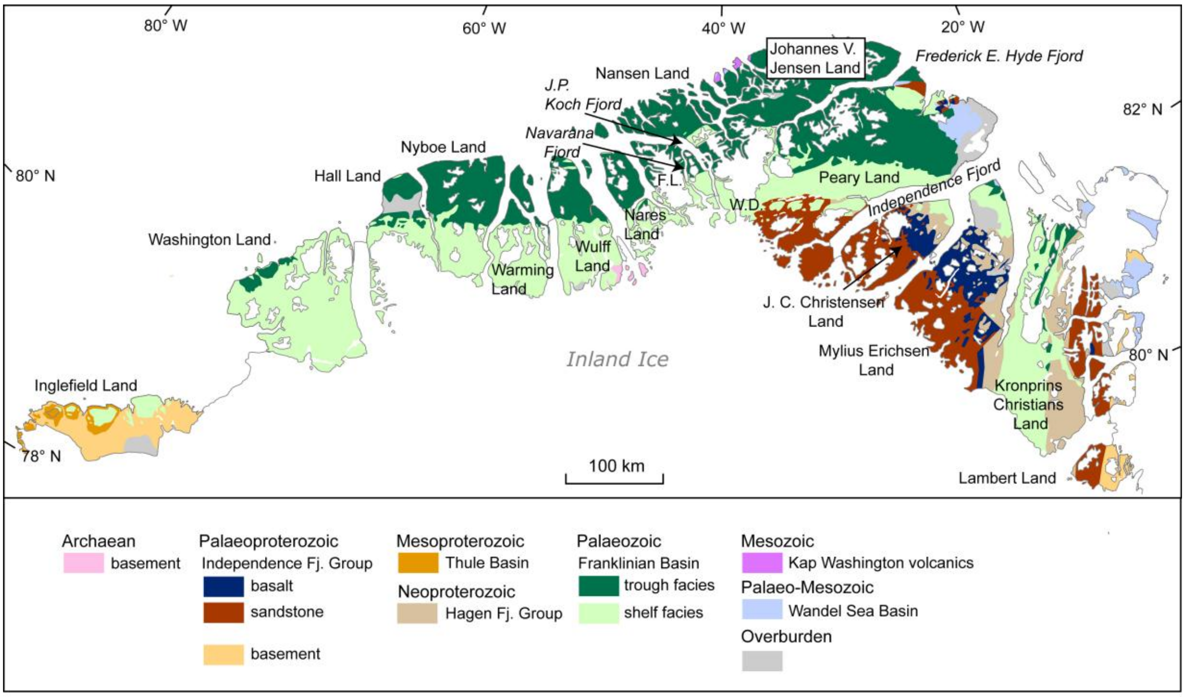

Figure 1. *Simplified geological map of North Greenland modified from Escher & Pulvertaft (1995). F.L.: Freuchen Land; W.D.: Wandel Dal.*

In Northeast Greenland, Archaean to Early Proterozoic crystalline rocks form the basement upon which thick sequences of Middle Proterozoic fluvial and lacustrine sediments of the Independence Fjord Group were laid down, succeeded by Mesoproterozoic plateau basalts of the Zig Zag Dal Basalt Formation. After a hiatus of several hundred million years, the Neoproterozoic Hagen Fjord Group shelf sediments and their deep-water correlatives, were laid down on the older sediments and basalts. During Early Palaeozoic time, thick sedimentary sequences accumulated in the east–west-trending Franklinian Basin, a major feature that extends through the Arctic Islands of Canada and across all of North Greenland. Franklinian Basin deposits can be divided into a southern shelf succession dominated by carbonates, and a northern deep-water succession of mainly siliciclastic sediments. Deposition ended by the Devonian/Early Carboniferous Ellesmerian orogenic deformation (Figure 3), which affected mainly the deep-water sequence of the northern part of the basin and resulted in formation of the east–west trending North Greenland fold belt.

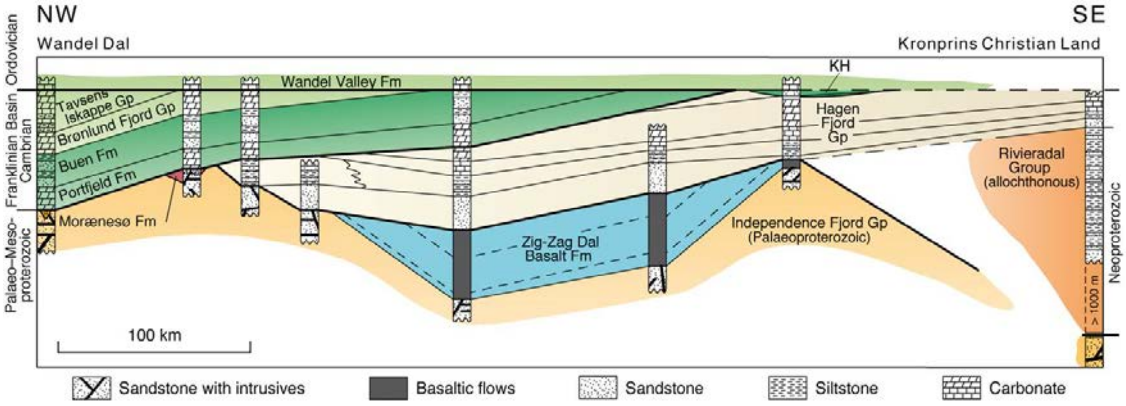

Figure 2. *Schematic cross-section of the Proterozoic-Ordovician succession in eastern North Greenland between Wandel Dal and Kronprins Christian Land. It shows the relationships between the different sedimentary sequences. Bold lines represent erosional unconformities. From Henriksen et al. (2000).*

The Silurian East Greenland Caledonian fold belt affected the eastern part of North Greenland, where north-south trending folds and westward directed thrusts deform both Proterozoic and Early Palaeozoic platform and deep water sequences.

In the following, the different areas and successions are described in more detail, in chronological order. The map sheet descriptions for the geological maps at scale 1:500 000 provide good reviews of the geology and comprehensive references (Dawes 2004; Henriksen 1992). They are included in the Zn data package.

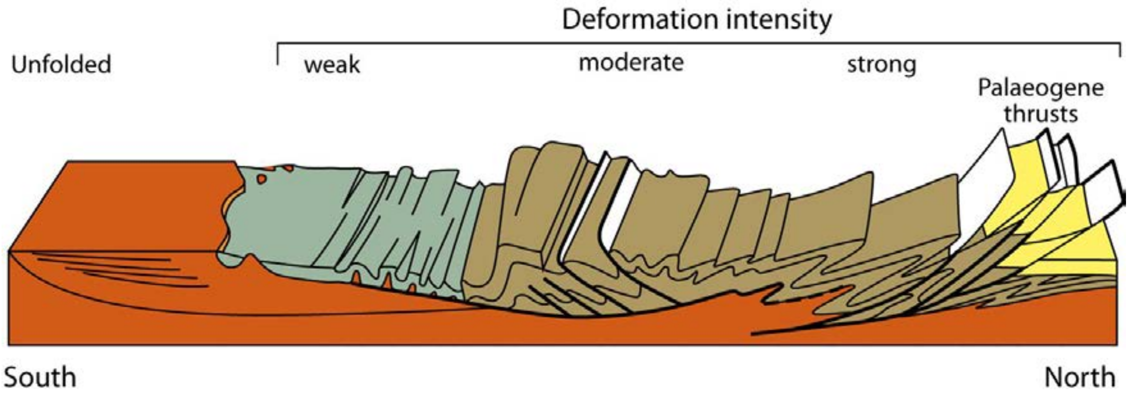

Figure 3. *Ellesmerian orogeny with decreasing deformation southwards. From Henriksen (2005).*

The Etah Group, Inglefield Land

Inglefield Land is situated in northwest Greenland (Figure 1). The basement consists of Palaeoproterozoic juvenile para- and orthogneisses; e.g. high-grade supracrustal- and granitoid rocks. The supracrustal rocks, called the Etah Group, are believed to be the oldest rocks in the area; these were dated by Nutman et al. (2008) and yield a unimodal detrital age population centred on 2000-1980 Ma.

Figure 4. *View of rust zones in northern Inglefield Land, looking north-east. In the foreground metre-size pyrrhotite mounds are covered by white and yellow oxidation minerals. From Thomassen et al. (2000).*

The supracrustal sequence consists of garnet rich paragneiss, calc-silicate gneiss, marble-dominated units, amphibolite, ultramafic rock and quartzite (Figure 4). The supracrustal sequence is intruded by the Etah meta-igneous complex, which is composed of intermediate to felsic meta-igneous rocks, metagabbros and orthogneisses. The ages of the meta-igneous rocks vary from c. 1950-1915, whereas younger granites yield ages of c. 1780-1740 Ma, containing inherited zircons up to 2650 Ma old (Nutman et al. 2008).

The Etah Group and the Etah meta-igneous complex were metamorphosed at 1920 Ma under low- to medium-pressure granulite facies conditions, coinciding with at least three phases of deformation. The Mesoproterozoic Thule Supergroup and the Cambrian deposits of the Franklinian Basin overlie the Palaeoproterozoic sequence. The Inglefield Mobile Belt is interpreted as a Palaeoproterozoic arc, formed by convergence of two Archaean crustal blocks. The rock sequences of the Inglefield Mobile Belt can be correlated across the northern Baffin Bay into Canada, without offset across the Nares Strait (Dawes 2004).

Independence Fjord Group

Middle Proterozoic deposits in North Greenland include an undisturbed cratonic sequence of mainly alluvial sandstones at least 2 km thick – the Independence Fjord Group – which is presumed to have been deposited on a peneplained crystalline basement; which is not exposed (Henriksen 1992). The Independence Fjord Group stratigraphy has been recognised over an area of 80 by 300 km. A formerly much larger extension of the basin is indicated by the occurrence of similar sandstones in north-eastern Peary Land about 150 km north-east of the main outcrop area. In the easternmost part, the Independence Fjord

Group is deformed during the Caledonian orogeny. U-Pb zircon ages suggest that the Independence Group was deposited before ca. 1740 Ma ago (Kalsbeek et al. 1999).

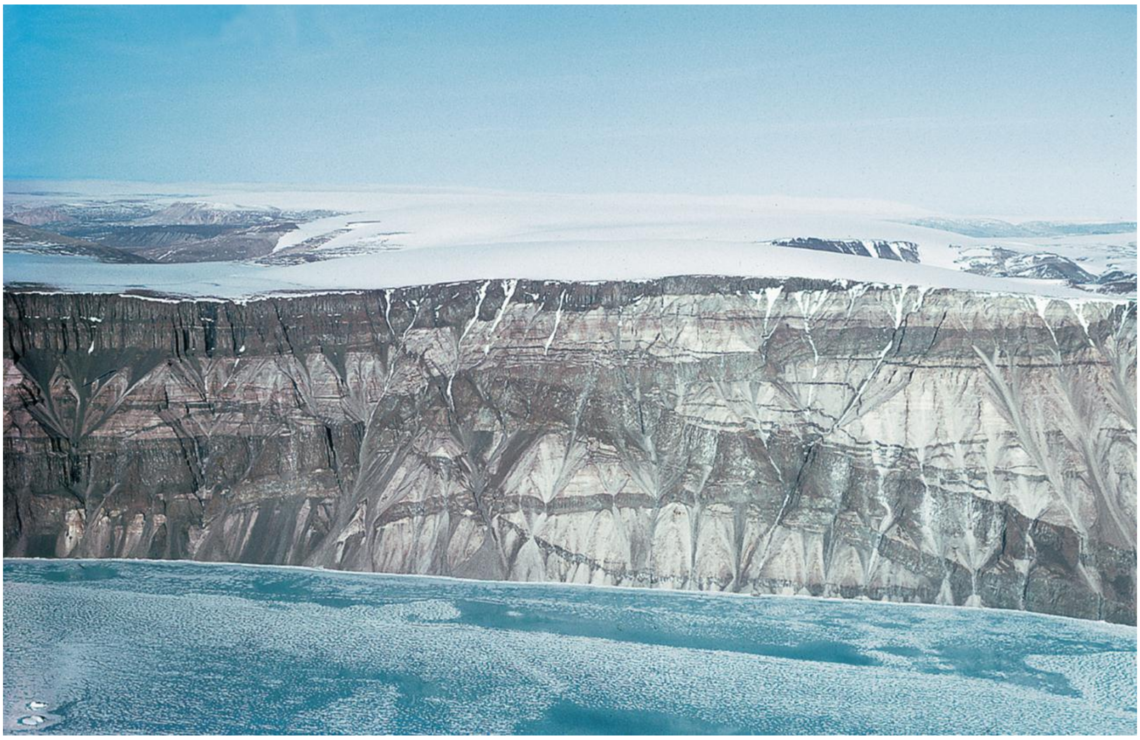

Figure 5. *Palaeoproterozoic Independence Fjord Group sandstones. Undeformed succession cut by Midsommersø Dolerite intrusions of the south side of Independence Fjord. Profile height is c. 800 m. From Henriksen et al. (2000).*

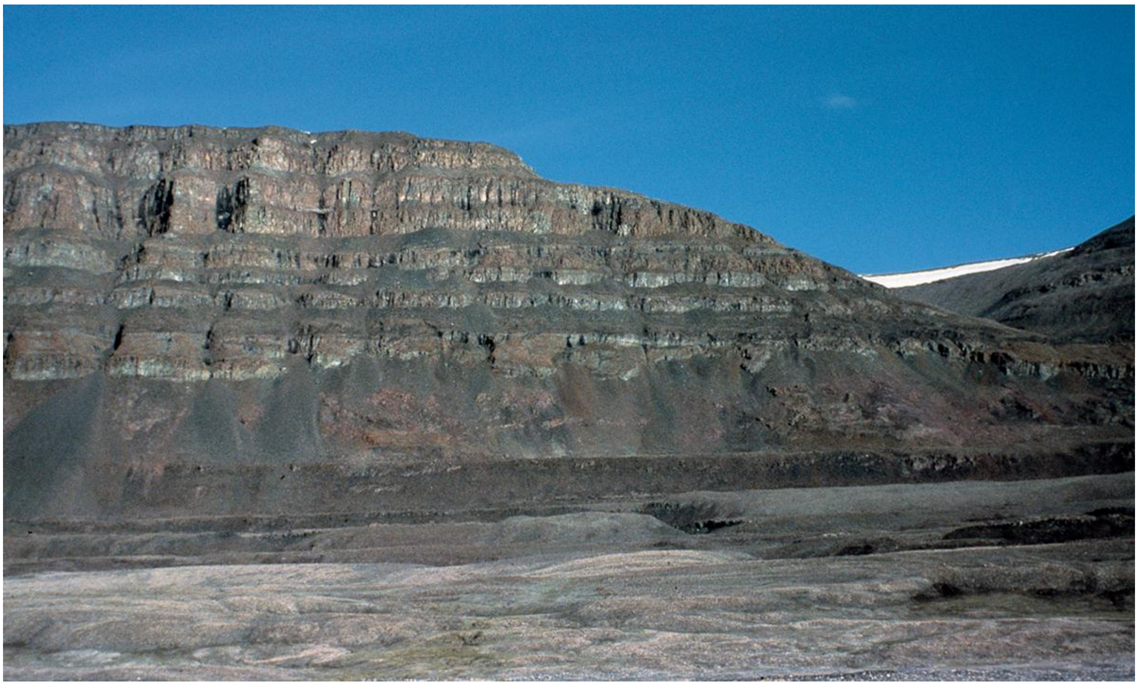

Figure 6. *Zig Zag Dal Basalt Formation.From Henriksen (2005).*

The Independence Fjord Group is everywhere intruded by numerous mafic sheets, sills and dykes (Figure 5) of the Midsommersø Dolerites (Kalsbeek & Jepsen 1983). These dolerites have yielded a U-Pb age of 1380 Ma (Upton et al. 2005).

Zig Zag Dal Basalt Formation

The Zig Zag Dal Basalts consist of 1380 m of well-preserved tholeiitic flood basalts (Figure 6) deposited conformably on top of the Independence Fjord Group. So far it has not been possible to obtain an age of the Zig Zag Dal Basalts, but they are assumed to be of the same origin as the Midsommersø Dolerites as they have the same chemical composition.

Hagen Fjord Group

The Hagen Fjord Group is deposited unconformably on top of the Zig-Zag Dal Basalt formation, between 800 and 590 Ma ago. The age is based on microfossil evidence. The Hagen Fjord Group is an up to 1000 m thick succession of siliciclastic and carbonate sediments deposited on a shallow water shelf. In the lower part it comprises mainly sandstones with minor siltstone layers, whereas the upper part is characterised by limestones and dolomites with abundant stromatolites, and a sandstone unit caps these (Figure 7).

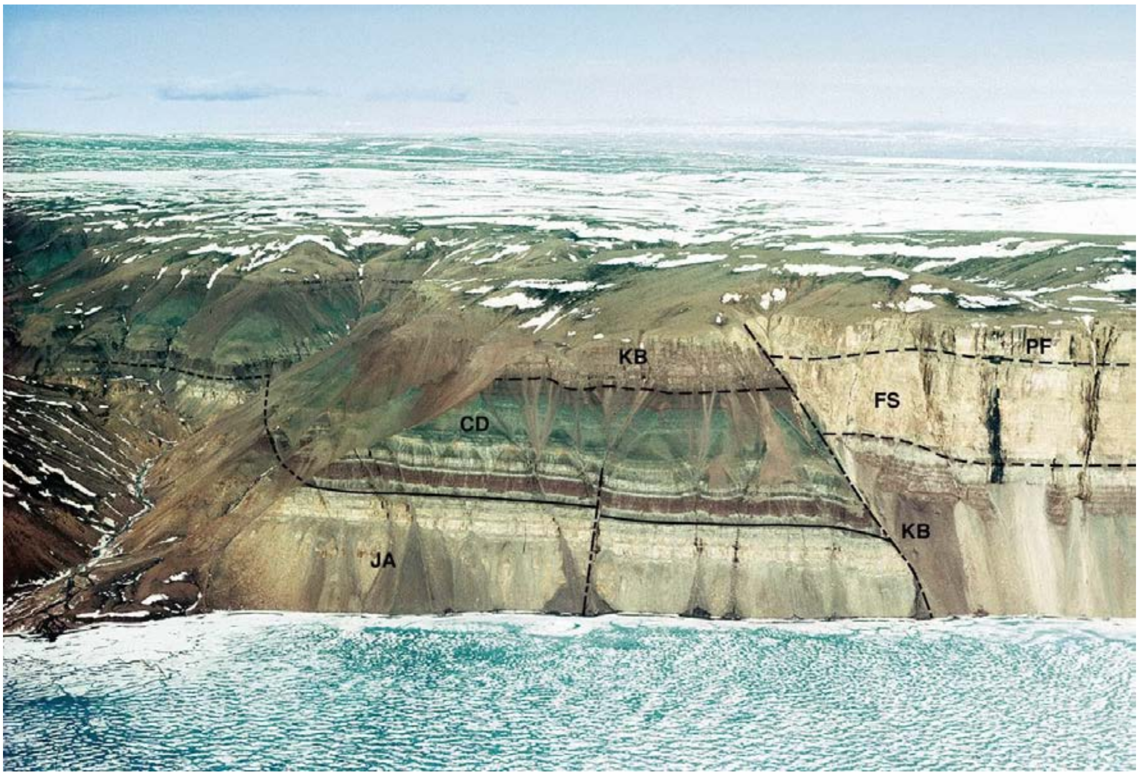

Figure 7. *Hagen Fjord Group on the north-west side of Hagen Fjord. A lower light coloured sandstone (JA) is overlain by a multicoloured sandstone-siltstone association (Campanuladal and Kap Bernhard Formations, CD and KB), with a light coloured limestone-dolomite succession at the top (Fyns Sø Formation, FS, and Portfjeld Formation, PF). The fault has a displacement of c. 300 m down to the right (north). The section is c. 600 m high. From Henriksen et al. (2000).*

Franklinian Basin

The Palaeozoic Franklinian Basin extends for more than 2500 km through the Canadian Arctic Islands and northern Greenland preserving a stratigraphic record of early Cambrian to late Silurian age. In Greenland, the outcrops of the basin strata occupies a region of 800 km (Figure 1) from Kronprins Christians Land in the east, over Peary Land continuously to Washington Land in the west, and with smaller exposures in Inglefield Land (Peel & Sønderholm 1991). The thickest sedimentary section is in Peary Land, where the basin forms a platform and orogenic belt 200 km wide. With the exception of the earliest phase of development, the basin was differentiated into two E–W-trending provinces: a southern shelf and slope and a northern deep-water trough. The shelf and slope sequence is up to 4 km thick, whereas the deep-water trough comprises 8 km of clastic sediments (Figure 8).

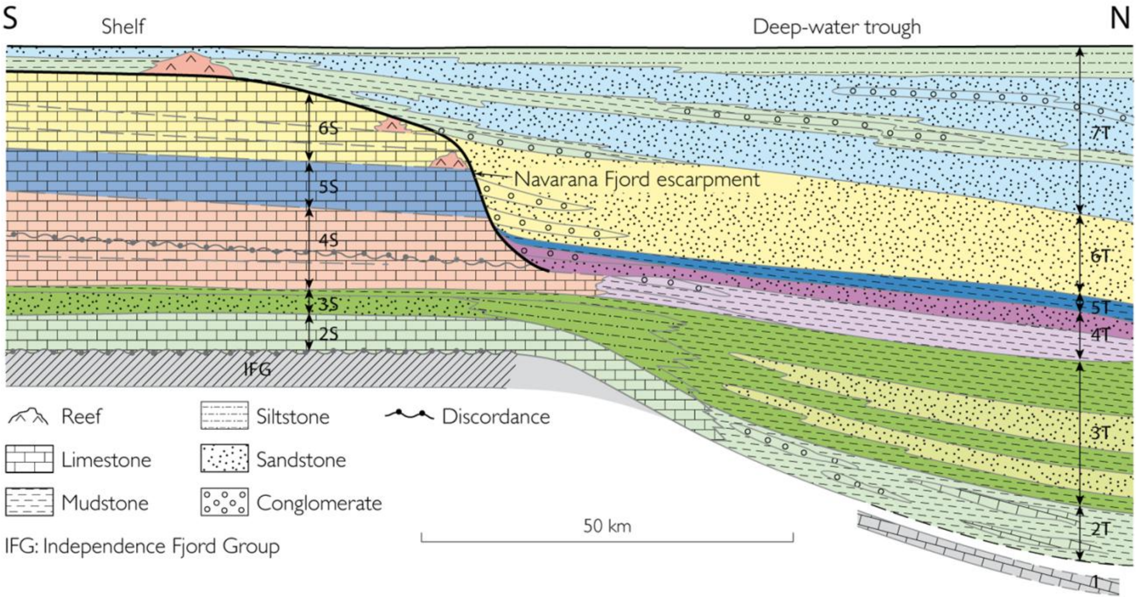

Figure 8. *Cross section of the Franklinian Basin, with the carbonate shelf to the south and the deep-water trough to the north. S refers to the stages described in the text and shown in Figure 9. From Henriksen (2005).*

The boundary between shelf and trough shifted position with time and southerly basin expansion in the Silurian resulted in a final drowning of the shelf that led to deposition of clastic sediments over the carbonate platform (Dawes 2004). The base of the sequence is seen only locally in southern Peary Land and around Victoria Fjord and the top of the succession is not exposed. Initiation of deposition in the basin is thought to have begun in the latest Precambrian and may have continued until the earliest Devonian, but almost all of the preserved succession is Cambro-Silurian. The Devonian – Middle Carboniferous Ellesmerian Orogeny affected strata of the northern part of the Franklinian Basin, and led to formation of the E–W trending North Greenland fold belt. In eastern North Greenland, the Silurian Caledonian fold belt gave rise to N–S trending folds and westward directed thrusts that affected the Middle Proterozoic – Lower Palaeozoic strata of Kronprins Christian Land.

