Magmatic platinum-nickel occurrences in the Tertiary West Greenland Basalt Province: prospecting by Greenex A/S in 1985-1988

Finn Ulff-Møller

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April 1991

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Ujarassiortut Kalaallit Nunaanni Misissuisoqarfiat
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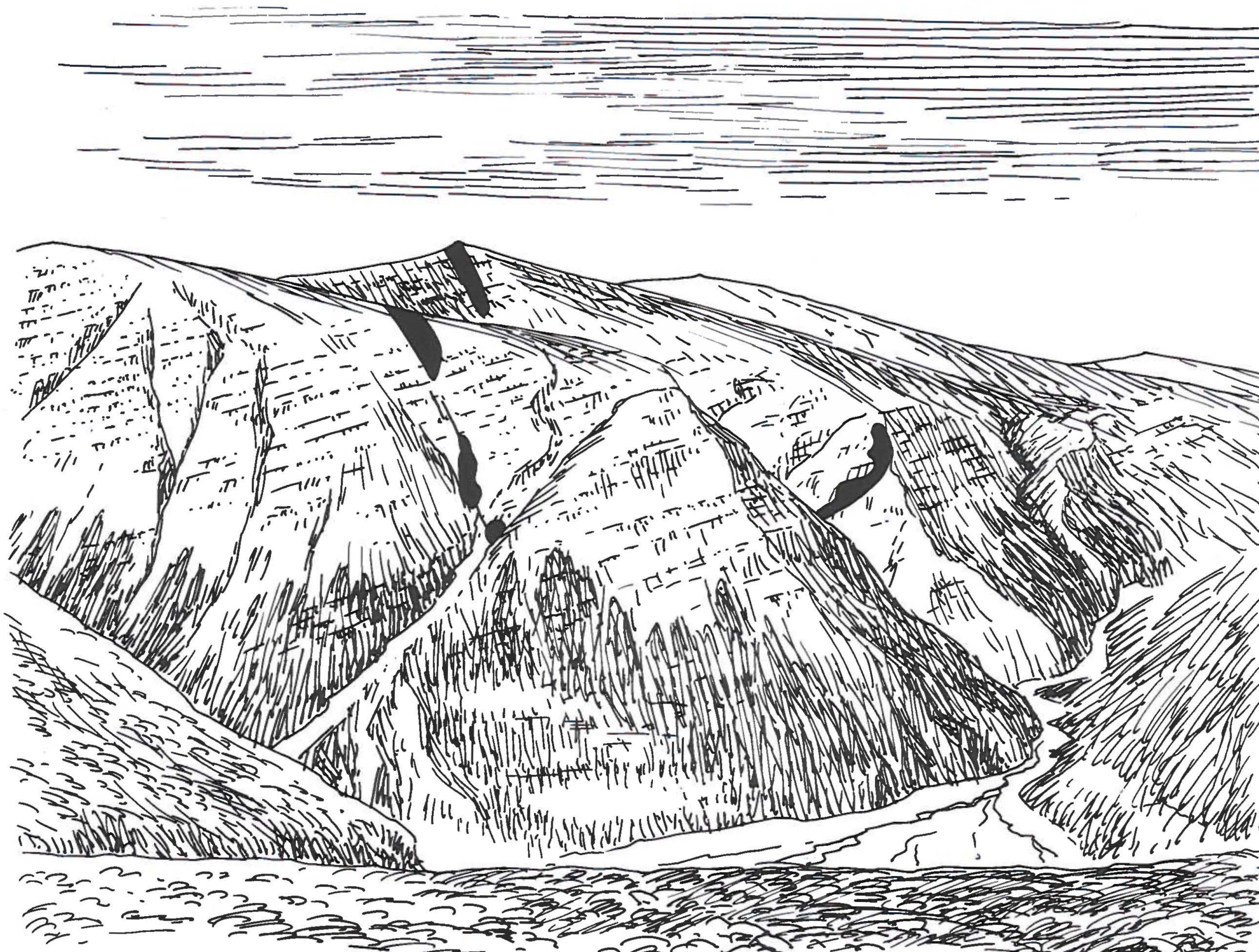

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Frontispiece: Hammer Dal, north-west Disko, viewed from the south. The subvolcanic Hammers Dal Complex, intruded into plateau basalts, is outlined in black. Drawn from a photography by Bodil Sikker Hansen.