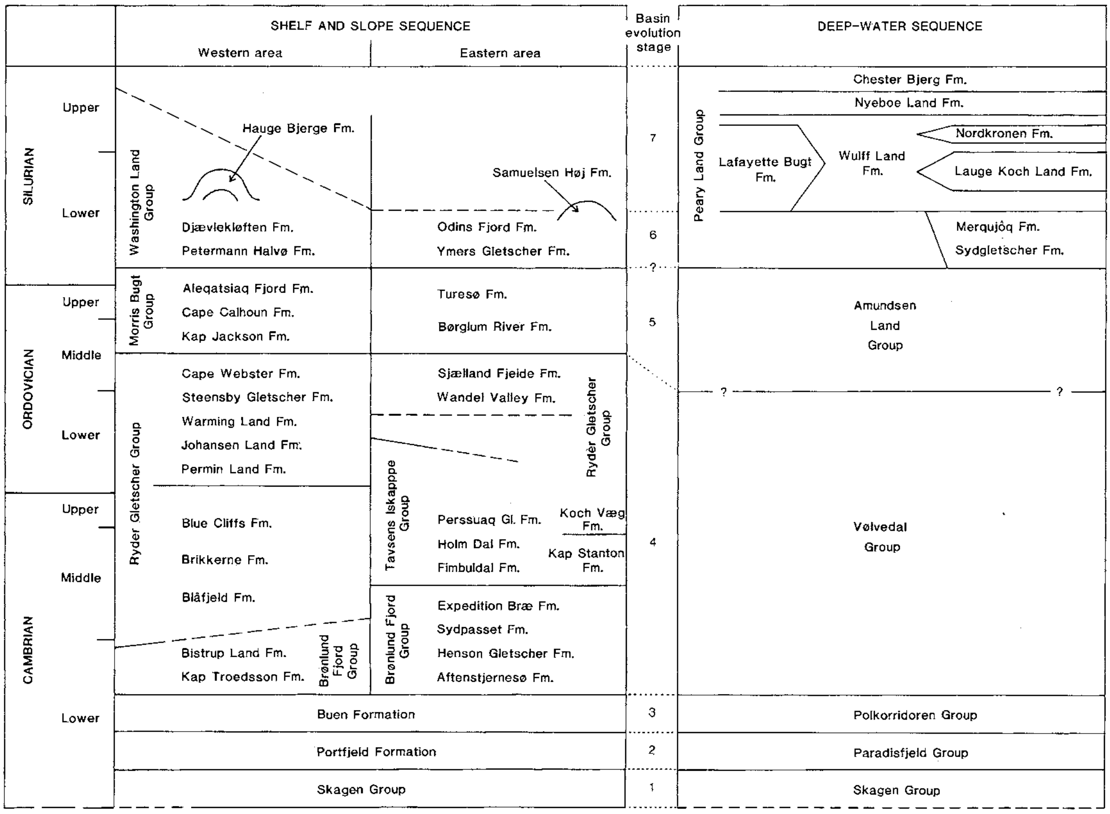

Figure 9. *Lithostratigraphic division of the Lower Palaeozoic successions in North Greenland. The shelf and slope sequence is a 4 km thick accumulation of carbonate sediments, whereas the deep water sequence comprises dominantly clastic sediments with a composite thickness of up to 8 km. From Henriksen (1992).*

The deep water and shelf sequences of the Franklinian Basin are distinguished as separate depositional successions, each comprising a number of lithostratigraphic units. Description of these below follows the subdivision into seven stages of basin evolution by Higgins et al. (1991a, b) and reviewed by Henriksen (1992); see references therein for more details.

Stage 1: Basin initiation, Late Proterozoic? – Early Cambrian shelf

This stage records the initial subsidence and transgression of the Proterozoic basement in North Greenland.

Skagen Group

The Skagen Group is restricted to scattered outcrops between northeast Peary Land and northern Wulff Land in the northernmost parts of North Greenland. The base is nowhere seen. In its type area at Skagen in northeast Peary Land, it consists of tightly-folded quartzitic sandstones and mudstones conformably overlain by the Paradisfjeld Group. The Skagen Group is restricted to the northernmost parts of North Greenland.

Figure 10. *The lower part of the carbonate platform, from Jørgen Brønlund Fjord, southern part of Peary Land. From Henriksen (2005).*

Stage 2: Early Cambrian platform and incipient trough

At this stage, a clear differentiation into shelf and deep-water sequences is apparent. The shelf is represented by the Portfjeld Formation and the trough sequence by the Paradisfjeld Group (Figures 8 and 9).

Portfjeld Formation

The formation is poorly fossiliferous but remains of cyanobacteria indicate a probable Early Cambrian age. In southern Peary Land it is up to 250 m thick, but it thickens to the north and west and reaches 400–700 m in northeast Peary Land and around J. P. Koch Fjord; the thickest developments are close to the platform edge. The formation comprises typically dolomites, silty dolomites and algal-laminated dolomites occasionally with stromatolites. A remarkable mega-breccia unit of the Portfjeld Formation is found around the head of Victoria Fjord. The breccia unit is interpreted as a mass slump of giant rafts of the Portfjeld Formation together with material from underlying sequences.

Paradisfjeld Group

The Paradisfjeld Group comprises at least 1000 m of lime mudstones; at the top it has a series of thick beds of limestone conglomerates. It overlies the Skagen Group and is viewed as the deep-water equivalent of the Portfjeld Formation; the transition zone between the Portfjeld Formation and Paradisfjeld Group is obscured by Ellesmerian thrusts.

Stage 3: Early Cambrian siliciclastic shelf and turbidite trough

This stage is characterised by terrigenous sand and mud deposits on the southern shelf and red and green mudstones on the wide transitional slope e.g. Buen Formation. Coarse siliciclastic turbidites of the Polkorridoren Group were deposited in the northern trough (Figures 8 and 9).

Buen Formation

The siliciclastic Buen Formation varies in thickness from 250 to 500 m and is dominated by sandstones in the lower part and mudstones in the upper part. It conformably overlies the Portfjeld Formation but the contact relations outside the type area at Brønlund Fjord suggest a break in sedimentation between the two formations. The Buen Formation can be traced from the western shores of Danmark Fjord in the east to Warming Land in the west. Towards the north it thickens rapidly and passes into the turbiditic Polkorridoren Group. Middle to late Early Cambrian age of the Buen Formation is suggested by fossil assemblages from the middle of the formation. The Buen Formation is interpreted as deposited in a tide and storm dominated shallow marine shelf environment.

Polkorridoren Group

The Polkorridoren Group comprises a sequence of at least 2 km of alternating thick sandstone and mudstone units. The mainly semipelitic and psammitic units are turbiditic developments. They occur as thin bands in the transitional slope sequence, and thicken northwards and dominate the trough succession. In Nansen Land and on adjacent islands, two levels of carbonate conglomerates occur about 600 m above the base of the Polkorridoren Group. These conglomeratic levels are dominated by Portfjeld Formation clasts; the blocks have been interpreted as broken away from the Portfjeld shelf edge to the south. Thus, the edge of the Portfjeld shelf seems to have existed as a positive feature well into Buen times. The uppermost unit of the Polkorridoren Group consists of a sequence of up to 400 m of purple and green mudstones. At the shelf-slope break the mudstone grades into the upper part of the Buen Formation. The Polkorridoren Group is widely exposed throughout Johannes V. Jensen Land and Nansen Land.

Stage 4: Late Early Cambrian – Middle Ordovician shelf and starved Trough

During this stage the shelf area was influenced by; (1) differential subsidence and (2) uplift in eastern North Greenland. In the east, there was a progradational shelf whereas the western areas were characterised by an aggradational shelf with uniform subsidence. In the late Early Ordovician, after the end of uplift in eastern North Greenland, shallow-water aggradational shelf conditions expanded to all of North Greenland, marked by the Wandel Valley Formation of the Ryder Gletscher Group. The trough expanded southward during this stage with deposition of mudstones and turbiditic sandstones of the Vølvedal Group (Figures 8 and 9).

Brønlund Fjord and Tavsens Iskappe Groups

During the late Early Cambrian to latest Cambrian the Eastern area was subject to uplift resulting in a strong northward progradation of the carbonate platform and slope facies reflected by the Brønlund Fjord and Tavsens Iskappe Groups. The Brønlund Fjord Group in the type area is up to c. 250 m thick and is dominated by fine-grained limestones and dolomites, with carbonate breccias interpreted as debris flows. Sandstone beds occur in some formations. The Tavsens Iskappe Group is up to 700 m thick, and is a sequence of thin-bedded carbonates with carbonate breccias and sandstones.

Ryder Gletscher Group

In the western part, the deposits of the Cambrian–Ordovician aggradational shelf up to 1100 m thick have been placed in the Ryder Gletscher Group, dominantly comprising carbonates. In the earliest Ordovician these shelf deposits expanded eastwards such that the upper part of the group covered the entire North Greenland shelf. The lower Cambrian part of the Ryder Gletscher Group is up to 470 m thick and consists of burrow mottled dolomites, silty lime mudstones and mud-cracked stromatolitic and cryptalgal dolomites.

Vølvedal Group

The deep-water trough succession of stage 4 is made up of the 600–700 m thick Vølvedal Group. The Vølvedal Group is a sequence of alternating dark mudstones and turbiditic sandstones, which is confined to the Amundsen Land – Frederick E. Hyde Fjord region. The lowest formation consists of dark mudstones and thin-bedded turbidites. The central formation is characterised by greenish chert and cherty mudstones and siltstones, about 50 m thick. Quartzitic turbidites alternating with thin black mudstone beds form the 240 m thick upper formation

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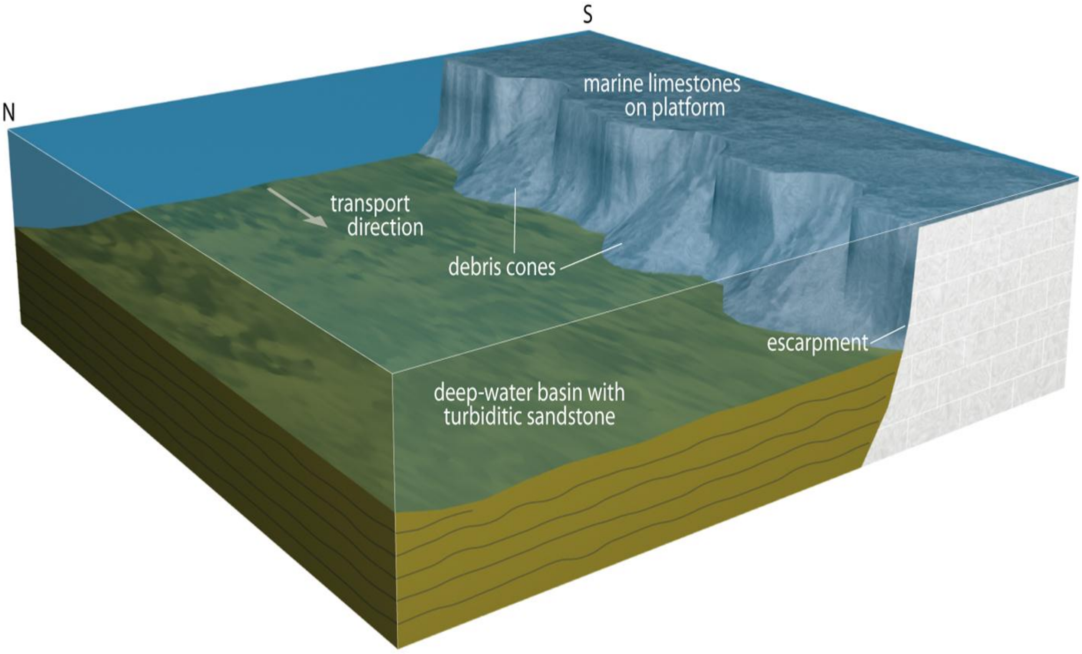


Figure 11. *Model of the carbonate platform to the south, and the deep-water basin to the north, separated by the Navarana Fjord Escarpment . From Henriksen (2005)*

Stage 5: Middle Ordovician – Early Silurian aggradational carbonate platform, starved slope and trough

This stage extends from approximately the Middle Ordovician to Early Silurian. Carbonate deposition continued on the platform in the south, a very thin sequence of siliciclastic sediments accumulated on the slope, and a 350–500 m thick sequence of mainly fine-grained sediments (Amundsen Land Group) were deposited in the trough to the north. The shelf-slope boundary of this stage followed a pronounced east–west trending lineament, the Navarana Fjord escarpment, which can be traced between J. P. Koch Fjord in the east and northern Hall Land in the west (Figures 8 and 11).

Morris Bugt Group

The platform sequence is represented by the Morris Bugt Group and the basal part of the Washington Land Group in western areas of North Greenland, and by the Børglum River, Turesø and Ymers Gletscher Formations in eastern areas. Throughout the region the total thickness of the platform sequence is constant at about 650 m. The upper part of the shelf sequence reflects a period of pronounced shallowing followed by a deepening of the shelf.

Figure 12. *Exposure at Navarana Fjord. The Carbonate platform to the right, and the deep-water sediments to the left, separated by the Navarana Fjord Escarpment. Profile is 1300 m high. From Henriksen (2005)*

Amundsen Land Group

The slope deposits of this stage are represented by a very restricted starved sequence of cherts and cherty shales, with units of siltstones and mudstones, and totals only 50–100 m in thickness. It is assigned to a formation of the Amundsen Land Group and can be traced as a thin unit along the northern coastal area between J. P. Koch Fjord and northern Nyeboe Land, mainly in anticlinal fold cores. The Amundsen Land Group in its type area represents deposits of the southern part of the deep-water trough. The group is dominated by cherts and mudstones, and includes some thin turbiditic units, as well as conspicuous thick units of carbonate conglomerates derived from the nearby southern carbonate shelf. Three formations with a total thickness of 350–500 m are distinguished. The lowest formation comprises deposits of mud and siliceous ooze. The middle formation made up of sheets of re-deposited Early Ordovician carbonate conglomerate and turbidites is up to c. 200 m thick. The youngest formation includes black cherts and mudstones, siltstones and silty turbidites.

Figure 13. *Cambro-Ordovician platform margin sequence in the foreground and Ordovician shelf sequence clastic rocks in the middle distance. View from the south. Profile height is c. 500 m. From Henriksen et al. (2000).*

Stage 6: Early Silurian ramp and rimmed shelf, and turbidite trough

Trough sedimentation changed abruptly in the early Silurian with the incoming of vast amounts of sandy turbidites of the Peary Land Group (Sydgletscher and Merqujôq Formations), which were derived from the rising Caledonian mountains to the east. At the beginning of stage 6, the shelf-trough boundary still followed the Navarana Fjord escarpment, which extended from north of Hall Land in the west to south of the mouth of Frederick E. Hyde Fjord in the east. Later in this stage, the outer shelf down-flexed due to loading in the trough and turbiditic sediments onlapped the outer platform carbonates. Carbonate deposition continued on the shelf during the general deepening (Figures 8 and 9).

Odins Fjord and Djævlekløften Formations

The shelf margin retreated during stage 6 to a new, more southerly position and in Kronprins Christian Land and Peary Land down flexing resulted in a widespread deepening of the platform. The carbonates in the east are assigned to the Odins Fjord Formation, a 200 to 350 m thick sequence characterised by medium to thick-bedded dark limestones and wackestones. Two lime-mudstone members can be distinguished.

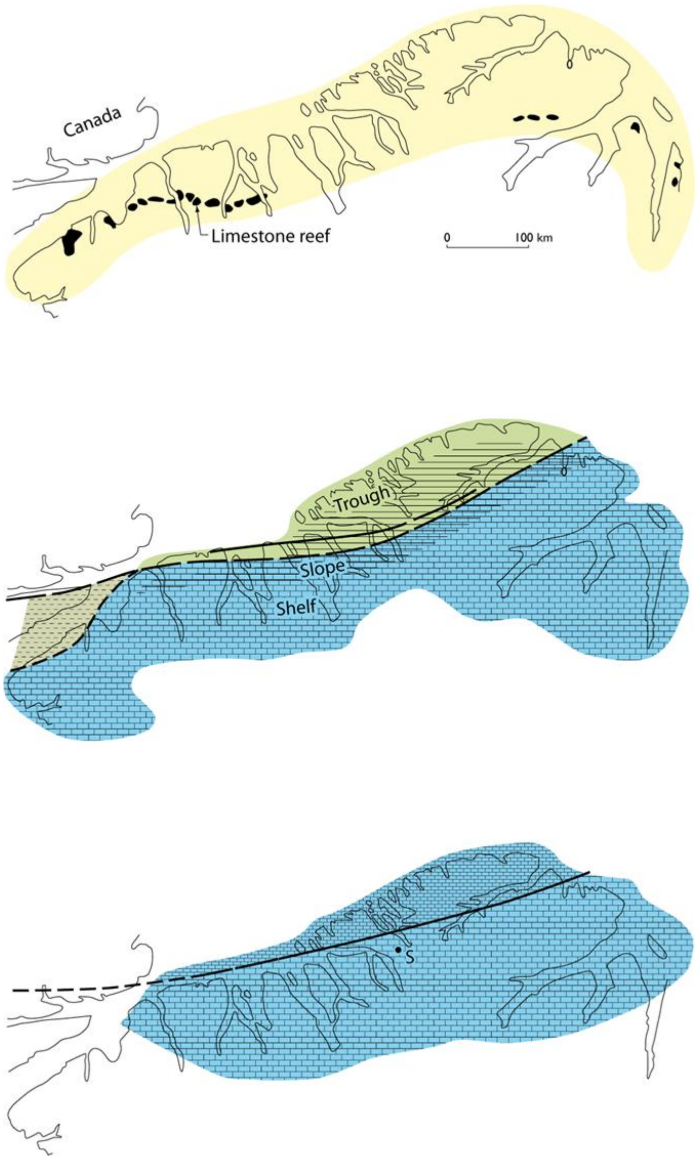


Figure 14. *Simplified evolution of the Franklinian Basin, from the early Cambrian, where the whole area was covered by a carbonate platform (lower picture). Until the late Ordovician, where the northern half of the platform was flooded and the deep water trough, as well as the Navarana Fjord escarpment was formed. In late Silurian the trough expanded southwards due to subsidence and most of the platform was drowned and 300 km long limestone reefs were formed. Mudstones were deposited and buried the escarpment. Henriksen (2005).*

Lower part of the Peary Land Group

In the trough north of the Navarana Fjord escarpment the major longitudinal accumulations of turbidites, mudstones and conglomerates of this stage are assigned to the Merqujôq Formation of the Peary Land Group. The Merqujôq Formation is widely distributed between

Frederick E. Hyde Fjord and northern Nyeboe Land, and ranges from 500 m to 2000 m in thickness. In Johannes V. Jensen Land the turbidite succession of the Peary Land Group was initiated with a sandstone sequence (more than 150 m thick) made up of massive up to 30 m thick turbidite beds – the Sydgletscher Formation.

Stage 7: Final drowning of the platform

This stage was marked by a dramatic southward expansion of the trough, turbidites onlapped and buried the Navarana Fjord escarpment and widespread subsidence affected former shelf areas. The shelf areas of stage 6 were inundated by trough mudstones and siltstones forming the middle and upper part of the Peary Land Group. Carbonate deposition was maintained only locally around major mound complexes (Samuelsen Høj and Hauge Bjerge Formations) (Figures 8 and 9).

Figure 15. *Silurian Mounds/Reefs growing on top of the carbonate platform. From Henriksen (2005).*

Samuelsen Høj and Hauge Bjerge Formations

The shelf margin retreated southwards during this state to a line trending through southern Hall Land to southern Peary Land and central Kronprins Christian Land, and is marked by a prominent linear belt of large, isolated outer shelf mound complexes, which range in thickness from 200 to 1000 m. The eastern mound complexes are referred to the Samuelsen Høj Formation, whereas those in the west are referred to the Hauge Bjerge Formation. The latter extends for almost 300 km. Mounds are not found between western Peary Land and western Wulff Land, probably due to later erosion.

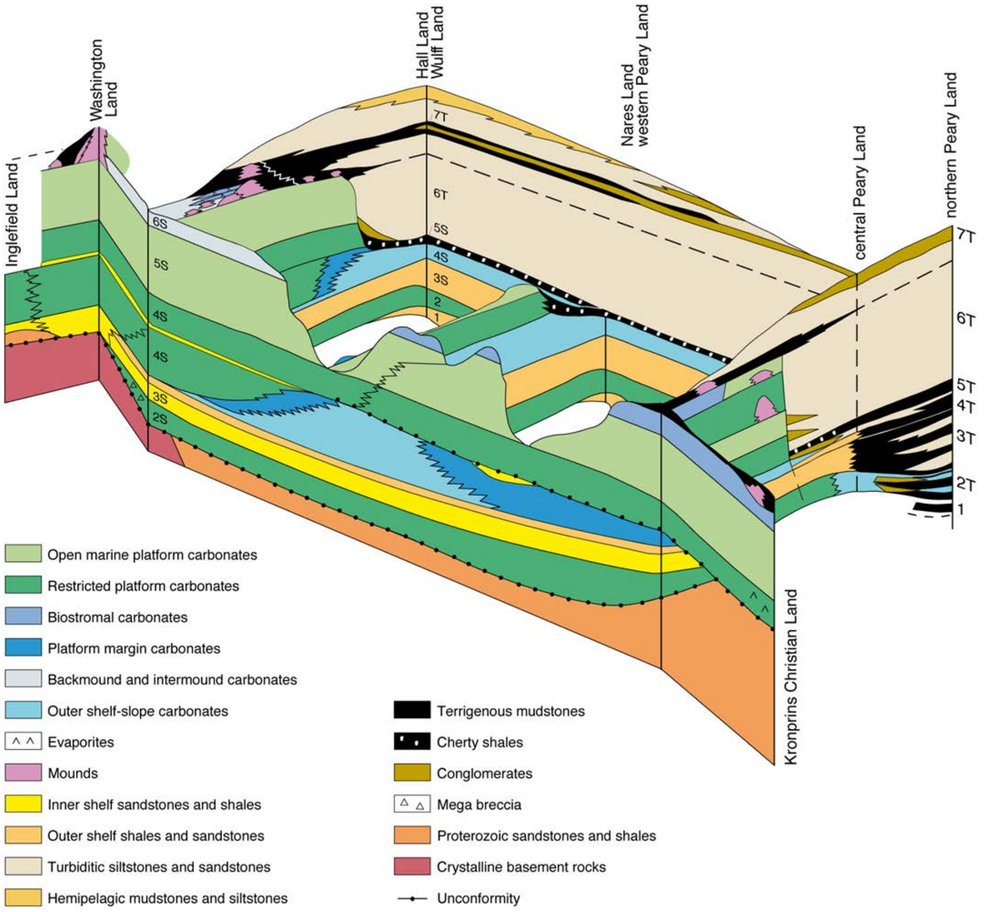


Figure 16. *Block diagram illustrating relationships between shelf, slope and trough sequences in the Lower Palaeozoic Franklinian Basin. The schematic fence diagram covers a region of c. 800 km east-west and c. 200 km north-south. Shelf stages (S) and trough stages (T) are divided into time intervals. 1: late Proterozoic? – Early Cambrian; 2: Early Cambrian; 3: Early Cambrian; 4: Late Early Cambrian – Middle Ordovician; 5: middle Ordovician – Early Silurian; 6: Early Silurian; 7: later Silurian. From Henriksen et al. (2000).*

Types of zinc deposits

Carbonate-hosted zinc deposits – MVT deposits

Carbonate-hosted zinc deposits also known as Mississippi Valley Type (MVT) ore deposits, are important and have highly valuable concentrations of zinc sulphide ore hosted with in carbonate (limestone, marl and dolomite) formations. The most important ore controls are faults and fractures, dissolution collapse breccias and lithological transitions. Most MVT deposits are hosted in Phanerozoic rocks and are significantly less common in Proterozoic rocks. MVT ores are located in carbonate platform sequences in passive margin environments and are commonly related to extensional domains landwards of contractional tectonic belts. The ore bodies range from 0.5 million tonnes of contained ore, to 20 million tonnes or more, and have grades of between approximately 3% to 12% zinc. MVT deposits usually occur in extensive districts consisting of several to hundreds of deposits (Leach & Taylor 2009).

Sedimentary exhalative deposits – Sedex deposits

Sedimentary exhalative deposits also called sedex deposits are finely laminated or bedded sulphide ore deposits, which are interpreted to have formed by release of ore-bearing hydrothermal fluids into a water reservoir, usually the ocean, resulting in the precipitation of stratiform ore (Carne & Cathro 1982). Sedex deposits are the most common type of zinc deposits. Sedex deposits are hosted in rift-generated intracratonic or epicratonic sedimentary basins, often related to a nearby carbonate platform. Deposits occur in carbonaceous shales in basin sag-phase carbonate rock, shale or siltstone facies mosaics that were deposited on thick sequences of rift-fill conglomerates, red beds, sandstones or siltstones and mafic or felsic volcanic rocks.

Sedex deposits are the most important sources of zinc, and they are typically associated with lead and barite mineralisation. It is common for multiple sedex deposits to be distributed many tens of kilometres along basin-controlling faults. Thus, areas along large fault systems with evidence of mineralisation should be viewed as very favourable for undiscovered deposits (Emsbo 2009).

Volcanogenic massive sulphide ore deposits – VMS deposits

Volcanogenic massive sulphide ore deposits (VMS) are a type of metal sulphide ore deposit precipitated from volcanic-associated hydrothermal events in extensional submarine environments. The tectonic setting for VMS deposits includes extensional zones within oceanic ridges, volcanic arcs and volcanic back-arcs. The volcanic rocks hosting VMS deposits range from felsic to mafic in composition, but it is the felsic successions, which tend to be Zn rich. Typical maximum horizontal dimensions of VMS deposits are 100-500 m, widths or down-dip extents can be as much as 3500 m. Shape ranges widely from stratiform lenses to lenticular mound to discordant pipes. Many deposits, but not all, overlie discordant sulphide-bearing vein systems that represent fluid-flow conduits below the sea floor. Deposits range in age from Archaean on ancient cratons to present-day systems in modern ocean basins. (Shanks III et al. 2009).

Zinc occurrences in North Greenland

North Greenland hosts a number of zinc mineral occurrences and is considered a highly prospective part of Greenland for zinc. The known occurrences represent several types and ages of zinc mineralisation as described in this section. Table 1 lists names and hosts for the occurrences and Figure 17 shows their location.

MO_id	Class	Locality name	Type
M436/2	Prospect	Citronen Fjord, Peary Land"Discovery area"	shale-hosted Zn, Pb
M436/1	Prospect	Citronen Fjord, Peary Land"Beach area"	shale-hosted Zn, Pb
M436/3	Prospect	Citronen Fjord, Peary Land"Esrum area"	shale-hosted Zn, Pb
M436/4	Prospect	Citronen Fjord, Peary Land"West Gossan area"	shale-hosted Zn, Pb
M6112/1	Prospect	Cass Prospect, Washington Land	carbonate-hosted Zn, Pb, Ba
M6111/4	Prospect	Petermann Prospect, Washington Land	carbonate-hosted Zn, Pb, Ag
M432/1	Showing	Navarana Fjord, Freuchen Land	stratabound Zn, Pb, Ba
M432/2	Showing	Navarana Fjord, Lauge Koch Land	stratabound Zn, Pb, Ba
M431/1	Showing	Sulphide zone, Navarana Fjord vein	calcite vein hosted Zn, Ba
M431/2	Showing	Barite zone, Navarana Fjord vein	calcite vein hosted Ba
M421/1	Showing	Kap Schuchert, Washington Land	carbonate-hosted Pb, Zn
M423/1	Showing	Kayser Bjerg SE, Hall Land	carbonate-hosted Zn, Pb
M423/2	Showing	Kayser Bjerg NW, Hall Land	carbonate-hosted Zn, Pb
M432/3	Showing	Kap Wohlgemuth, Nares Land	stratabound Zn, Pb, Ba
M432/4	Showing	Hand Bugt, Nyboe Land	stratabound Zn, Pb, Ba
M432/5	Showing	Repulse Havn, Nyboe Land	stratabound Zn, Pb, Ba
loc. 5	Showing	Marshall Bugt, Inglefield Land	paragneiss-hosted Zn
loc. 10	Showing	Western Septembersøer, Inglefield Land	paragneiss-hosted Cu, Au, Zn

Table 1. *List of zinc prospects and showings in North Greenland. Information extracted from the GEUS-BMP GMOM mineral occurrence database. MO_id is the ID of the GMOM database. The Zinc data package –North Greenland includes a data sheet for each MO_id. Two localities in Inglefield Land have been added because of rock samples with high Zn concentrations. Locality numbers for these are those of Thomassen et al. (2000).*

In this report, the term “mineral showing” defines observed mineralisations of unknown importance; no data on neither the dimensions nor the grade is available. The term “mineral prospect” applies to mineral occurrences carrying the potential to host economic deposits; it may or may not have been licensed and drilled exploration companies – but not yet proven as a mineral resource.

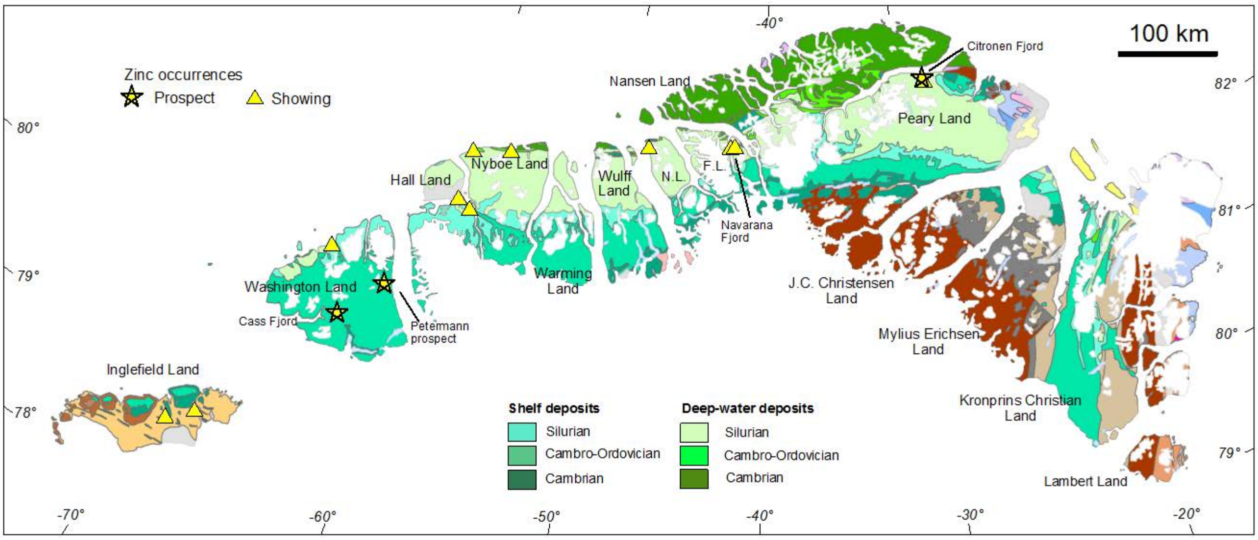


Figure 17. *Location of zinc mineral prospects and showings in North Greenland. The geological legend is for main units of the Franklinian Basin. Units outside the basin is the same as in Figure 1. N.L. is Nares Land, F.L. is Freuchen Land*

Zinc prospects

Citronen Fjord prospect, Peary Land

The Citronen Fjord massive sulphide deposit, located at the eastern end of the Palaeozoic Franklinian Basin, is the largest of the zinc deposits known in North Greenland. It is presently licensed by Ironbark Zinc Ltd. who calls the deposit “Citronen” (Ironbark company-website). Platinova A/S discovered surface mineralisation in the area in 1993, during a reconnaissance exploration program. Since then, the deposit has been studied and investigated using geological and geophysical exploration methods and extensive core drilling (van der Stijl & Mosher 1998; Kragh 2000); see further detail and references in the GMOM data sheets of the Zinc data package – North Greenland. The deposit is hosted in the Middle Ordovician Amundsen Land Group, it is generally flat lying with a thickness up to 50 m and it extends from outcrop level to depth of 300 m (Van der Stijl & Mosher 1998).

Three main stratiform sulphide sheets occur within a 200 m thick stratigraphic sequence; these are composed of massive and bedded pyrite with variable amounts of sphalerite and minor galena. The proven mineralisation is continuous over a strike length of at least 3 km with a maximum width of 500 m; an additional 5 km of mineralisation along the same trend is suggested by geological mapping and gravity surveys. The total tonnage of sulphides is estimated to exceed 350 million tons. Ironbark Zinc Ltd. (their website) announced in January 2012 resources as follows (not updated since November 2008):

Global resource of 101.7 Mt @4.7% Zn+Pb at a 2% Zn cut-off, medium grade of 56 Mt @6.1% Zn+Pb at 3.5% Zn cut-off with a higher grade core of 22.6 Mt @ 8.2% Zn+Pb at 5% Zn cut-off

Figure 18. *View of the Discovery area seen from the north, showing two of the main gossans with exposures of massive sulphides at the base of the mountain slope immediately east of "Citronen Elv". From Van der Stijl & Mosher (1998).*

Figure 19. *Fine-grained laminated sulphides in black mudstone. The sulphide laminae consist of framboidal pyrite in a matrix of sphalerite and carbonate. Zn-content is the upper sulphide layer is 25-30% and in the lower layer 1-3%. Platinova drill-core CF-15, 3.6 cm across. From Kragh (1996).*

The zinc-lead deposit is interpreted to be of sedex type formed by the precipitation of sulphides from metal-bearing fluids introduced onto the sea floor through underlying fractures. The precise tectonic control of the fractures is debatable, as is the role of the Navarana Fjord Escarpment assumed to lie immediately to the south of the Citronen Fjord (Van der Stijl & Mosher 1998).

Petermann prospect, Washington Land

Carbonate-hosted zinc-lead-silver mineralisation was discovered in 1997 along 19 km of a fault-controlled valley on Petermann Halvø in Washington Land with the main sites along NW–SE- to NNW–SSE-trending fault lineaments that splay off the main E–W- to ENE–WSW-trending, steeply-inclined fault (see summary and references in Dawes et al. 2000 and Dawes 2004). It comprises the ‘Petermann prospect’ of the Platinova / Rio Tinto exploration venture (Jensen 1998; Jensen & Schønwandt 1998; Cope & Beswick 1999; Pirie et al. 1999). The Petermann prospect is presently licensed by Avannaa Exploration Ltd.

The mineralisation is situated within the upper part of the lower Ordovician Cape Clay Formation (Dawes et al. 2000) and is associated with intense dolomitic alteration zones and strong gravity signatures, being dominated by pyrite, with marcasite, smithsonite and hydrozincite, and with galena and sphalerite. These ore minerals occur as open space infills within massive, burrow-mottled, micritic to stromatolitic dolomitised limestones and lime mudstones. Grab samples have yielded values up to 41% zinc, 0.3% lead and 211 ppm silver (Pirie et al. 1999). Drill core from ten holes revealed no economic-grade intersections but impressive local mineralisation, for example, a 23 m thick bed of massive pyrite (Cope & Beswick 1999).

According to Iannelli (2002), the mineralisation can be referred to as a Mississippi Valley-type deposit. Lead isotope data suggest that the source of lead in galena is the Precambrian shield underlying the Franklinian Basin (Dawes et al. 2000).

Cass prospect, Washington Land

Zinc-lead-barium mineralisation was discovered near Cass Fjord in Washington Land during the 1999 Platinova / Rio Tinto exploration venture. It comprises several mineralised sites along a 4 km strike length zone adjacent to a major ESE–WNW-trending regional fault (Cope & Beswick 1999; Iannelli 1999, 2002). The mineralisation is hosted in three massive ‘reactive’ limestone levels in the lower half of the upper Cambrian Cass Fjord Formation, with the lowest being the most pervasively dolomitised and most extensively mineralised. The main mineralisation consists of fine-grained, brown amber sphalerite, and medium- to coarse-grained galena and barite set in a buff to brown ferroan dolomite. Barite also forms seams and open space infills (Dawes et al. 2000). The single 107 m deep drill hole returned an intersection of 8.4% zinc, 0.04% lead and 94 ppm silver over an interval of 1.2 m (Cope & Beswick 1999). The Cass prospect is presently licensed by Ironbark Zinc Lth.

The mineralisation is considered an MVT (Thomassen 2007) showing affinities with an ‘Irish-type’ model (Dawes 2004 quoting Iannelli 2002).

Zinc showings

Navarana Fjord Ba-Zn mineralisation

The Navarana Fjord barium-zinc occurrence is the most important of the showings. It was discovered in Freuchen Land on an east facing cliff facing Navarana Fjord during geochemical mapping in 1984 (Steenfelt 1985; Jakobsen and Steenfelt 1985), and was studied further as reported in Jakobsen & Stendal (1987), Jakobsen (1989 a, b) and Jacobsen & Ohmoto (1993). The locality is situated at the Navarana Fjord anticline and hosts two types of mineralisation, syngenetic stratabound barite- (sphalerite) and epigenetic sphalerite-barite vein-type.

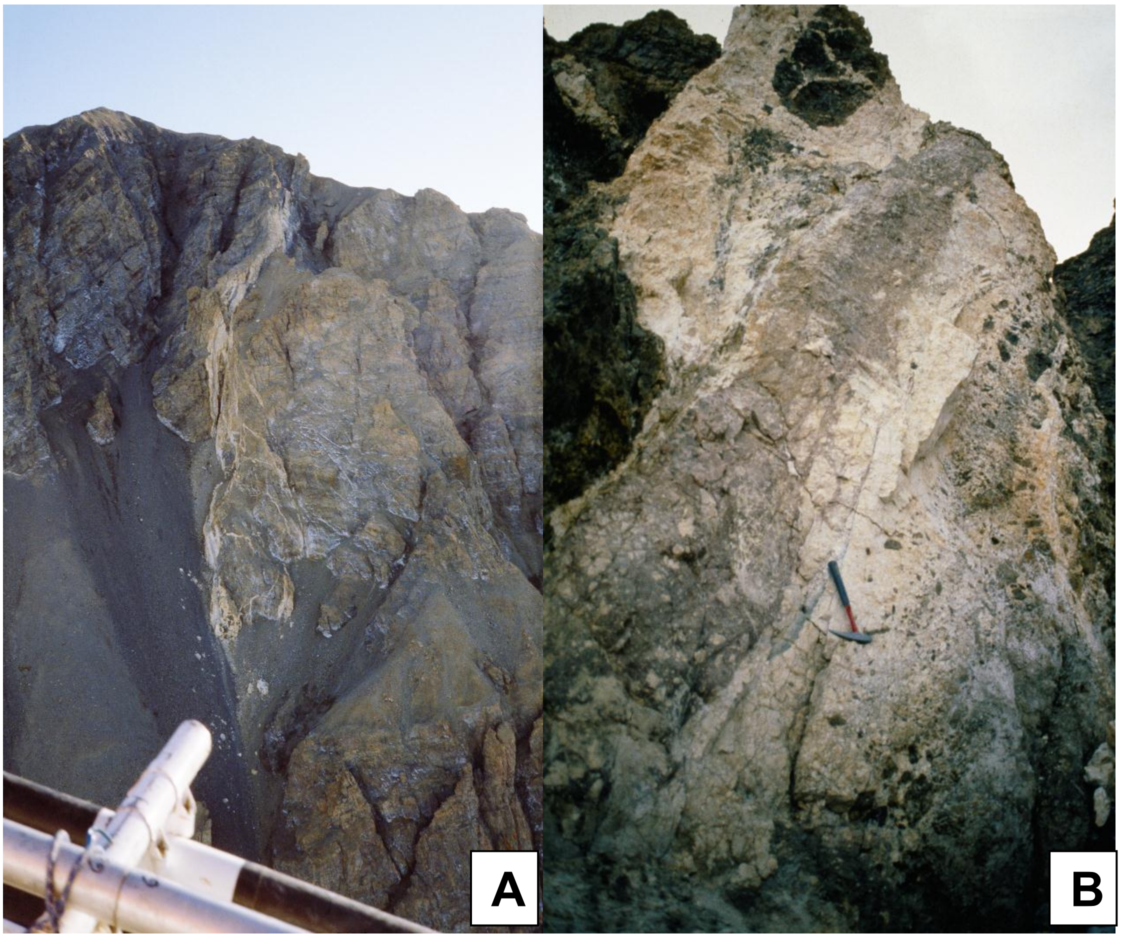


Figure 20. *The Navarana Fjord calcite vein centrally mineralised with barite and sphalerite. The vein is exposed over 60 m in an east-facing cliff section (A), and has a central zone of massive grey-brown sphalerite (B). Photos: A. Steenfelt.*

The most conspicuous mineralisation is the epigenetic vein-type. Massive sphalerite occurs together with barite and minor galena, chalcocite, chalcopyrite, pyrite, quartz and fluorite in a breccia zone within a 5 to 7 m wide calcite vein hosted by dolomite of the Cambrian Portfjeld formation (Figures 20 A, B). The vein has an E-W strike and has been followed westwards over c. 300 m (Jakobsen, 1989b). Fractures in the vicinity of the vein are sphalerite mineralised. A chip sample of a mineralised breccia from the opposite side of Navarana

Fjord, on Lauge Koch Land, has yielded 2% Zn and 0.2% Pb (von Guttenberg & van der Stijl 1993).

The mineralisation is clearly epigenetic and the vein occupies a fracture zone on the flank of the Navarana Fjord anticline. Several minor E-W trending faults were observed in the surroundings of the vein. The time of the mineralisation is estimated at Devonian to Early Carboniferous, associated with Ellesmerian folding (Jakobsen 1989b).

A pronounced rusty-yellow gossan zone that has developed at the surface north of the vein drew attention to the area of mineralisation. The gossan contains large volumes of hydrated iron sulphates (Jakobsen 1989a), that are preserved in the dry arctic climatic conditions.

Several stratabound Ba- and Zn-mineralised layers are present in carbonaceous shale and chert of the Amundsen Land Group sediments. A chert unit of this group has concentrations of up to 6 wt. % Ba and black cherts and shales from another layer Ba concentrations of 1 wt. %. There is no chemical or mineralogical correlation between Ba and Zn, and they are clearly located in different horizons. According to Jakobsen (1989b), the mineralisation can immediately be classified as an unmetamorphosed equivalent to the Aberfeldy deposit in Scotland on the basis of: (a) deposition in a starved 2nd to 3rd order basin, (b) Ba mineralisation associated with chert units, and (c) the presence of several Ba silicates.

Kap Schuchert and Kayser Bjerg, SE and NW

The showings at Kap Schuchert and Kayser Bjerg occur in rocks of the shelf deposits are small, but they are evidence of mineralising events in this part of the Franklinian Basin (see references in Dawes, 2004, and GMOM data sheets). At Kap Schuchert on the north coast of Washington Land, vug fillings of galena and sphalerite (1.47% Zn, 2.03% Pb) occur in Silurian reef carbonates. At eastern Hall Land, sphalerite-pyrite-galena-fluorite-barite mineralisation (1.9% Zn at locality SE, 0.4% Pb, 20% Zn at locality SE) is confined to zones of calcite veining in organic-rich carbonate rocks of the Silurian Washington Land Group. The maximum size of sphalerite-rich lenses observed in calcite veins reaches 1.5x1.0x0.4 m, the maximum strike length of zones with intermittent mineralisation is about 1400 m.

Nyboe Land and Nares Land

Three showings on Nyboe Land and Nares Land (see GMOM data sheets) are occurrences of epigenetic Zn-Pb-Ba mineralisation. They are hosted in stratabound brecciated dolomitic mudstones like those on either side of Navarana Fjord. The localities are Kap Wohlgemuth in Nares Land, and Hand Bugt and Repulse Havn at the north coast of Nyboe Land, all visited and sampled by Platinova A/S & Nanisivik Mines Ltd. (van Guttenberg et al. 1993). They are situated close to the Nyboe Land fault zone, like the two occurrences at Navarana Fjord, and it is assumed that the fault zone provides the pathway for the mineralising fluids. A grab sample from Repulse Havn returned 11% Zn and 2% Pb.