ABSTRACT

Mafic and ultramafic magmas, which are potential carriers of Co, Ni and Cu and platinum group elements (PGE), were erupted in vast volumes in the West Greenland Basalt Province. Part of the magmas reacted with sulphur-rich carbonaceous sediments precipitating sulphide-rich liquid and metallic iron and produced Co, Ni, Cu and PGE bearing metallic iron and sulphide deposits which have been found in lavas and subvolcanic intrusions.

With this background Greenex A/S prospected for PGE ore deposits in 1985-1988. The prospecting comprised geophysical surveys, a panning programme and traditional geological field work. Traditional field work proved the most efficient to localize contaminated rocks in this generally well-exposed area: five contaminated lava sequences were traced throughout a large part of the Nûgssuaq peninsula and some contaminated dykes were discovered. Ten new occurrences of metallic iron and sulphides were discovered - two in a lava on Nûgssuaq and eight in dykes and subvolcanic intrusions on Disko. Among the geophysical methods employed, electromagnetic ground surveying was the most efficient for tracing subsurface mineralization.

A total of 288 grab and chip samples were analysed for Cr, Co, Ni, Cu and precious metals (Pt, Pd, Os, Ir, Ag and Au) which lead to identification of 16 Pt-Pd anomalies (>15 ppb Pt and >10 ppb Pd). Analyses from the most prominent and most intensely sampled occurrence, the Hammers Dal Complex, have a Pt/Ni ratio that is more than a factor 10 lower than previous records. This suggests that serious problems may be connected with sampling, preparation or analysis of the metallic iron bearing rocks.

Partial analyses (for TiO_2, MgO, Cr, Cu and Ni) of 314 rock samples from 26 profiles on Nûgssuaq indicate a total volume of at least 200 km^3 of contaminated lava. More than 50% of the samples are depleted for more than half of their initial Ni and Cu content by precipitation of sulphide or metallic iron. Because only a few samples are enriched in these elements, most of the extracted metals (PGE and more than 10 million tons of Ni) must occur at depth.

INTRODUCTION

Most of the World's reserves of Co, Ni and PGE (platinum group elements: Pt, Pd, Ir, Os, Ru and Rh) are derived from ultramafic and mafic igneous rocks or slices of the Earth's mantle (Desborough & Leonard, 1976) emplaced tectonically into the crust. The enrichment to ore grade concentration levels is often caused by a combination of magmatic, metamorphic, hydrothermal and weathering processes. An important magmatic process is precipitation of sulphide liquid enriched in Co, Ni, Cu and PGE by a factor 100 to more than 1000 relative to the magma. The sulphur may be of either magmatic or non-magmatic origin. Important PGE occurrences occur in minor gabbro intrusions in the Norilsk district, Siberia, where mafic magma ascended along fault systems and was trapped at the boundary between sediments and overlying plateau basalts and assimilated sulphurous sediments.

With the aim of locating Norilsk-type intrusions on the boundary between sediments and overlying plateau basalts in the West Greenland Basalt Province (Fig. 1), a regional exploration programme was initiated by Greenex A/S in 1985 that comprised an airborne magnetic and electromagnetic survey and satellite image interpretation. The investigation was followed by a regional heavy mineral panning programme, detailed magnetic, electromagnetic and gravimetric ground surveys and traditional field work in the summers of 1985, 1987 and 1988. The author participated as a consultant geologist in the summer of 1985 and part of 1987.

A final report of the exploration was never compiled by the company. This report is based on a compilation of the company reports (1985-1988) and the author's personal experience from geological mapping and prospecting in the area.

GEOLOGICAL SETTING AND PREVIOUS WORK

During the opening of the Davis Strait in late Mesozoic to early Tertiary time, basins were formed by subsidence and block faulting of the Precambrian metamorphic basement and were filled with continental and marine sediments (Fig. 2; Henderson, 1973). A seismic and gravity study of western Nûgssuaq shows the existence of >3 km sediments (Elder, 1975). In the early Tertiary, ultramafic and mafic magmas erupted as extensive picritic to basaltic lavas and pillow breccia and formed the West Greenland Basalt Province (Clarke & Pedersen, 1976). The present extent of the basalt province on land is c. 40,000 km^2 (Fig. 1); the offshore extent is somewhat larger (Denham, 1974).