Inglefield Land

A number of stream sediment samples from the supracrustal rocks of the Etah Group have elevated Zn concentrations (Steenfelt & Dam 2006 and present report, see section on geochemistry), and large rust zones provide evidence of widespread sulphide mineralisation within these rocks (Thomassen & Dawes 1996). Follow-up on sulphide mineralised sites in 1999 was focused on copper-gold targets (Thomassen et al. 2000), but analyses of rock and overburden confirm Zn enrichment associated with semi-massive lenses of iron and copper sulphides. Up to now, recorded Zn concentrations are moderate (max. 1.6% in rock samples), though it should be noted that Zn was not the prime aim of the investigations by Thomassen et al. (2000). The supracrustal rocks are in an orogenic setting and could be expected to host volcanogenic massive sulphide type of mineralisation. Perhaps the main significance is that the generally elevated level of Zn in these rocks makes them an excellent source of Zn for the occurrences in the Franklinian Basin, in accordance with Pb isotope evidence from Petermann prospect (Dawes et al. 2000).

Figure 21. *Rust zone in northern Inglefield Land. In the centre of the photograph, lenses of massive pyrrhotite are covered by white oxidation minerals. From Thomassen et al. (2000).*

Zinc occurrences in Northeast Canada

The Franklinian Basin continues to the west, through the Canadian Arctic Islands (Figure 22) and extents for more than 2,500 km E-W in total. Several zinc occurrences and showings are found in Northeast Canada (Gibbins 1991), which have also hosted two zinc mines, Polaris and Nanisivik as described below.

Polaris

The Polaris mine was in production from 1981 to 2002. It was an underground mine on Little Cornwallis Island in the Arctic Islands in the Canadian territory of Nunavut (Figure 22) and was the most northerly mine in the world at the time. Zinc comprised a little over 12% of the ore mined, while lead accounted for about 3.5%. The Polaris mine produced over 21 million tonnes of lead-zinc ore during the life of the mine, with a market value of over 15 billion dollars.

Polaris is an MVT deposit hosted by carbonates of the Middle to Upper Ordovician Thumb Mountain, which is part of the Cambrian to Devonian Franklinian shelf sequence (Christensen et al. 1995).

The economic ore consists of varying styles of epigenetic mineralization. Sphalerite and galena occur as replacements, open space fillings, colloform masses and veins as well as disseminations in the host rocks. Rb-Sr dating of sphalerite yields a consistent age of 366 ± 15 Ma (Christensen et al. 1995), e.g. confirming paleomagnetic measurements by Symons & Sangster (1992) that the deposit is significantly younger than the host rocks.

Nanisivik

The Nanisivik mine was in production between 1976 and 2002, located on Baffin Island. It was Canada's first mine in the Arctic.

The deposit is an MVT deposit hosted in grey dolostones of the Society Cliffs Formation. It is a carbonate platform sequence in the middle of the >600 m thick Mesoproterozoic Bylot Supergroup. The supergroup was deposited in the Borden rift basin, a graben that formed within the pre-existing Canadian Shield. The deposition of the supergroup occurred between c. 1270 and 1225 Ma.

The origin and the age of the sulphide deposit are still not clear. The sulphides are obviously epigenetic, but there are contrary views regarding the nature of the emplacement (Olsen 1984, 1986; Ford 1986). The argument revolves around whether the sulphides simply filled pre-existing open caverns or whether the ore fluids themselves were sufficiently corrosive to affect carbonate dissolution during the overall process of sulphide precipitation.

Paleomagnetic data has been used to indicate that the mineralization has an age of 1095 ± 10 Ma (Symons et al. 2000).

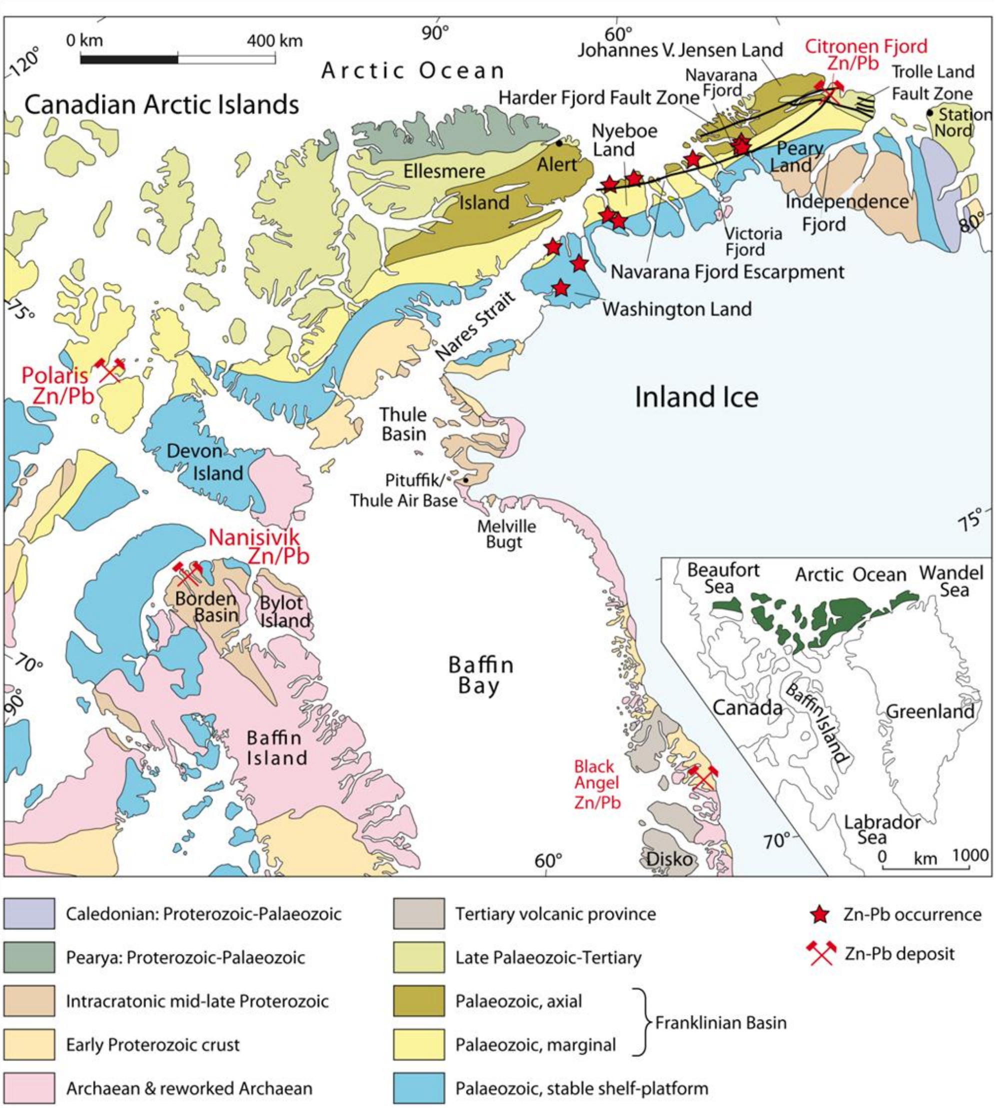


Figure 22. *Map of North Greenland and correlations to North-East Canada. Zn-Pb deposits and occurrences are shown. Modified after Van der Stijl & Mosher (1998).*

Compilation, quality assessment and calibration of stream sediment geochemical data from North Greenland

The present section of the report deals with compilation of existing and newly-acquired geochemical stream sediment data together with an assessment of their quality and comparability. Analytical data for Zn, Cu, Ba, Sr, Ca and K are made consistent and presented in geochemical maps. The distribution patterns displayed by the maps are discussed.

Previous experience

Geochemical exploration and geochemical mapping using stream sediment samples has been conducted over large areas in Greenland, and for West and South Greenland the coverage has been good enough to produce a geochemical atlas of 43 geochemical element maps that document the geochemical variation over large parts of the Precambrian shield (Steenfelt 2001b). The main difficulty in producing reliable geochemical maps has proven to be the achievement of a consistent data set from analyses of individual sample batches acquired over a long period of time and involving a range of analytical methods and laboratories (see Steenfelt 1999, 2001a). The solution to the problem comprises studies of data from internal reference samples analysed at the involved laboratories, and reanalysis of a sample set containing representatives from each of the previously analysed batches.

Sampling and analysis in North Greenland

Coverage prior to 2011

In North Greenland, stream sediment has been sampled for the purpose of mineral exploration at variable intensity over a time period from 1978 to 1999 (Figure 23). Altogether, data from 12 sampling campaigns within North Greenland have been recorded in the GEUS data base (Table 1). About half of the area (area A, C and E) from Inglefield Land in the west to Lambert Land in the east has been covered with systematically collected and evenly distributed samples at reconnaissance scale sampling density (1 sample per 30 to 50 km^2). Over the remaining area (areas B and D), sampling has been scarce with very irregular sample coverage, mainly at camp sites by geological mapping teams or local sampling of sites with known or suspected mineralisation.

The map, Figure 23, immediately illustrates the need for supplementary samples in areas B and D to obtain a density of data required to identify geochemical trends in the poorly covered areas.

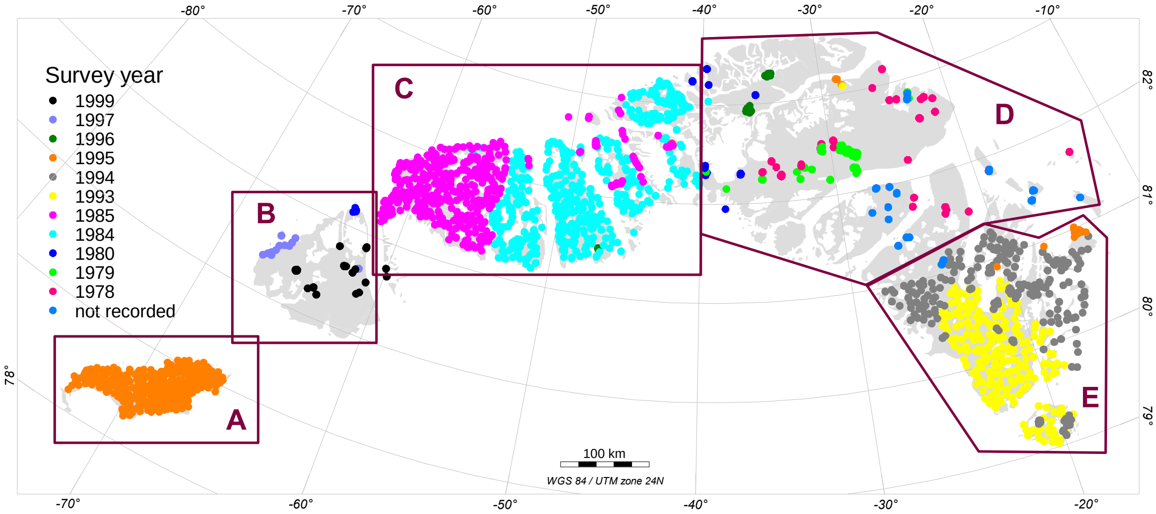


Figure 23. *Location of stream sediment samples across North Greenland as recorded in the GEUS database prior to present project. Colour symbols refer to the time of sample collection.*

Methods of sampling and sample preparation

Regional surveys in areas A, B, C and E have followed the procedures for sampling and sample treatment employed in geochemical mapping over remaining Greenland (Steenfelt 2001b). Documentation of the geochemical mapping in areas A and C are published in Steenfelt (1985, 1987, 1991), Steenfelt and Dam (1996), and Schjøth et al. (1996). The geochemical sampling in area E has been described in Ghisler et al. (1979), Ghisler and Stendal (1980), Henriksen (1980) and Steenfelt (1980).

The samples consist of up to 500 g of sediment collected from stream beds and banks into paper sample bags. These are dried in the field before shipped to Copenhagen, where they were further dried and screened. A split of each < 0.1 mm grain size fraction was submitted for analysis. The early sampling in area D was carried out before a routine method had been established and has, therefore, been more variable, but has largely followed the same procedures. Many of the analyses from area D were conducted on the grain size fraction < 0.15 mm.

Local sampling (the data also include analyses of soil samples – samples with GEUS_ID 505701 to 505765) in Inglefield Land has been documented by Thomassen et al. (2000), and in Washington Land by Steenfelt (1976) and later follow-up sampling is mentioned in Dawes et al. (2000), but actual stream sediment data are not given.

Area	Sampling campaigns		Data recorded in GEUS database prior to 2011							
			RISO		Major element oxides			Trace elements ACT		
			DNC	EDX	GGU-XRF	SGAB	ACT-XRF	INA	XRF	ICP
D	1978-1980	Geological mapping Peary Land	162	164	36	9		60		58
C	1984-1985	Geochemical mapping 40° to 64° W	44		10	986		50		50
E	1993-1994	Geochem mapping NE Greenland			519			520	1	521
A	1995	Geochemical mapping, Inglefield Land					268	281		263
A, B, C, D		Local sampling			95			161		161
Entire NG	**Total**		**206**	**164**	**660**	**995**	**268**	**1072**	**1**	**1053**

Table 2. *Stream sediment samples collected in North Greenland and registered in the data base with a digital location. RISO: Risø National Laboratory; DNC: Delayed Neutron Counting; EDX: isotope excited X-ray fluorescence spectrometry; GGU-XRF: X-ray fluorescence spectrometry at the Geological Survey of Greenland/GEUS; SGAB: X-ray fluorescence spectrometry at Swedish Geological AB; ACT-XRF: X-ray fluorescence spectrometry at Activation Laboratories; INA: Instrumental Activation Analysis; ICP: Inductively Coupled Plasma Emission Spectrometry. Location of samples in Figure 23.*

Analytical methods and elements determined

The availability of analytical methods and their capacities have changed over time. This is reflected in Table 3 giving an overview of analytical methods and laboratories used for sample batches from North Greenland (compare Table 2). Details of analytical methods are given in the appendix. The spatial distribution of samples analysed by specific methods is shown in Figures 24 to 27.

	ICP_97	**ICP_99**	**GEUS-XRF**	**SGAB-XRF**	**ACT-INA**	**RISO-EDX**	**RISO-DNC**	**ACT-XRF**	**ICP_95**
Major									
			SiO2	SiO2				SiO2	
	TiO2		TiO2	TiO2		TiO2		TiO2	Ti
	Al2O3		Al2O3	Al2O3				Al2O3	Al
			Fe2O3	Fe2O3	Fe2O3	Fe2O3		Fe2O3	
	MnO		MnO	MnO		MnO		MnO	Mn
	MgO		MgO	MgO				MgO	Mg
	CaO		CaO	CaO	CaO	CaO		CaO	Ca
			Na2O*	Na2O	Na2O			Na2O	
	K2O		K2O	K2O		K2O		K2O	K
	P2O5		P2O5	P2O5				P2O5	P
			vol					vol	
Trace									
	Ag				(Ag)				Ag
				((As))	As				
					Au				
			Ba	Ba	Ba				
	Be								Be
	Bi								Bi
					Br				
	Cd								Cd
				Cl					
				((Co))	Co				
			Cr	Cr	Cr	(Cr)			
					Cs				
	Cu	Cu	Cu*	(Cu)		Cu			Cu
					Hf				
	Mo	Mo		Mo	(Mo)				Mo
				Nb					
	Ni	Ni	Ni	Ni		(Ni)			Ni
	Pb	Pb		((Pb))		(Pb)			Pb
			Rb	Rb	Rb				
		S		S					
					Sb				
					Sc				
					Se				
				((Sn))					
	Sr	Sr	Sr	Sr					Sr
					Ta				
				((Th))	Th				
					U		U		
	V	V	V	V		((V))			V
				((W))	W				
	Y	Y		((Y))					Y
	Zn	Zn	Zn	Zn	(Zn)	Zn			Zn
			Zr	Zr		Zr			
					La				
					Ce				
					Nd				
					Sm				
					Eu				
					Tb				
					Yb				
					Lu				

*atomic absorption spectrometry; () poor quality; (()) very poor or invalid data

Table 3. *Elements determined in analytical packages for stream sediment samples from North Greenland, and their quality according to Jensen (1995) and the present assessment. Laboratories: Activation Laboratories Ltd. (ACT), GEUS Rock Chemical Laboratory (GEUS), RISO, Swedish Geological (SGAB). Analytical methods: Inductively coupled plasma emission spectrometry (ICP), Instrumental neutron activation analysis (INA), X-ray fluorescence spectrometry (XRF).*

Analytical data from samples collected within area E are the most complete with valid data for major element oxides and 36 trace elements, and also area A has a good suite of elements determined (except Nb and Zr). An assessment of the consistency between some of the data sets was made by Jensen (1995) and that revealed that data for half of the trace elements determined by XRF (SGAB laboratory) are of unacceptable quality. This means that in area C only a limited suite of the trace element data is regarded valid. Another quality test concerned U determined by SGAB. A number of 44 samples from area C were analysed by DNC (previously tested to give reliable results), and in result SGAB determinations were deemed invalid.

The experience gained in the compilation, quality assessment and calibration of data for the geochemical atlas of West and South Greenland (Steenfelt 1999) has been used to further assess the analytical data from North Greenland.

In the investigation documented by Jensen (1995), 100 stream sediment samples from areas C and D were re-analysed using INA and ICP methods. While the purpose was a quality assessment of early analytical results, the data contribute to the coverage in element data.

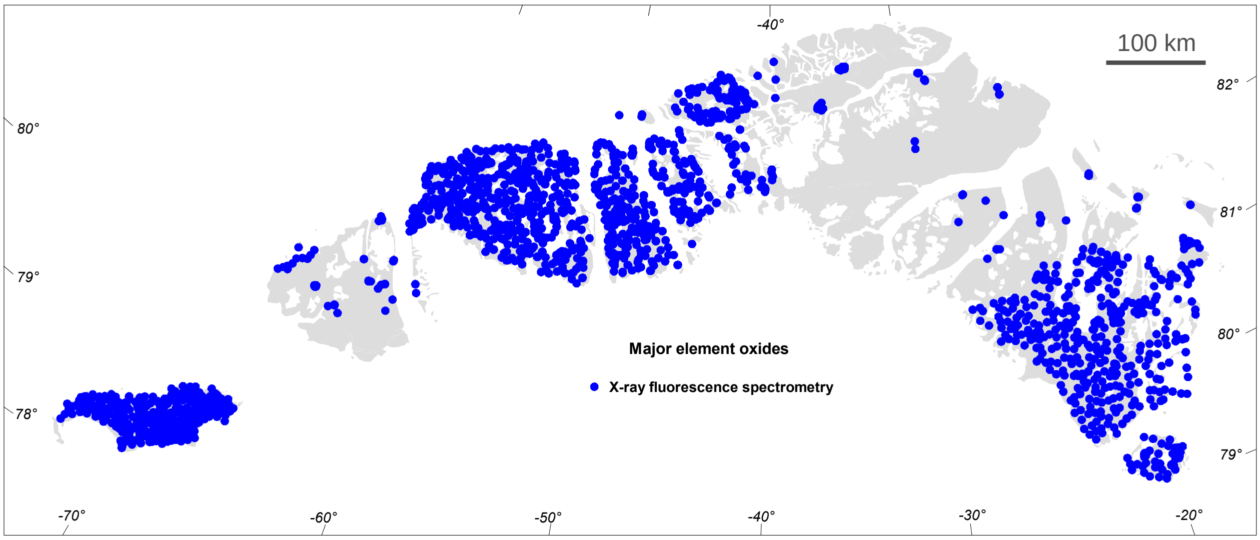


Figure 24. *Location of stream sediment samples analysed for major element oxides by X-ray fluorescence spectrometry.*

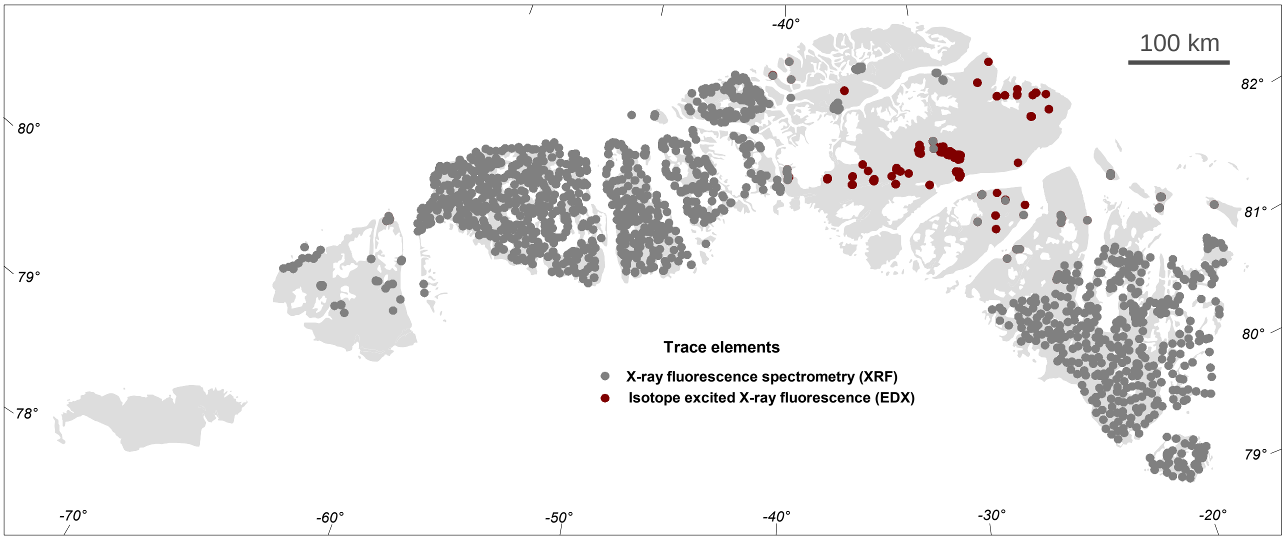


Figure 25. *Location of stream sediment samples analysed for trace elements by X-ray fluorescence spectrometry. Suites of elements determined vary between laboratories (see Table 2 and 3 for element suites).*

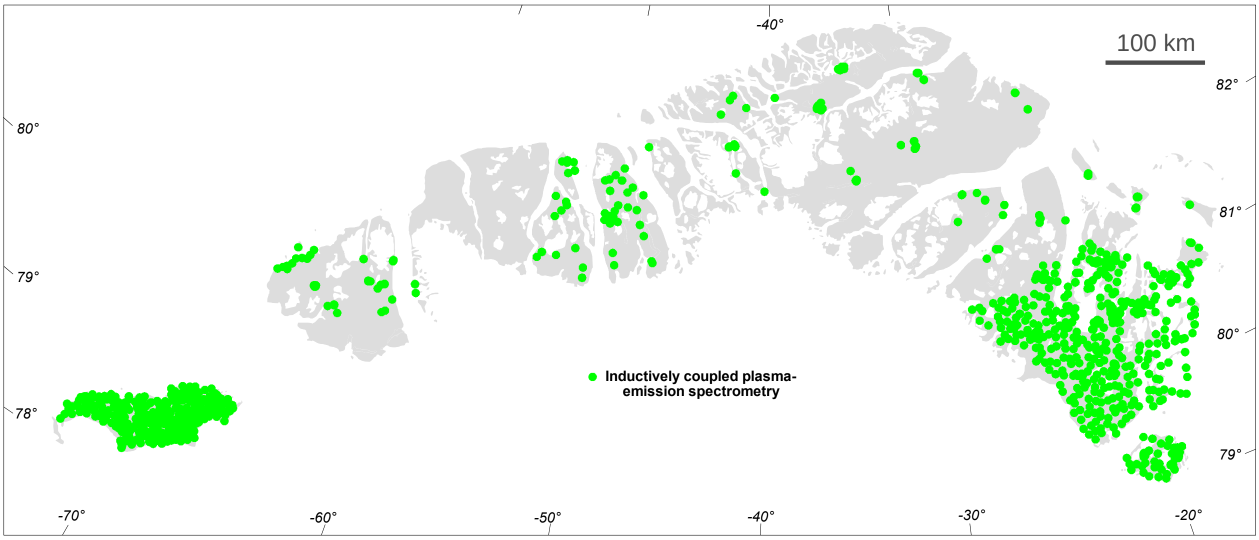


Figure 26. *Location of stream sediment samples analysed for trace elements by Inductively coupled plasma emission spectrometry (see element suite in Table 3) at Activation Laboratories.*

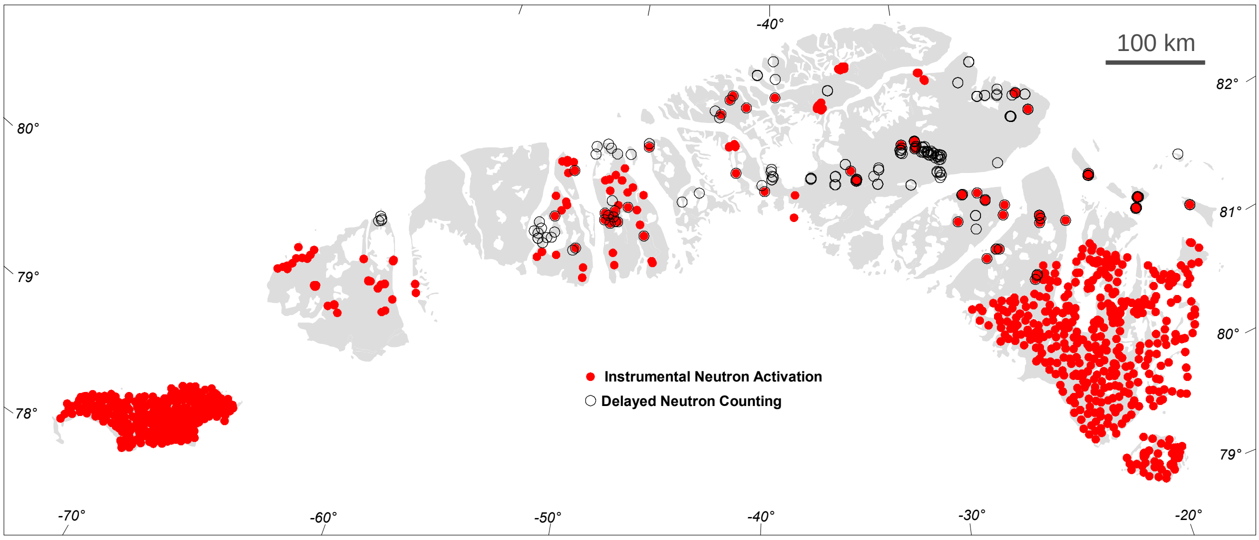


Figure 27. *Location of stream sediment samples analysed for trace elements by Instrumental Activation Analysis at Activation Laboratories (see element suite ACT-INA in Table 3) and for U by Delayed Neutron counting (DNC) at RISO.*

Summary of available data prior to 2011

Tables and figures above provide an overview of samples collected and analytical data recorded in the GEUS data base. On an area basis this can be summarised as follows:

Area	Coverage	Element suites
A	regional	almost complete
B	scarce	complete
C	regional	incomplete
D	scarce	incomplete
E	regional	complete

Any map presentation of geochemical variations requires that analytical data from individual analytical batches are made comparable, i.e. that any bias in analytical values between laboratories and methods should be eliminated. The so-called calibration or levelling of analytical data is a task within the present project.

Activities undertaken in 2011

During the effort to compile all existing data it was discovered that a large number of samples collected from 1976 to 1980 in areas B and D had been analysed, but their location had never been digitised. This has now been achieved. In addition, a considerable number of samples have been submitted for analysis by modern methods for a more complete suite of elements. The purpose is twofold, to establish a dataset by which all previous analytical data can be levelled, and to be able to geochemically characterise samples with high Zn concentrations and thereby deduce the type of zinc mineralisation sourcing the Zn-anomalous stream sediments.

Digitisation of sample location maps

When the samples from areas B and D were collected in 1976 (area B) and 1978 to 1980 (area D) neither topographical maps nor GPS recorders were available. Sample sites were marked on air photos and later transferred to overview maps at scale around 1: 1 000 000. For area B, a sample map is enclosed in Steenfelt (1976), and for area D a sample map was stored in the GEUS map archive. On the scale of these maps, it was impossible to show individual localities for samples collected at close distance, and it was impossible to obtain a high accuracy on the location. Hence, while the digital localities for the old samples provide a basis for identifying regional geochemical trends, they are not useful to identify the accurate location of an anomalous sample. The overview sample maps were scanned, fitted best possible to a digital topographical data base at scale 1:500 000, and then the sample localities were digitised using ESRI ArcMap software. An example of a sample location map is given in Figure 28.

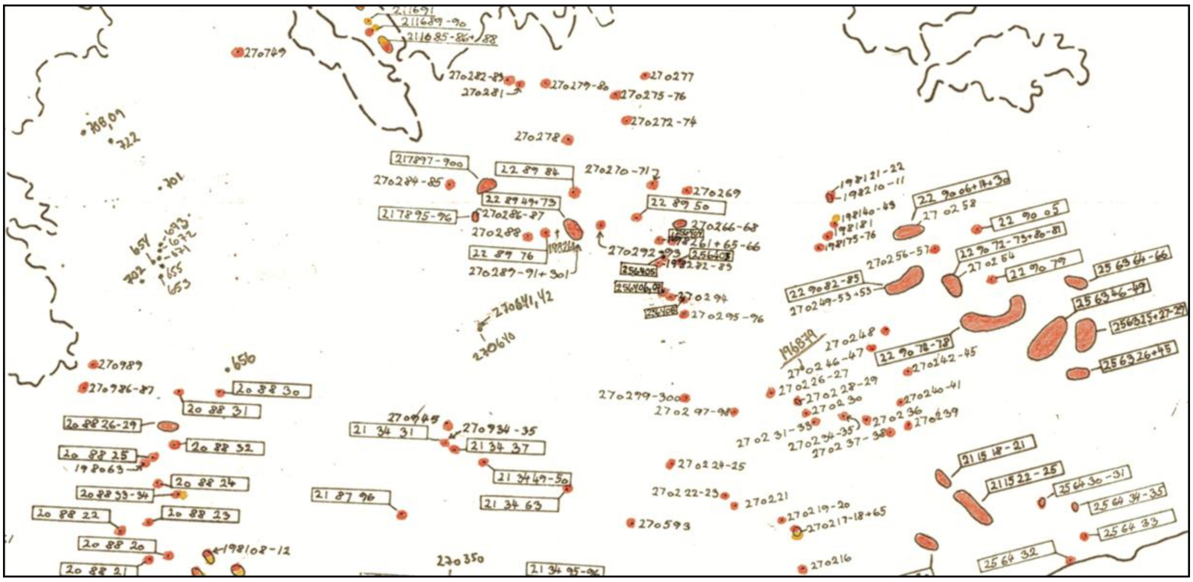


Figure 28. *Overview sample map for rock and stream sediment samples from southern Peary Land, see location in Figure 29.*

In this way, digital localities were obtained for 531 more samples previously analysed by RISO. The updated coverage of all stream sediment samples is shown in Figure 29.

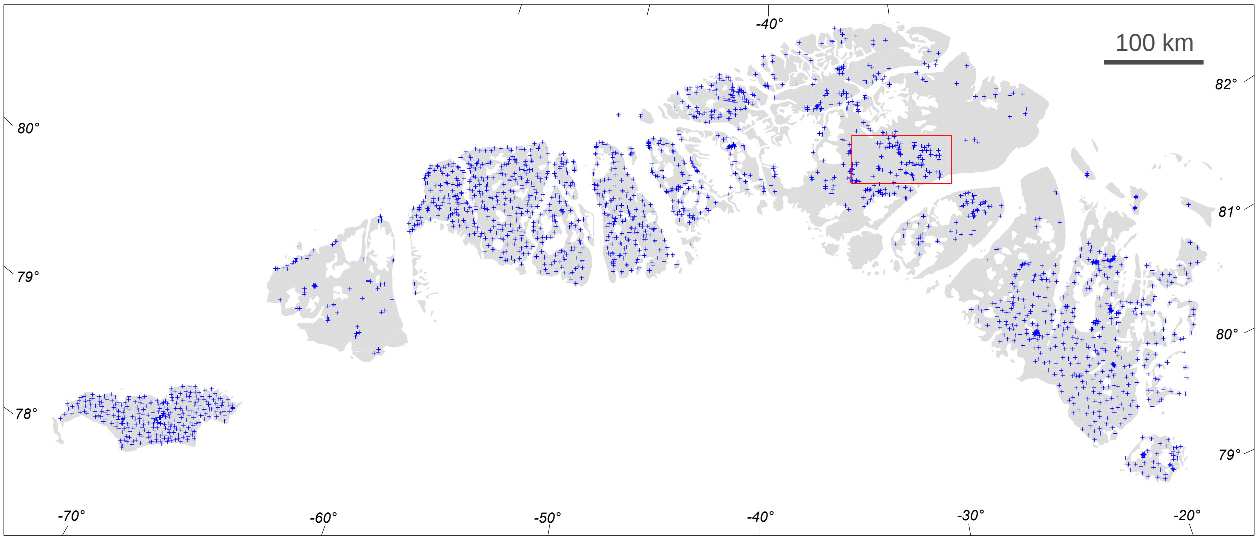


Figure 29. *Updated stream sediment sample location, compare with pre-project compilation in Figures 23 to 27. The red rectangle marks the area shown in Figure 28.*

Reanalysis of samples for calibration and improved chemical characterisation

Selection of samples for re-analysis

The most urgent need was to ensure that base metal data provided by SGAB for area C and RISO for area D were supplemented and calibrated (see Table 3 for abbreviations of laboratories and methods). Samples from area C were analysed at ACT for trace elements by a combination of INA and ICP methods used in other areas, while samples from area D were analysed for both major and trace elements, since RISO did not provide major element oxides.

A number of preselected samples were retrieved from the GEUS archive and a split of c. 5 g of each sample in the < 0.1 mm grain size fraction was submitted for analysis. The samples were selected so as to form a new dataset with the most even spacing possible as illustrated in Figure 30.

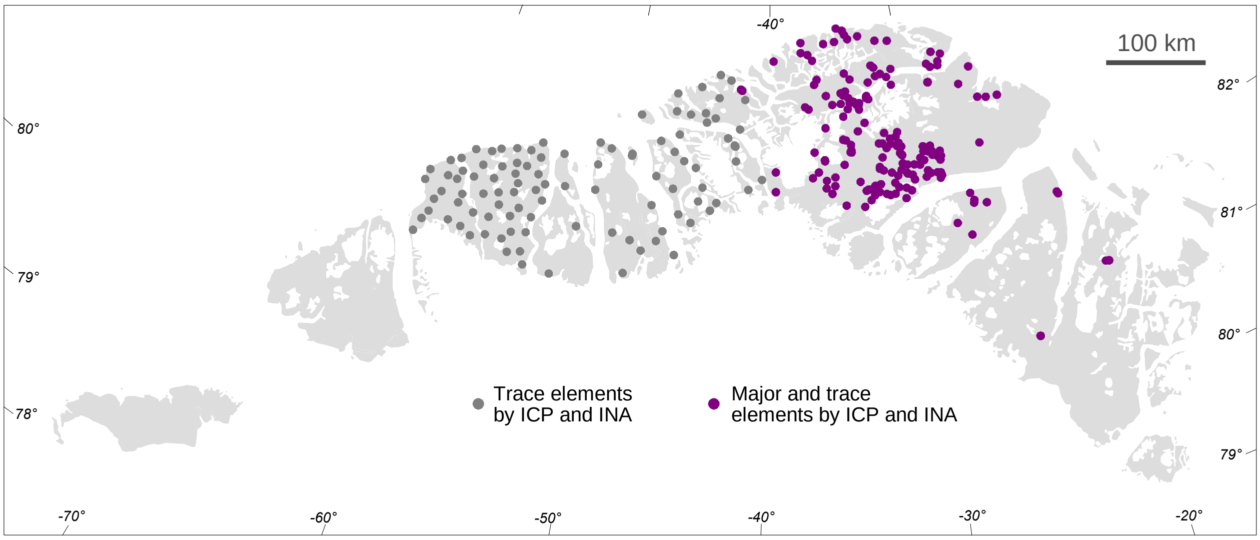


Figure 30. *Samples selected for reanalysis. Grey symbols previously analysed by SGAB, mauve symbols previously analysed by RISO.*

Calibration

The need for calibration primarily concerns data for samples analysed by SGAB and RISO, but experience has shown (Steenfelt 1999) that also ICP and INA data determined at different times at ACT need adjustments to be entirely comparable. In the present project, the primary concern has been the establishment of reliable datasets for Zn, Cu and Ba, together with three elements, Ca, K and Sr, reflecting lithological variation. Calibration of additional elements can be made according to future needs.

The main principles for the conducted calibration are the same as in Steenfelt (1999), and they are given here; detailed documentation of the calibration procedure will be provided in a future GEUS report.

The first step was to identify analytical batches and data for the GEUS reference samples accompanying each sample batch submitted for analysis. Data for Zn, Cu and Sr analysed by ACT-ICP, data for Ba analysed by ACT-INA, and data for CaO and K_2O analysed by XRF (both GEUS and ACT) were then calibrated by means of the data for the reference samples. The calibration also included the analytical data acquired in 2011, so that consistent data for the five elements were achieved.

Figure 31 shows the distribution of samples for eleven analytical batches accompanied by reference material. The batches are labelled by letters in chronological order of their analyses. Since samples have been re-analysed at various times, the analytical batch letters are different from the ones that were used to assign areas in Figure 23. The batches comprise samples collected as part of geochemical mapping as well as data obtained during reanalysis for quality assessment purpose and data from local sampling at mineralised sites.

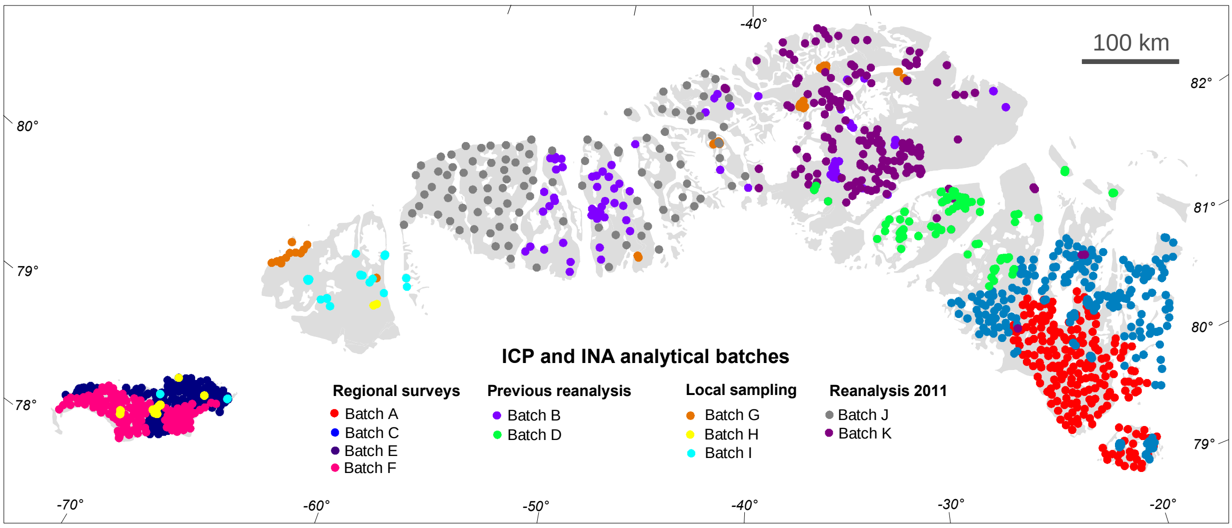


Figure 31. *Location of stream sediment samples analysed by ACT-ICP and ACT-INA. Analytical data were calibrated by means of data for reference samples. Previous reanalysis refers to samples previously analysed by RISO or SGAB, see next figure.*

Analyses by RISO-EXD and SGAB-XRF were made before monitoring with internal reference samples was made a routine procedure, and, therefore, the next step was to use the regression parameters with calibrated data for the reanalysed samples as a means of levelling the old data. As a result, selected element data for the samples shown in Figure 32 were calibrated.

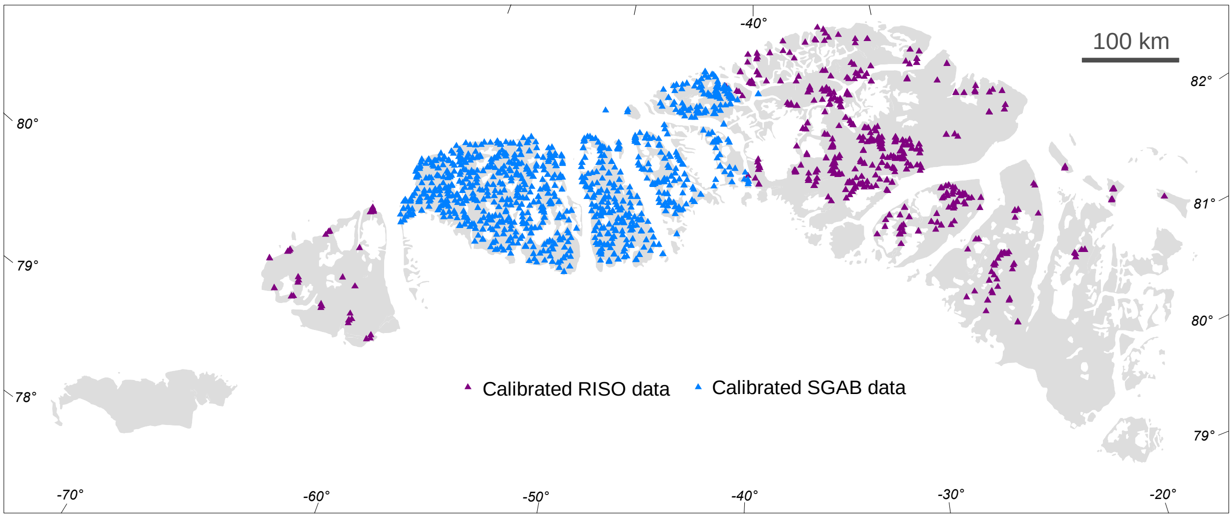


Figure 32. *Location of stream sediment samples analysed by RISO (EDX) and SGAB (XRF). Analytical data were calibrated by means of correlation with data from batches J and K, see Figure 30.*

Result of quality assessment and calibration

The comparison of the new analytical data with the old data from SGAB and RISO has shown that data for Zn, Sr, CaO and K_2O by both SGAB and RISO are reliable and can be made consistent. The RISO data did not include Ba, but Ba values by SGAB are correlated with ACT-INA data. The Cu values from SGAB on the other hand are not correlated with the new ACT-ICP data, and the SGAB Cu data are judged as poor quality in accordance with the conclusion of Jensen (1985) based on a smaller population of analytical data. The Cu values determined by EDX at RISO were found reliable and have been made consistent with the Cu values determined by ACT-ICP.

The calibration of Ba values was difficult because data for the reference samples show that Ba determined by ACT-INA has poor precision in accordance with results in Steenfelt (1999). This should be kept in mind in an evaluation of the Ba variation.

The final result of the quality assessment and calibration are datasets for the six elements mentioned comprising 2648 records for Zn, 2647 for Sr, 2642 for CaO and K_2O,1810 for Cu, and 2255 for Cu. The main statistical parameters for the calibrated data are listed in Table 4, and histograms of the frequency distributions are shown in the colour coded symbol maps Figures 33 to 38. The maps may also be studied in larger copies in Appendix 2.

	CaO %	K_2O %	Ba ppm	Sr ppm	Cu ppm	Zn ppm
Maximum	77.5	7.2	20400	6281	1385	1237
98th percentile	39.0	5.2	1671	527	148	193
50th percentile	6.1	2.4	430	119	23	55
Minimum	0.0	0.1	28	5	0	3

Table 4. *Main statistical parameters for the calibrated data.*

Files with the calibrated data for the 6 elements as well as all analytical data for the samples analysed in 2011 are included in the Zn data package on GEUS' website.

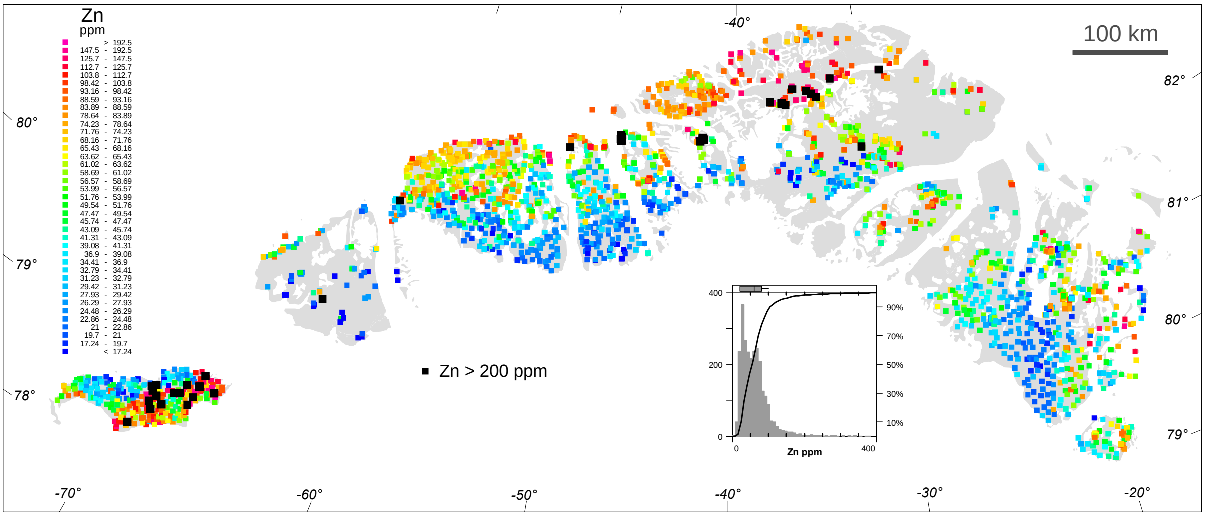


Figure 33. *Geochemical map of Zn based on calibrated stream sediment data.*

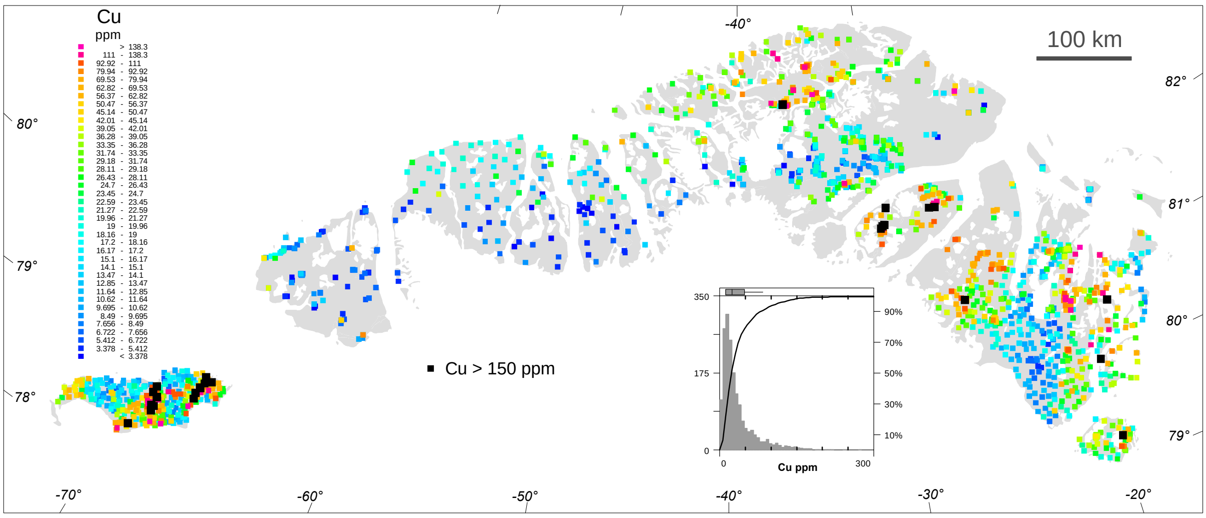


Figure 34. *Geochemical map of Cu based on calibrated stream sediment data.*

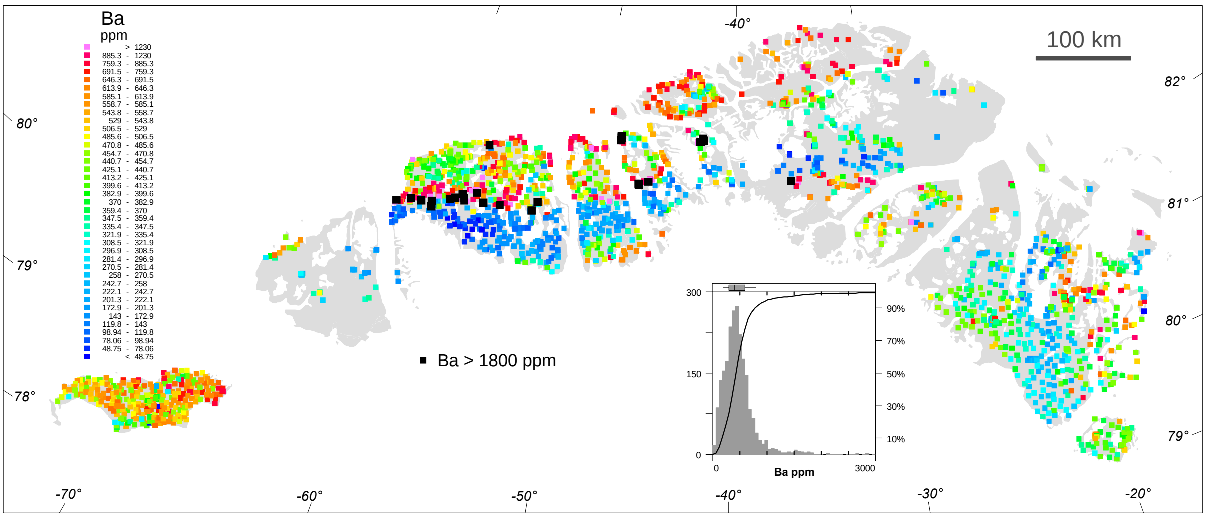


Figure 35. *Geochemical map of Ba based on calibrated stream sediment data.*

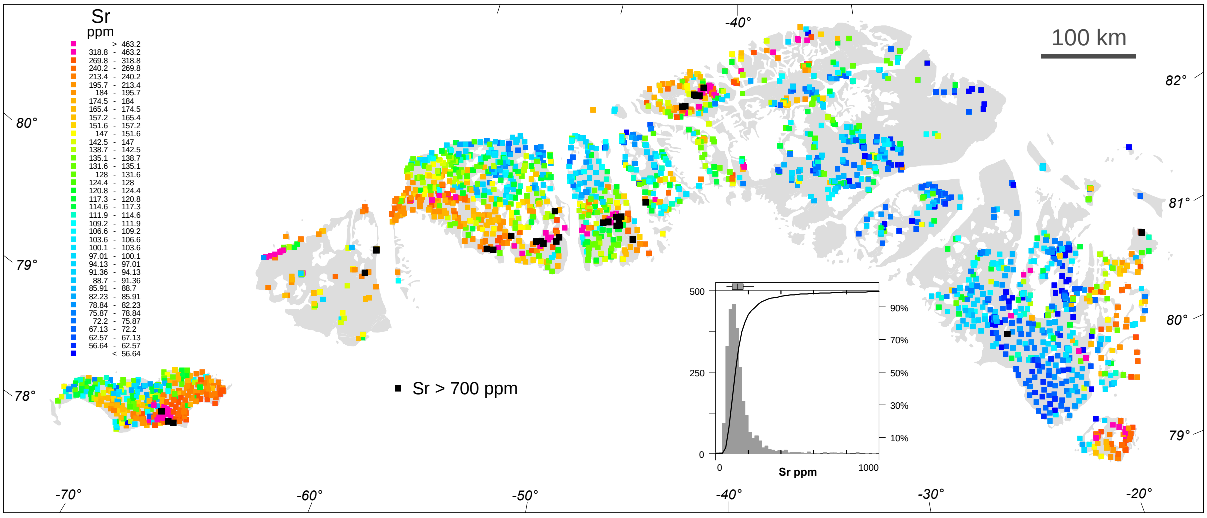


Figure 36. *Geochemical map of Sr based on calibrated stream sediment data.*

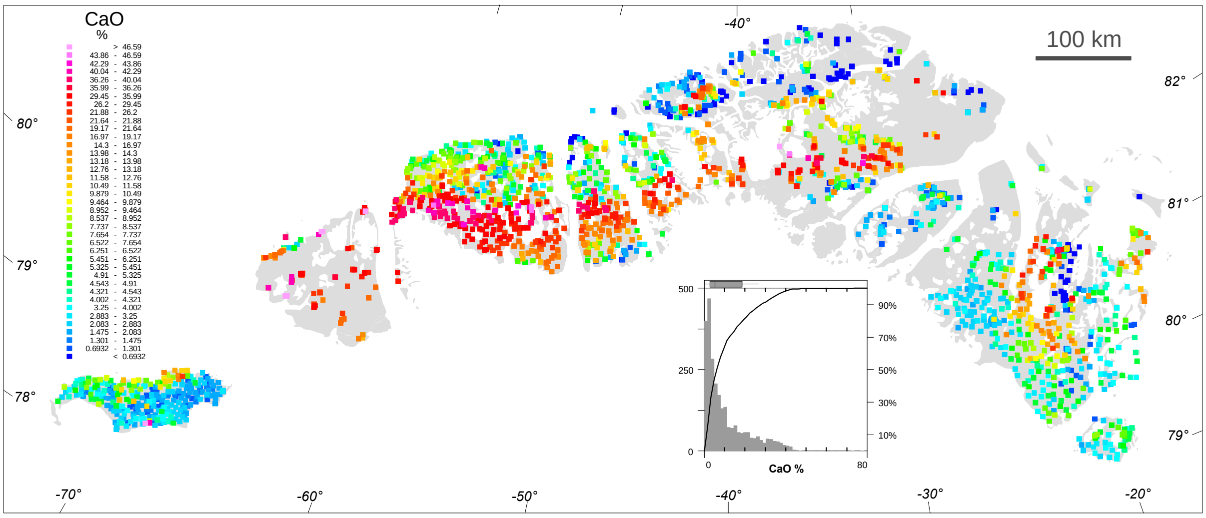


Figure 37. *Geochemical map of CaO based on calibrated stream sediment data.*

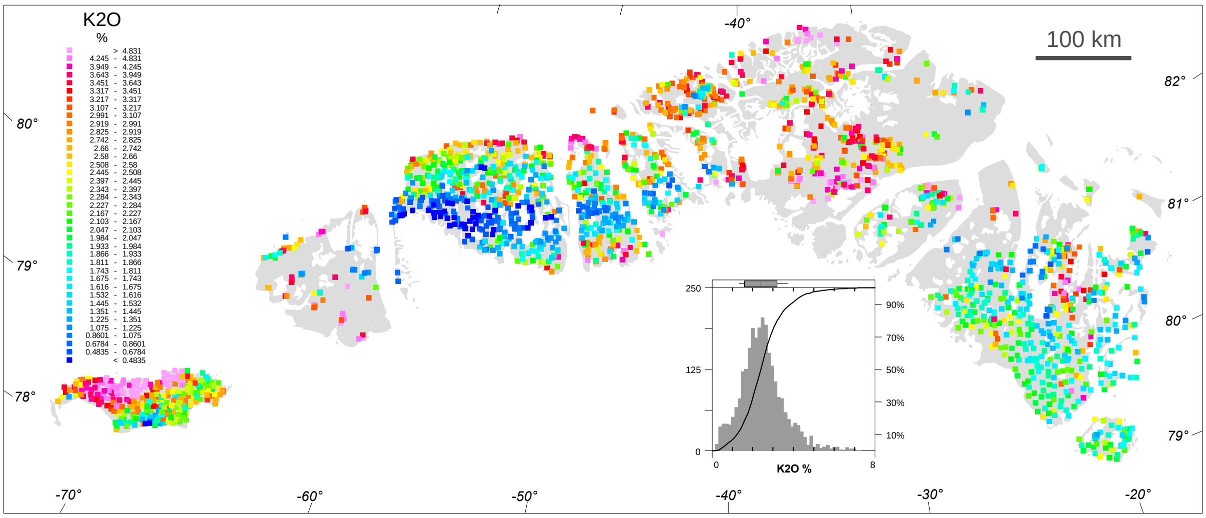


Figure 38. *Geochemical map of K_2O based on calibrated stream sediment data.*

Comments on the element distribution patterns

All six maps display clear trends in the distribution patterns that are related to lithological variation and structure. In areas of the Franklinian Basin, the background variation shows high CaO (as expected) and elevated Sr over the exposed carbonate-rich rock units. The other elements display low concentration levels in the same areas. Elevated concentrations of K_2O coincide with occurrences of clastic shelf units and most of the trough deposits. The background variations of Zn, Cu and Ba have many similarities and they are all enriched in the trough facies rocks relative to shelf rocks. Cu, however, is mostly enriched outside the Franklinian Basin. Steenfelt (1985, 1987a,b, 1991) described how Ba and Zn were correlated in the central part of the area, and the present (calibrated) data confirm the correlation and show that an identified zone with high Zn and Ba values extends towards east into Peary Land and Kronprins Christians Land (locality names in Figure 39).

In Inglefield Land, element variations are less clearly associated with the lithology, but on the other hand the Palaeoproterozoic lithology and structure is much more complicated. Steenfelt & Dam (2006) discuss the element distribution patterns and their significance. In the present context, the most interesting observation is that the abundance of high values in Inglefield Land stream sediment data is unusual by comparison with remaining data from Greenland (Steenfelt 2001b). The areas with high Zn coincide with high values for Cu, Figure 33 and 34.

Distribution of anomalies

The highest values of the elements Zn, Cu, Ba, and Sr have been defined as anomalous. In this presentation, the upper 1 percent of the measured concentrations for each element, corresponding to ca. 26 samples, has been defined as the anomalous population. In order to study the position of the anomalies in relation to geology and structure, a combined anomaly map has been constructed (Figure 39).

This map clearly demonstrates that most of the stream sediment anomalies for Zn ad Ba in the Franklinian Basin coincide and are related to main tectonic structures, where a number of epigenetic barite and spalerite showings have been located along the Nyboe Land fault, Navarana Fjord vein in particular, and the Permin Land flexure. However, some of the anomalous samples are considered to reflect syngenetic enrichment in bituminous units (Jakobsen and Stendal 1987; Jakobsen 1989b). Thin folded units of dolomitic mudstone of the Ordovician Amundsen Land Group that lie close to the Nyboe Land fault are one example. The mudstones are bituminous and contain chert, and they represent starved basin deposits. Silurian bituminous shales of the Washington Land Group occurring along the Permin Land flexure are another example. They are enriched in finely disseminated sulphides and are the probable reason for high Ba concentrations in some of the stream sediment samples (Steenfelt 1987; Jakobsen & Stendal 1987).

Zn anomalies form an elongate cluster in south-western Johannes V. Jensen Land in an area underlain by imbricated units of Vølvedal and Amundsen Land Groups. Both groups are characterised by sequences of black mudstone and chert, so that syngenetic enrichment of Zn (and Cu in one sample) is possible. The abundance of tectonic disturbance, however, provide favourable conditions for remobilisation and depositions of Zn in faults and fractures.

Anomalies for Zn are spatially related to Cu anomalies in Inglefield Land and in one single place in the cluster of Zn anomalies in Peary Land. Cu anomalies are associated with the Independence Fjord Group of sandstones and dolerites.

Sr anomalies make up a trend in the southern part of the shelf deposits and they have been spatially related to the occurrence of evaporites within dolomites of the middle Ordovician Cape Webster Formation (Steenfelt 1985). This is interesting in the context of evaluating the Zn potential because evaporites provide evidence for the existence of brines that may be an important participant in the formation of sedex type deposits. The isolated Sr anomaly in the Wandel Sø Basin on the east coast of Kronprins Christians Land has not been explained.

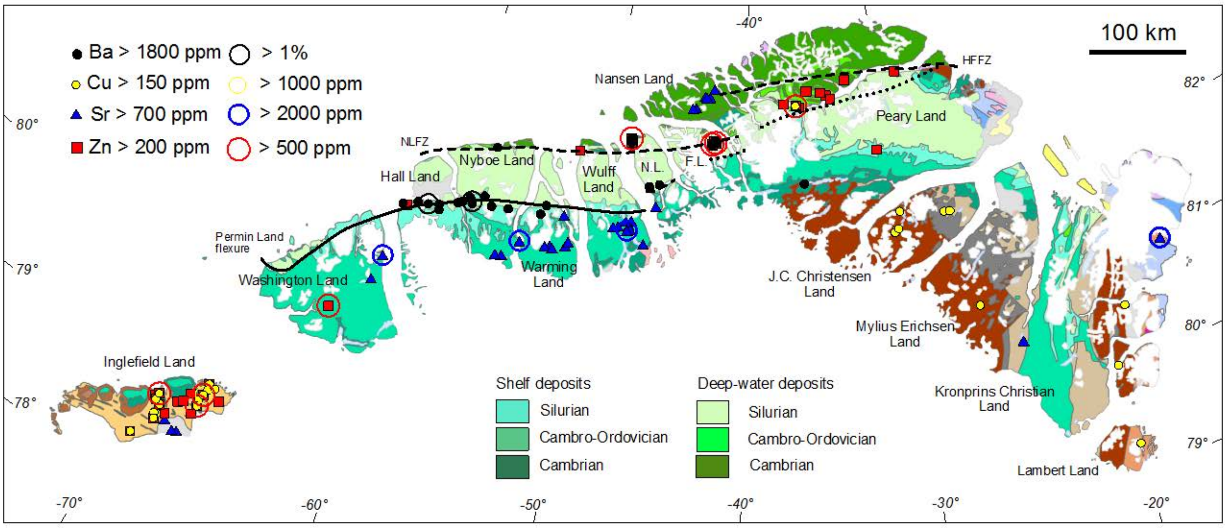


Figure 39. *Stream sediment anomalies on map of major litho-stratigraphical units of North Greenland modified from Escher & Pulvertaft (1995). The legend refers to the Franklinian Basin, other units are the same as in Figure 1. Major tectonic lineaments as depicted in Surlyk and Hurst (1983, figure 23) include the Nyboe Land fault zone (NLFZ), the Permin Land flexure, the Navarana fault (dotted lines) and Harder Fjord fault zone (HFFZ). N.L.: Nares Land. F.L.: Freuchen Land.*

Anomalies in Inglefield Land are mainly Zn and Cu, and they are seen in samples of the first regional sampling (Steenfelt & Dam 1996), but in particular samples of the follow-up work reported in Thomassen et al. (2000). These authors investigated copper-gold mineralisation and collected rock, stream sediment and soil samples around sulphide-mineralised sites. The Zn values in the rock samples were elevated (200 to 1000 ppm) and could, therefore, explain the values found in the surface samples. The highest values recorded in rock samples were 0.16% Zn in mafic-ultramafic-hosted sulphide mineralisation and 0.15% in paragneiss-hosted semi-massive iron sulphide mineralisation. The two Sr anomalies in Inglefield Land are associated with a syenite.

Rock samples – North Greenland

A search in the GEUS database for rock samples with registered location and analysed for Zn yielded the following result:

Method	Number of samples	Number above 1000 ppm	Number above 10000 ppm
assay	15	12	8
ICP total	414	57	16
ICP HNO3	31	3	1
XRF	106	0	0
INA	391	56	16

However, many samples have been analysed by both INA and ICP, and in fact all INA values above 1000 ppm are redundant. The INA data for Zn are not as reliable as those determined by ICP, hence the latter are preferred. The distribution of samples with Zn content indicating mineralisation is shown in Figure 40, and the data are listed in the Zn data package – North Greenland.

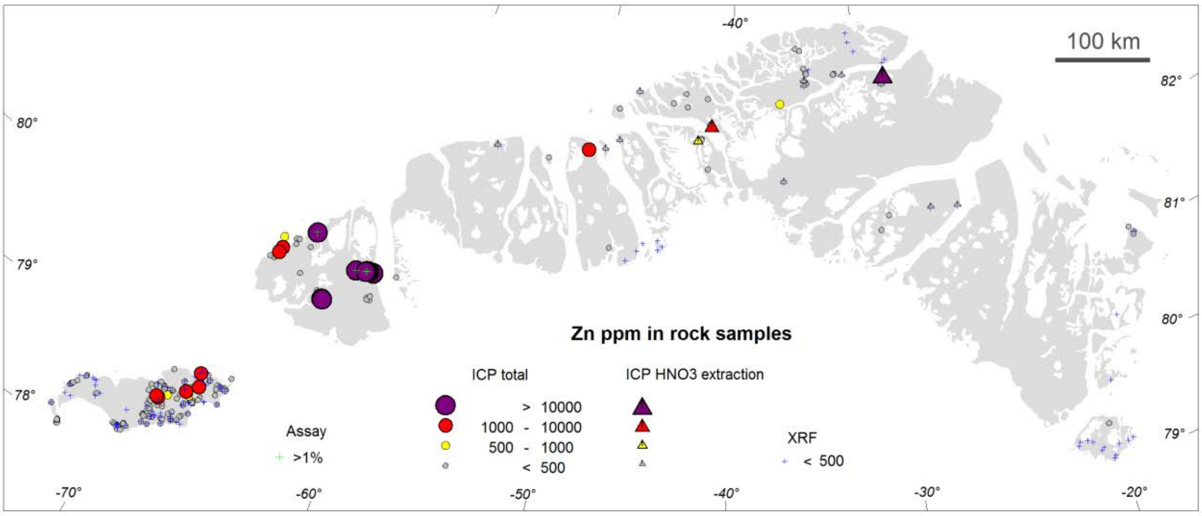


Figure 40. *Distribution of rock samples analysed for Zn by one of four different methods. Large symbols mark samples with contents indicating mineralisation.*

Summary and conclusion

Figure 41 shows all indications of Zn mineralisation in North Greenland achieved during the present project. Many of the sites, where high Zn values have been recorded in stream sediment, have been followed up and mineralisation has been ascertained in showings or prospects. The significance of the structures in localising Zn mineralisation is obvious. A Zn-Ba association characterises the anomalies and mineral occurrences along the Permin Land flexure in particular, but also along the Nyboe Land fault zone (see Figure 39 and description of mineral occurrences). This encourages continued exploration along the indicated structures, for Mississippi Valley Type mineralisation. Three additional sites of high Zn values in stream sediment or rocks are worth mentioning in this connection, northernmost Wulff Land on the Nyboe Land fault zone, western Hall Land and northern Washington Land on the Permin Land flexure.

In fact, the Ba concentrations documented in several places along the same structures seem to justify an additional potential for barite occurrences.

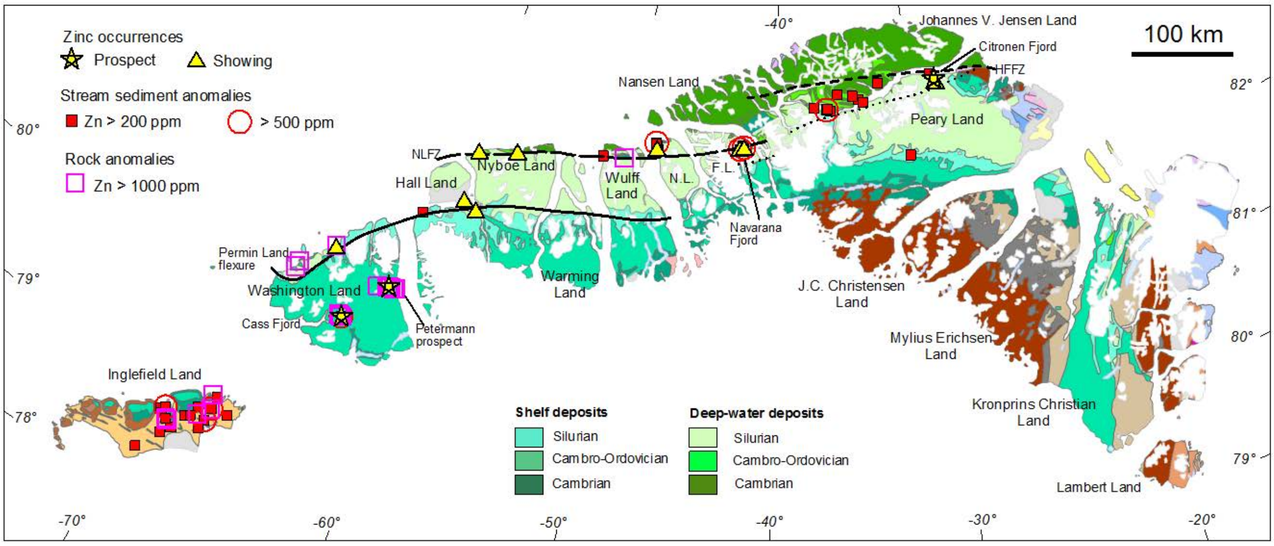


Figure 41. *Distribution of Zn anomalies and occurrences illustrating favourable trends for zinc deposits in North Greenland. Abbreviations as in figure 39.*

Two pronounced clusters of stream sediment Zn anomalies seem to warrant further inspection, the one in Inglefield Land and the other in southern Johannes V. Jensen Land between Citronen Fjord and Navarana Fjord. Our evidence collected thus far suggests that Inglefield Land with its Cu-Zn association has a potential for massive volcanogenic sulphide deposits. Less information is available for the anomalies in Johannes V. Jensen Land. Since most of the anomalous samples are from streams draining the Amundsen Land Group, the host formation of the Citronen Fjord deposit, a sedex type of occurrence somewhere in that area is a possibility that ought to be pursued.

Altogether, the compilation of data undertaken in the present project emphasises that favourable conditions have existed in extensive areas of North Greenland for the formation of several types of Zn deposits.

Acknowledgements

Large parts of the geology section of the report are based on previous work supervised by Niels Henriksen, and he is thanked for helping out and answering questions.

Many other people contributed to this report and the data package. Jens Gregersen helped retrieving samples from the sample archives, and Mojagan Alaei prepared samples for reanalyses. Mette Svane Jørgensen scanned and digitized sample locations. Frands Schjøth is thanked for constructing the ArcGIS presentation and organising the files for the data package, Thorkild Maack Rasmussen compiled the geophysical data for the data package, while Marianne Vestergaard took care of getting the data package accessible on line.

References

Carne, R.C. & Cathro, R.J. 1982: Sedimentary exhalative (sedex) zinc-lead-silver deposits, northern Canadian Cordillera: CIM Bulletin 1974, **75**, 66–78.

Christensen, J.N., Halliday, A.N., Leigh, K.E., Randell, R.N. & Kesler, S.E. 1995: Direct dating of sulphides by Rb-Sr: A critical test using the Polaris Mississippi Valley-type Zn-Pb deposit. Geochimica et Cosmochimica Acta **59**, 5191-5197.

Cope, I. & Beswick, J. 1999: Washington Land Report, 30 pp. + enclosures. Unpublished report Rio Tinto Mining and Exploration Limited, Bristol, UK (in archives of Geological Survey of Denmark and Greenland, GEUS Report File 21718).

Dawes, P.R. 2004: Explanatory notes to the Geological map of Greenland, 1:500 000, Humboldt Gletscher, Sheet 6. Geological Survey of Denmark and Greenland Map Series **1**, 48 pp + map.

Dawes, P.R., Frisch, T., Garde, A.A., Iannelli, T.R., Ineson, J.R., Jensen, S.M., Pirajno, F., Sønderholm, M., Stemmerik, L., Stouge, S., Thomassen, B. & van Gool, J.A.M. 2000: Kane Basin 1999: mapping, stratigraphic studies and economic assessment of Precambrian and Lower Palaeozoic provinces in north-western Greenland. Geology of Greenland Survey Bulletin **186**, 11–28.

Emsbo, P. 2009: Geologic Criteria for the Assessment of Sedimentary Exhalative (Sedex) Zn-Pb-Ag Deposits. USGS Open File Report **2009-1209**, 25 pp.

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

Ford, D.C. 1986: Genesis of paleokarst and strata-bound zinc-lead sulphide deposits in a Proterozoic dolostone, Northern Baffin Island, Canada – A discussion. Economic Geology **81**, 1562-1563.

Gibbins, W.A. 1991: Economic mineral resources, Arctic Islands. In Trettin, H.P. (ed.) Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland. Geology of Canada **3**, 533–539. Ottawa: Geological Survey of Canada.

Ghisler, M., Henriksen, N., Steenfelt, A. & Stendal, H. 1979: A reconnaissance geochemical survey in the Proterozoic-Phanerozoic platform succession of the Peary Land region, North Greenland. Rapport Grønlands Geologiske Undersøgelse **88**, 85–91.

Ghisler, M. & Stendal, H. 1980: Geochemical and ore microscopic investigations on drainage sands from the Peary Land region, North Greenland. Rapport Grønlands Geologiske Undersøgelse **99**, 121–128.

Henriksen, N. 1980: Collection of stream sediments for a reconnaissance geochemical survey from the Peary Land region, North Greenland. Rapport Grønlands Geologiske Undersøgelse **99**, 119–120.

Henriksen, N. 1992: Descriptive text to 1:500 000 sheet 7, Nyeboe Land, and sheet 8, Peary Land, 40 pp. Copenhagen: Geological Survey of Greenland.

Henriksen, N. 2005: Grønlands geologiske udvikling fra urtid til nutid. Geological Survey of Denmark and Greenland, Ministry of Environment.

Henriksen, N., Higgins, A.K., Kalsbeek, F. & Pulvertaft, T.C. 2000:Greenland from Archaean to Quaternary. Descriptive text to the Geological map of Greenland 1:2 500 000. Geology og Greenland Survey Bulletin **185**, 93pp.

Higgins, A. K., Ineson, J. R., Peel, J. S., Surlyk, F. & Sønderholm, M. 1991a: Lower Palaeozoic Franklinian Basin of North Greenland. Geology of Greenland Survey Bulletin **160**, 71–139.

Higgins, A.K., Ineson, J.R., Peel, J.S., Surlyk, F. & Sønderholm, M. 1991b: Cambrian to Silurian basin development and sedimentation, North Greenland. In Trettin, H.P. (ed.). The Innuitian orogen and arctic platform of Canada and Greenland. Geology of Canada **3**, 111–161 (also The geology of North America E). Calgary: Geological Survey of Canada.

Iannelli, T.R. 1999: Preliminary report on the results of field work: Kane Basin project, northwestern Greenland, 24 pp. Unpublished report TRI-EX Consultants Ltd., London, Ontario, Canada (in archives of Geological Survey of Denmark and Greenland, GEUS File report 21851).

Iannelli, T.R. 2002: A review of Cass Fjord Formation stratigraphy and Cambro-Ordovician carbonate-hosted base metal mineralization, Washington Land, north-western Greenland, 32 pp. Unpublished report TRI-EX Consultants Ltd., London, Ontario, Canada (in archives of Geological Survey of Denmark and Greenland, GEUS File report 21852).

Jakobsen, U.H. 1989a: Hydrated iron sulphate occurrences at Navarana fjord, Central North Greenland. Bulletin of the Geological Society of Denmark **37**, 175–180.

Jakobsen, U.H. 1989b: Geochemical stream sediment and overburden surveys of a zinc- and barium-mineralized area, Freuchen Land, central North Greenland. Journal of Geochemical Exploration **31**, 117–134.

Jakobsen, U.H. & Steenfelt, A. 1985: Zinc mineralisation at Navarana Fjord, central North Greenland. Rapport Grønlands Geologiske Undersøgelse **126**, 105–109.

Jakobsen, U.H. & Stendal, H. 1987: Geochemical exploration in central and western North Greenland. Rapport Grønlands Geologiske Undersøgelse, **133**, 113–121.

Jakobsen, U. & Ohmoto, H. 1993: Bitumen associated with precipitation of sulphides in carbonate-hosted vein mineralization, North Greenland. In: Parnell, J., Kucha, H. & Landais, P. (eds): Bitumens in ore deposits **9**: Berlin, Heidelberg: Springer-Verlag, 399–414.

Jensen, S.M. 1995: Re-analysis of ‘old’ stream sediment samples from North Greenland: comparison of old and new data, assessment of results and recommendations. Grønlands Geologiske Undersøgelse Internal Report, 16 pp.,101 figs.

Jensen, S.M. 1998: Carbonate-hosted Zn-Pb-Ag mineralisation in Washington Land, western North Greenland. Geology of Greenland Survey Bulletin **180**, 67–72.

Jensen, S.M. & Schønwandt, H.K. 1998: A new carbonate-hosted Zn-Pb-Ag occurrence in Washington Land, western North Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **1998/3**, 31 pp.

Kalsbeek, F. & Jepsen, H.F. 1983: The Midsommersø Dolerites and associated intrusions in the Proterozoic platform of eastern North Greenland – a study of the interaction between intrusive basic magma and sialic crust. Journal of Petrology **24**, 605–634.

Kalsbeek, F., Nutman, A.P., Escher, J.C., Friderichsen, J.D., Hull, J.M., Jones, K.A. & Pedersen, S.A.S. 1999: Geochronology of granitic and supracrustal rocks from the northern part of the East Greenland Caledonides: ion microprobe U-Pb zircon ages. Geology of Greenland Survey Bulletin 184, 31–48.

Kragh, K. 1996: Geologisk setting og teksturelle undersøgelser af Citronen Fjord ekshalative sulfidforekomst, Nordgrønland, 62 pp. Unpublished M.Sc. thesis, Aarhus Universitet, Denmark.

Kragh, K. 2000: The Citronen Fjord sedimentary exhalative sulphide deposit, North Greenland. A study of primary and diagenetic textures, oxygen and carbon isotopes, and fluid inclusions, 277 pp. Unpublished Ph.D. thesis, University of Copenhagen and Geological Survey of Denmark and Greenland.

Leach, D.L. & Taylor, R.D. 2009: Mississippi Valley-Type Lead-Zinc Deposit Model. USGS Open File Report **2009-1213**, 8 pp.

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

Olson, R.A. 1984: Genesis of paleokarst and strata-bound zinc-lead sulphide deposits in a Proterozoic dolostones, Northern Baffin Island, Canada. Economic Geology **79**, 1056-1103.

Olson, R.A. 1986: Genesis of paleokarst and strata-bound zinc-lead sulphide deposits in a Proterozoic dolostones, Northern Baffin Island, Canada a reply. Economic Geology **81**, 1563-1566.

Peel, J.S. & Sønderholm, M. (eds) 1991: Sedimentary basins of North Greenland. Geology of Greenland Survey Bulletin **160**, 164 pp.

Pirie, J., Valle, G.D., van der Stijl, F., Coppard, J. & Andersen, E. 1999: Report on August 1998 exploration activity, Washington Land Project, 21 pp. + enclosures. Unpublished report, Platinova A/S, Nuuk, Greenland (in archives of Geological Survey of Denmark and Greenland, GEUS Report File 21833).

Shanks III, W.C.P., Dusel-Bacon, C., Koski, R., Morgan, L.A., Mosier, D., Piatak, N.M., Ridley, I., Seal, R.R., Schulz, K.J., Slack, J.F. & Thurston, R. 2009: A New Occurrence Model for National Assessment of Undiscovered Volcanogenic Massive Sulfide Deposits. USGS Open File Report **2009-1235**, 31 pp.

Steenfelt, A. 1976: Reconnaissance drainage sampling for geochemical exploration, Washington Land, 1976. Grønlands Geologiske Undersøgelse Internal Report, 7 pp., 7 tables, 6 figs.

Steenfelt, A. 1980: The geochemistry of stream silt, North Greenland. Rapport Grønlands Geologiske Undersøgelse **99**, 129–135.

Steenfelt, A. 1985: Reconnaissance scale geochemical survey in central and western North Greenland. Preliminary results concerning zinc and barium. Rapport Grønlands Geologiske Undersøgelse **126**, 95–104.

Steenfelt, A. 1987a: Geochemical trends in central and western North Greenland. Rapport Grønlands Geologiske Undersøgelse **133**, 123–132.

Steenfelt, A. 1987b: Geochemical mapping and prospecting in Greenland - a review of results and experience. Journal of Geochemical Exploration **29**, 183–205.

Steenfelt, A. 1991: Economic mineral resources, North Greenland. In: Trettin, H.P. (ed.): Geology of the Innuitian orogen and Arctic Platform of Canada and Greenland. Geology of Canada **3**, 539–541. Ottawa: Geological Survey of Canada (also The geology of North America E, Geological Society of America).

Steenfelt, A. & Dam, E. 1996: Reconnaissance geochemical mapping of Inglefield Land, North-West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **1996/12**, 27 pp., 49 maps.

Steenfelt, A. 1999: Compilation of data sets for a geochemical atlas of West and South Greenland based on stream sediment surveys 1977 to 1997. Danmarks og Grønlands Geologiske Undersøgelse Rapport **1999/41**, 33 pp.

Steenfelt, A. 2001a: Calibration of stream sediment data from West and South Greenland. A supplement to GEUS Report 1999/41. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2001/47**, 43 pp.

Steenfelt, A. 2001b: Geochemical atlas of Greenland - West and South Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2001/46**, 39 pp., 1 CD-ROM.

Surlyk, F. & Hurst, J.M. 1983: Evolution of the early Paleozoic deep-water basin of north Greenland - aulacogen or narrow ocean? Geology **11**, 77–81.

Symons D. T. A. & Sangster D. F. 1992: Late Devonian paleomagnetic age for the Po-laris Mississippi Valley-type Zn-Pb deposit, Canadian Arctic Archipelago. Canadian Journal of Earth Science **29**, 15-25.

Symons D. T. A., Symons, T.B. & Sangster D. F. 2000: Paleomagnetism of the Society Cliffs dolostone and the age of the Nanisivik zinc deposits, Baffin Island, Canada. Mineralium Deposita **35**, 672-682.

Thomassen, B. 2007: The lead and zinc potential of the Franklinian Basin in North Greenland. Fact Sheet **15**, 2 pp. Nuuk and Copenhagen: Bureau of Minerals and Petroleum & Geological Survey of Denmark and Greenland.

Thomassen, B. & Dawes, P.R. 1996: Inglefield Land 1995: geological and economic reconnaissance in North-West Greenland. Bulletin Grønlands Geologiske Undersøgelse **172**, 62–68.

Thomassen, B., Pirajno, F., Iannelli, T.R., Dawes, P.R. & Jensen, S.M. 2000: Economic geology investigations in Inglefield Land, North-West Greenland: part of the project Kane Basin 1999. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2000/100**, 98 pp.

Upton, B.G.J., Rämö, O.T., Heaman, L.M., Blichert-Toft, J., Kalsbeek, F., Barry, T.L. & Jepsen, H.F. 2005: The Mesoproterozoic Zig-Zag Dal Basalts and associated intrusions of eastern North Greenland: mantle plume-lithosphere interaction. Contributions to Mineralogy and Petrology **149**, 40-56.

Van der Stijl, F.W. & Mosher, G.Z. 1998: The Citronen Fjord massive sulphide deposit, Peary Land, North Greenland: discovery, stratigraphy, mineralization and structural setting. Geology of Greenland Survey Bulletin **179**, 44 pp.

von Guttenberg, R. & van der Stijl, F. 1993: Nanisivik Mines Ltd., Platinova A/S. NorthGreenland project 1992, report of work. January 1993. Internal report, Strathcona Mineral Services Ltd., 65 pp., 12 app., 8 plates (In archives of Geological Survey of Denmark and Greenland, GEUS Report File 21304).

Appendix 1

Zinc data package - North Greenland

This data package contains much of the current data available regarding zinc in North Greenland. Additional information can be found at our website: www.geus.dk.

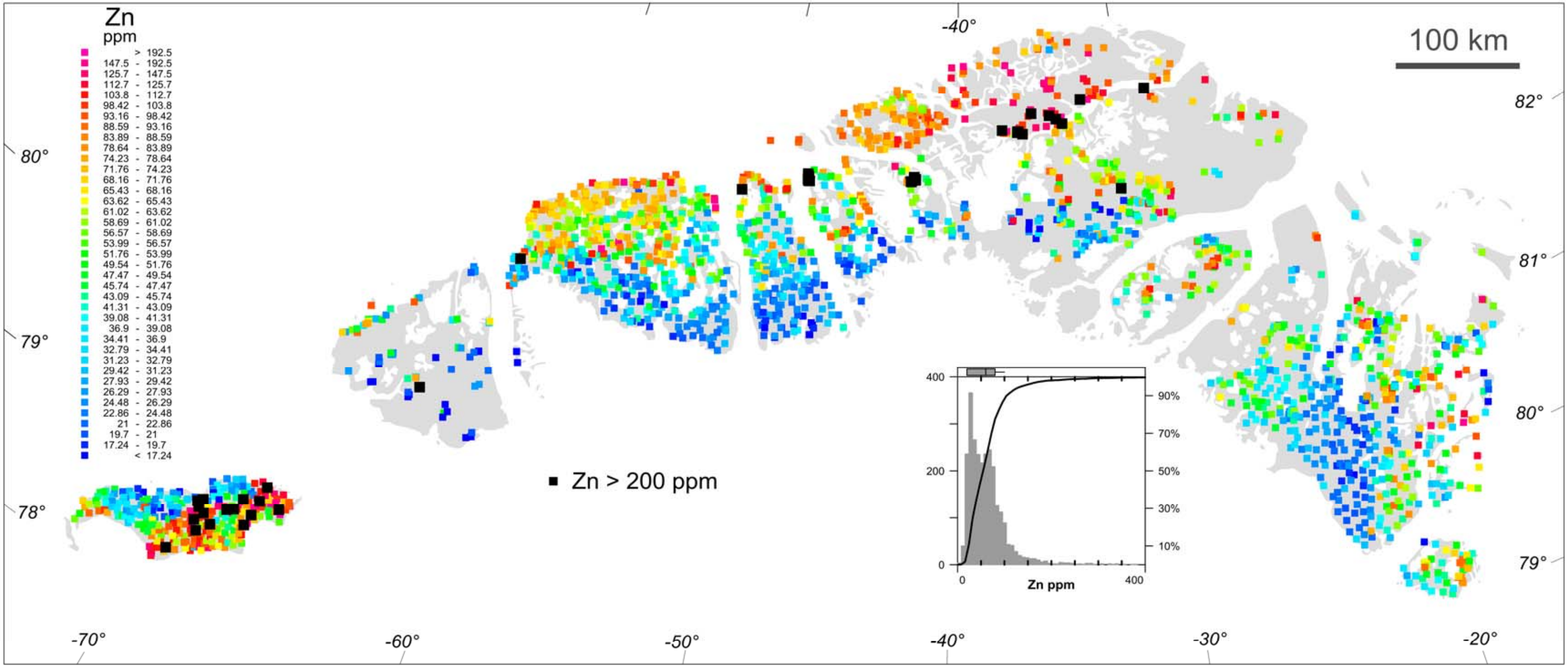
Contents

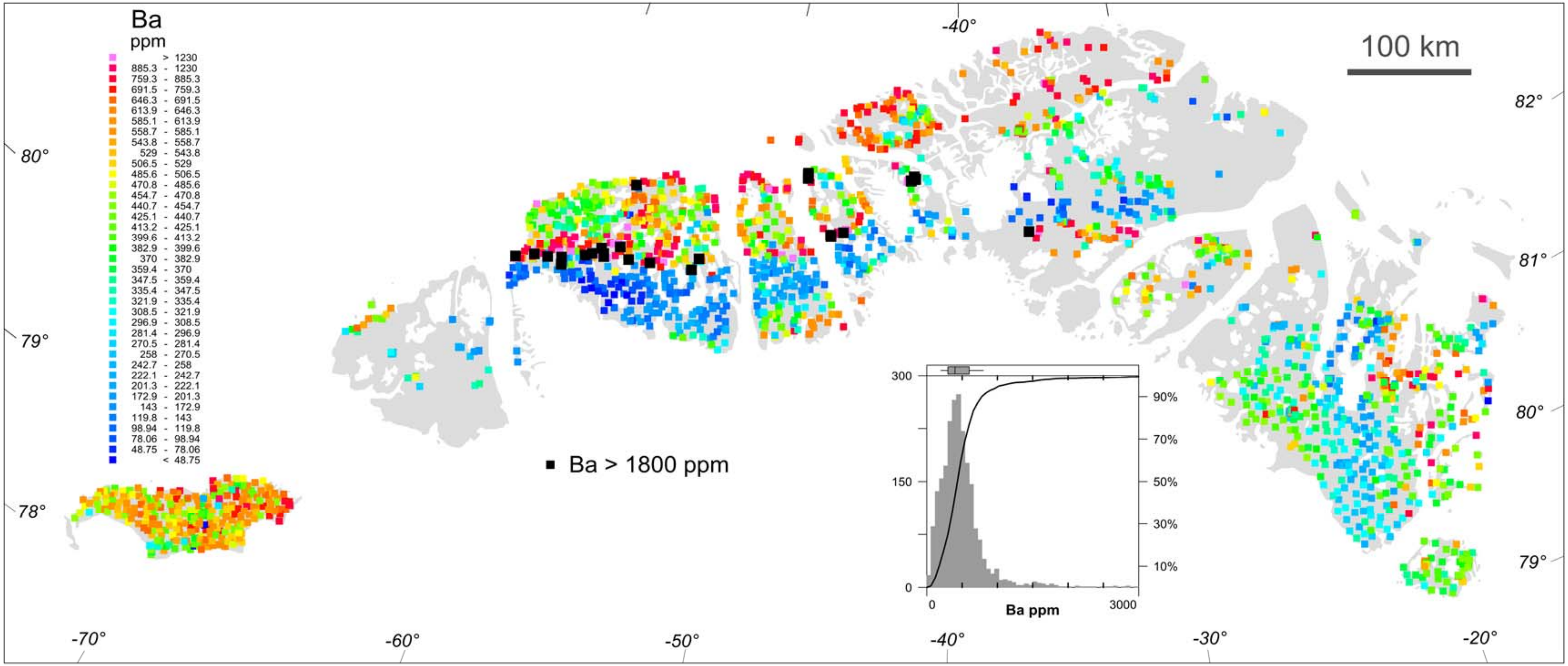
1) Geological maps of North Greenland in 1:500.000 scale (Adobe pdf files) and map descriptions
    a) Map description of Geological map no. 6. Dawes P.R. (2004): Explanatory notes to the Geological map of Greenland, 1:500 000, Humboldt Gletscher, Sheet 6. Geological Survey of Denmark and Greenland Map Series 1.
    b) Map description of Geological map no. 7 and 8. Henriksen N. (1992): Descriptive text to 1:500 000 sheet 7, Nyeboe Land, and sheet 8, Peary Land. Copenhagen: Grønlands Geologiske Undersøgelse.
    c) Geological map sheet no. 6, Humboldt Gletscher incl. legend
    d) Geological map sheet no. 7, Nyeboe Land
    e) Legend – map sheet no. 7
    f) Geological map sheet no. 8, Peary Land
    g) Legend – map sheet no. 8
    h) Geological map sheet no. 9, Lambert Land incl. legend
2) Mineral occurrences
    a) List of all known mineral occurrences in the area
    b) Descriptions of the individual mineral occurrences
3) Geochemistry
    a) Rock samples
        1. Note on the rock sample data
        2. Excel files containing tables of Zn values
        3. Geochemical maps for Zn, Ba, Cu, Pb, Cd and Co
    b) Stream sediment samples
        1. Note on the stream sediment sample data
        2. Various anomaly maps of Zn, Cu, Ba, Sr, K and Ca
        3. Scanned location maps
        4. Excel files containing tables of geochemistry
4) Summary of geophysical data
    a) Report on Geophysical data
    b) AEM Greenland 1994-1998
        1. GEUS Report 2001/58 on AEM Greenland 1994-1998 project, including instruction for Quick View.
        2. Quick View of AEM Greenland 1994-1998 data in Internet Explorer. Information on all AEM surveys is included. Click on the specific area to get information.
5) ArcGIS data presentation (map of the geology in 1:500.000)
6) ArcGIS data presentation with digital data (at cost)
7) Zinc potential in North Greenland. Thrane, K., Steenfelt, A. & Kalvig, P. 2011: Zinc potential in North Greenland. Danmark og Grønland Geologiske Undersøgelse Rapport **2011/143**, 64pp.

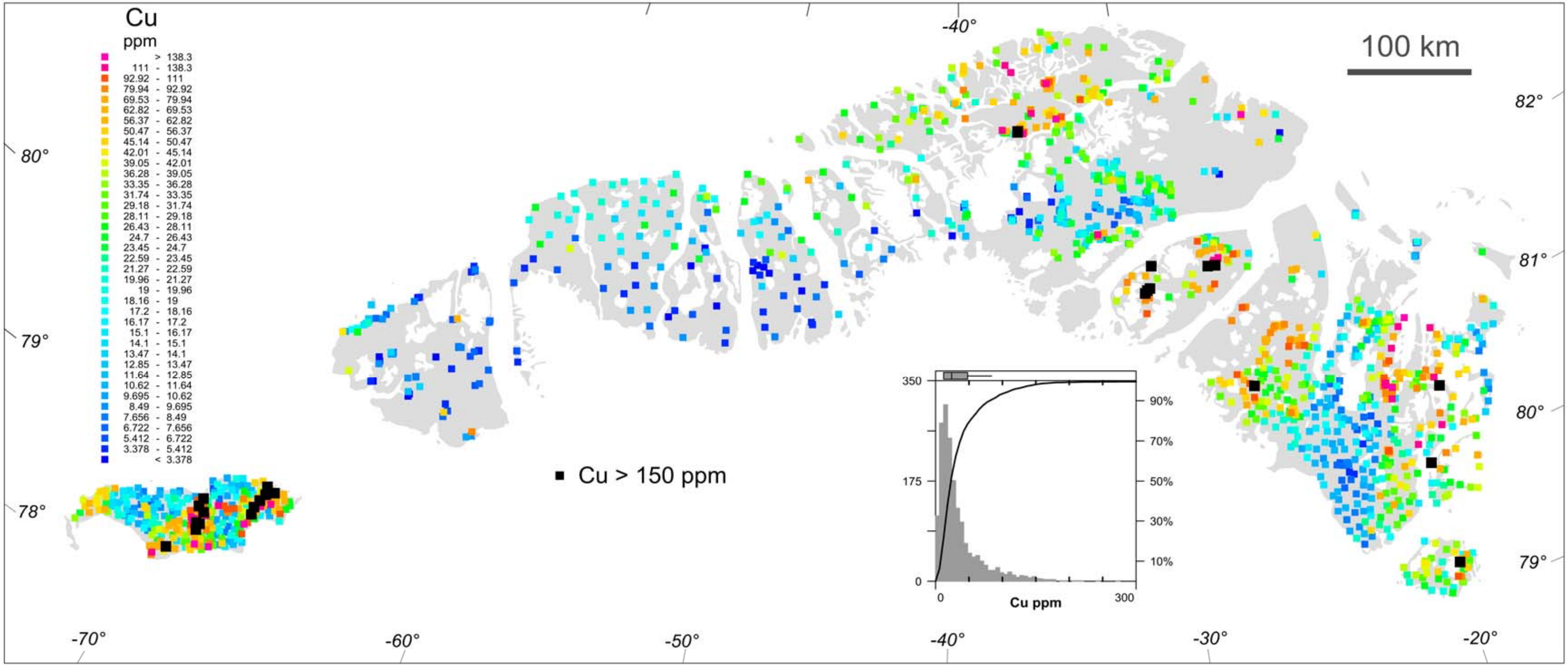
- The AEM data summarized in 4.b (AEM Greenland 1994-1998) can be purchased for 25.000 DKK for each survey.
- An ArcGIS presentation of available data is included in the zinc data package (item 5). The corresponding digital geological and topographical data (item 6), can be purchased for 11.000 DKK. For ordering digital data (item 6), please send an e-mail to: petromalm@geus.dk

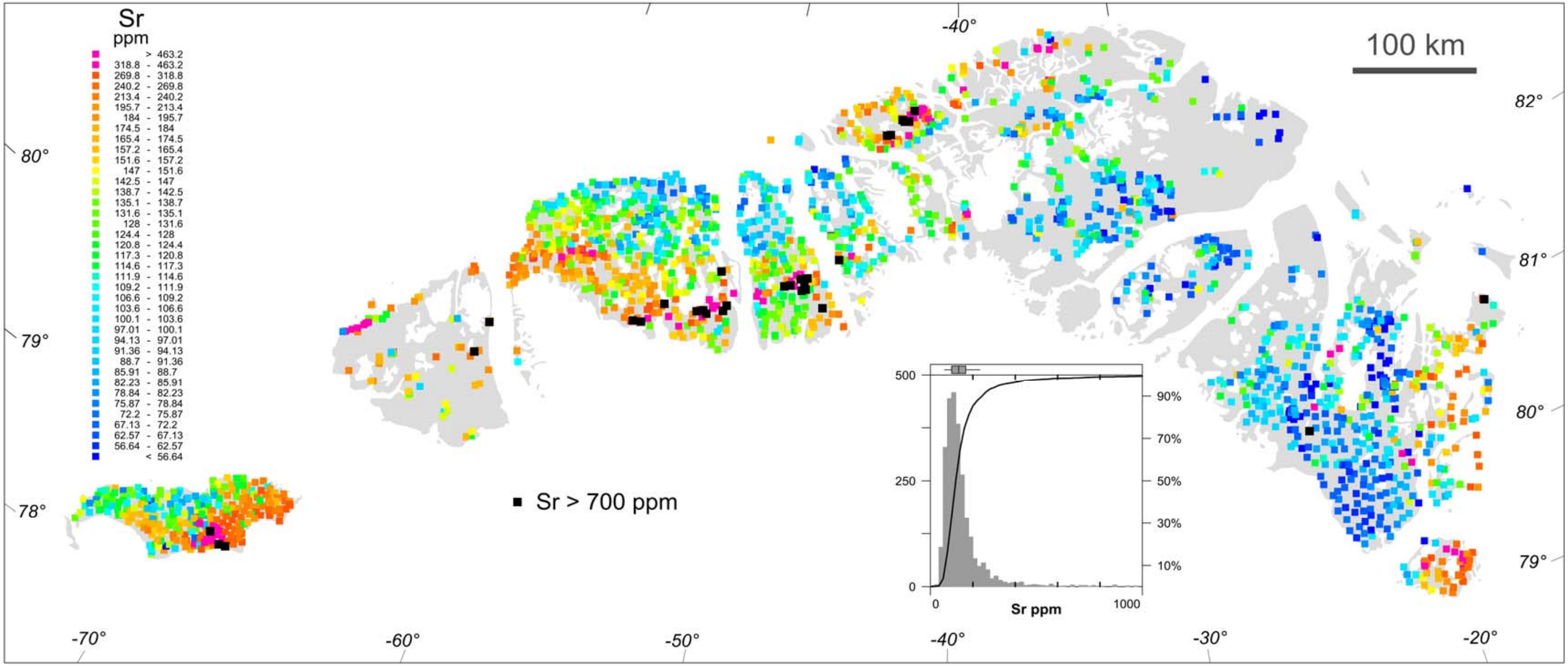
Appendix 2

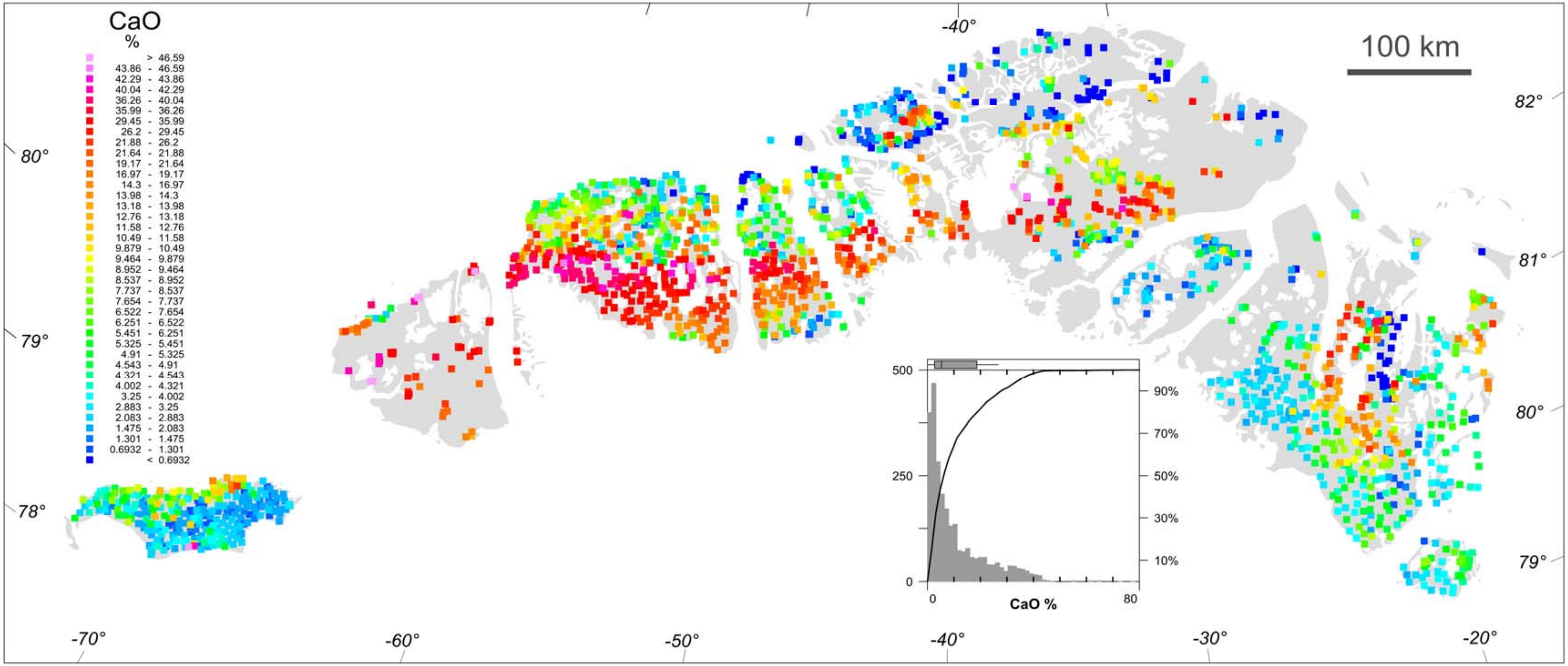
Geochemical maps of Zn, Ba, Cu, Sr, CaO and K_2O based on fine fraction of stream sediment samples

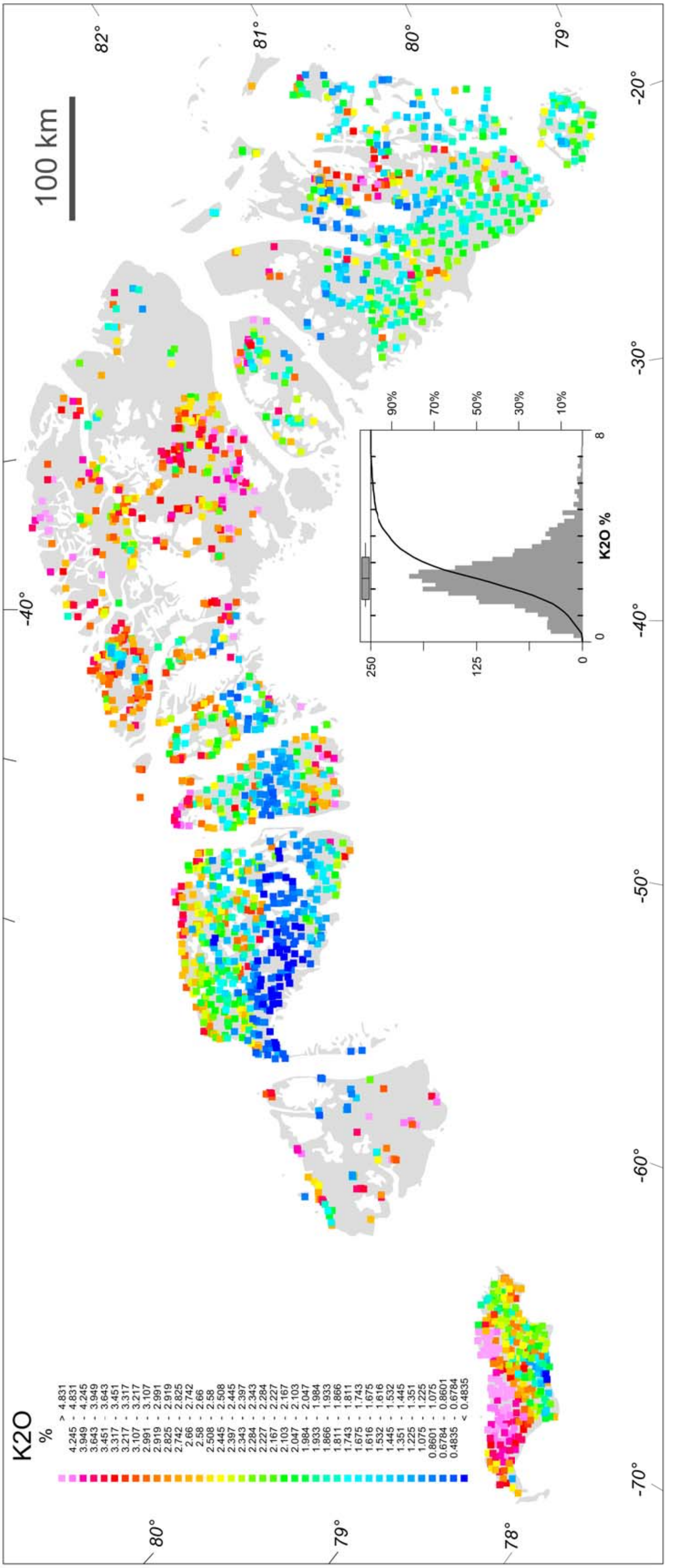

Zn
ppm
> 192.5
147.5 - 192.5
125.7 - 147.5
112.7 - 125.7
103.8 - 112.7
98.42 - 103.8
93.16 - 98.42
88.59 - 93.16
83.89 - 88.59
78.64 - 83.89
74.23 - 78.64
71.76 - 74.23
68.16 - 71.76
65.43 - 68.16
63.62 - 65.43
61.02 - 63.62
58.69 - 61.02
56.57 - 58.69
53.99 - 56.57
51.76 - 53.99
49.54 - 51.76
47.47 - 49.54
45.74 - 47.47
43.09 - 45.74
41.31 - 43.09
39.08 - 41.31
36.9 - 39.08
34.41 - 36.9
32.79 - 34.41
31.23 - 32.79
29.42 - 31.23
27.93 - 29.42
26.29 - 27.93
24.48 - 26.29
22.86 - 24.48
21 - 22.86
19.7 - 21
17.24 - 19.7
< 17.24
■ Zn > 200 ppm
100 km
-40°
82°
81°
80°
79°
80°
79°
78°
-70°
-60°
-50°
-40°
-30°
-20°
400
200
0
0
400
Zn ppm
90%
70%
50%
30%
10%


Ba
ppm
> 1230
885.3 - 1230
759.3 - 885.3
691.5 - 759.3
646.3 - 691.5
613.9 - 646.3
585.1 - 613.9
558.7 - 585.1
543.8 - 558.7
529 - 543.8
506.5 - 529
485.6 - 506.5
470.8 - 485.6
454.7 - 470.8
440.7 - 454.7
425.1 - 440.7
413.2 - 425.1
399.6 - 413.2
382.9 - 399.6
370 - 382.9
359.4 - 370
347.5 - 359.4
335.4 - 347.5
321.9 - 335.4
308.5 - 321.9
296.9 - 308.5
281.4 - 296.9
270.5 - 281.4
258 - 270.5
242.7 - 258
222.1 - 242.7
201.3 - 222.1
172.9 - 201.3
143 - 172.9
119.8 - 143
98.94 - 119.8
78.06 - 98.94
48.75 - 78.06
< 48.75
■ Ba > 1800 ppm
100 km
-40°
82°
81°
80°
79°
80°
79°
78°
-70°
-60°
-50°
-40°
-30°
-20°
300
150
0
0
3000
Ba ppm
90%
70%
50%
30%
10%


Cu
ppm
> 138.3
111 - 138.3
92.92 - 111
79.94 - 92.92
69.53 - 79.94
62.82 - 69.53
56.37 - 62.82
50.47 - 56.37
45.14 - 50.47
42.01 - 45.14
39.05 - 42.01
36.28 - 39.05
33.35 - 36.28
31.74 - 33.35
29.18 - 31.74
28.11 - 29.18
26.43 - 28.11
24.7 - 26.43
23.45 - 24.7
22.59 - 23.45
21.27 - 22.59
19.96 - 21.27
19 - 19.96
18.16 - 19
17.2 - 18.16
16.17 - 17.2
15.1 - 16.17
14.1 - 15.1
13.47 - 14.1
12.85 - 13.47
11.64 - 12.85
10.62 - 11.64
9.695 - 10.62
8.49 - 9.695
7.656 - 8.49
6.722 - 7.656
5.412 - 6.722
3.378 - 5.412
< 3.378
100 km
■ Cu > 150 ppm
350
175
0
0
300
Cu ppm
90%
70%
50%
30%
10%
80°
79°
78°
82°
81°
80°
79°
-40°
-70°
-60°
-50°
-40°
-30°
-20°


Sr
ppm
> 463.2
318.8 - 463.2
269.8 - 318.8
240.2 - 269.8
213.4 - 240.2
195.7 - 213.4
184 - 195.7
174.5 - 184
165.4 - 174.5
157.2 - 165.4
151.6 - 157.2
147 - 151.6
142.5 - 147
138.7 - 142.5
135.1 - 138.7
131.6 - 135.1
128 - 131.6
124.4 - 128
120.8 - 124.4
117.3 - 120.8
114.6 - 117.3
111.9 - 114.6
109.2 - 111.9
106.6 - 109.2
103.6 - 106.6
100.1 - 103.6
97.01 - 100.1
94.13 - 97.01
91.36 - 94.13
88.7 - 91.36
85.91 - 88.7
82.23 - 85.91
78.84 - 82.23
75.87 - 78.84
72.2 - 75.87
67.13 - 72.2
62.57 - 67.13
56.64 - 62.57
< 56.64
■ Sr > 700 ppm
100 km
-40°
80°
79°
78°
82°
81°
80°
79°
-70°
-60°
-50°
-40°
-30°
-20°
500
250
0
0
1000
Sr ppm
90%
70%
50%
30%
10%


CaO
%
> 46.59
43.86 - 46.59
42.29 - 43.86
40.04 - 42.29
36.26 - 40.04
35.99 - 36.26
29.45 - 35.99
26.2 - 29.45
21.88 - 26.2
21.64 - 21.88
19.17 - 21.64
16.97 - 19.17
14.3 - 16.97
13.98 - 14.3
13.18 - 13.98
12.76 - 13.18
11.58 - 12.76
10.49 - 11.58
9.879 - 10.49
9.464 - 9.879
8.952 - 9.464
8.537 - 8.952
7.737 - 8.537
7.654 - 7.737
6.522 - 7.654
6.251 - 6.522
5.451 - 6.251
5.325 - 5.451
4.91 - 5.325
4.543 - 4.91
4.321 - 4.543
4.002 - 4.321
3.25 - 4.002
2.883 - 3.25
2.083 - 2.883
1.475 - 2.083
1.301 - 1.475
0.6932 - 1.301
< 0.6932
100 km
-40°
82°
81°
80°
79°
78°
-70°
-60°
-50°
-30°
-20°
500
250
0
90%
70%
50%
30%
10%
0
80
CaO %


K2O
%
> 4.831
4.245 - 4.831
3.949 - 4.245
3.643 - 3.949
3.451 - 3.643
3.317 - 3.451
3.217 - 3.317
3.107 - 3.217
2.991 - 3.107
2.919 - 2.991
2.825 - 2.919
2.742 - 2.825
2.66 - 2.742
2.58 - 2.66
2.508 - 2.58
2.445 - 2.508
2.397 - 2.445
2.343 - 2.397
2.284 - 2.343
2.227 - 2.284
2.167 - 2.227
2.103 - 2.167
2.047 - 2.103
1.984 - 2.047
1.933 - 1.984
1.866 - 1.933
1.811 - 1.866
1.743 - 1.811
1.675 - 1.743
1.616 - 1.675
1.532 - 1.616
1.445 - 1.532
1.351 - 1.445
1.225 - 1.351
1.075 - 1.225
0.8601 - 1.075
0.6784 - 0.8601
0.4835 - 0.6784
< 0.4835
100 km
82°
81°
80°
79°
-20°
-30°
-40°
-50°
-60°
-70°
80°
79°
78°
250
125
0
0
8
K2O %
90%
70%
50%
30%
10%