The lava stratigraphy of Disko and Nûgssuaq is summarized in Fig. 3 (for geographical names see Fig. 4). The picrites represent the largest volume of ultramafic volcanics erupted in the later history of the Earth. A considerable volume of contaminated magma was formed by reaction with sulphur-rich carbonaceous sediments. Subsequent erosion has exposed more than seven contaminated lava sequences and a large number of subvolcanic intrusions which host the sulphide and metallic iron occurrences for which the province is famous. A review of previously known occurrences is given by Bøggild (1953) and Pauly (1969).

Limited prospecting occurred in the basalt province until 1985. A 15 tons sulphide lens in a dyke at Igdlukúnguaq on north-east Disko was "mined" around 1930 (Pauly, 1958), although it mainly had scientific value. The sulphide and metallic iron occurrences were also among the targets of prospecting by a Danish-Canadian company in the mid 1960s. By an electromagnetic survey at Igdlukúnguaq, they located a conductor at a depth of 70 metres but no ore body was found during subsequent drilling (Robertson et al. 1967; Huntec Ltd. 1968). They also located a metallic iron bearing dyke on the top of a hill between Hammer Dal and Giesecke Dal which must be a segment of the Hammers Dal Complex (see below). Their most important result was the investigation of the lead-zinc deposit a Mârmorilik that has been mined by Greenex A/S from 1973 to 1990.

Several new sulphide and metallic iron occurrences have been found since 1968 on Disko during a cooperative mapping programme by the Geological Museum (University of Copenhagen) and the Geological Survey of Greenland (Pedersen, 1973, 1975a, 1975b, 1977a, 1977b, 1977c, 1978, 1979, 1985a, 1985b, Pedersen et al, 1989; Pedersen & Ulff-Møller, 1980; Ulff-Møller, 1975, 1977, 1979, 1983, 1985, 1990). The occurrences occur mainly in sediment-contaminated dykes and subvolcanic intrusions. Most of the intrusions are related to extensive contaminated lavas which dominate the two youngest members of the Maligât Formation (Fig. 2 and 3) and which probably covered most of the island with a total stratigraphic thickness initially exceeding 100 to 600 m. The most important occurrence found so far is the Hammers Dal Complex on north-west Disko (Pedersen, 1975a) with an estimated 5 million tons of metallic iron with Co, Ni and trace amounts of PGE (Ulff-Møller, 1977).

GEOPHYSICAL SURVEYS

The activities in 1985 comprised a regional airborne magnetic survey (Fig. 1) and satellite image interpretation. Detail surveys and ground work focussed on north Disko in 1985 whereas the Nûssuaq peninsula was the main target in 1987 and 1988 (Fig. 5).

A regional structural analysis based on satellite image interpretation gave little new information (Stanton-Gray, 1985). A multispectral analysis of north-west Disko was unsuccesful in spotting mineralized localities, probably because one of the important test targets was mislocated or because the 80 x 80 m sized pixels on the Landsat pictures exceed the typical dimensions of the major sulphide bearing intrusions.

Airborne magnetic and electromagnetic surveys were conducted by Geoterrex Ltd (1985). A regional magnetic survey covers the south tip of Svartenhuk Halvø, Nûgssuaq, Hareøen and Disko (Fig. 1). The magnetic data were interpreted by Spector et al. (1985). Regretably, the radio altimeter used was only designed for a relief of 760 m compared to the actual topographic relief of 2000 m, so no terrain correction of the regional data was possible. A detailed magnetic and electromagnetic survey of north-west Disko (Fig. 5) was flown with 200 m ground clearance. The survey included flight lines along three major valleys (Fig. 5, lines A to C) which revealed a shallow conductor in the Kûgánguaq valley (line C) and a number of weaker conductors up to 10 km from the west coast of Disko. The data from north-west Disko show a fault-dominated pattern that requires detailed interpretation in order to reveal potential anomalies.

The Kûgánguaq anomaly (Fig. 5, loc. 5) and four other localities on north-west Disko (loc. 1-4) were investigated on the ground in 1985 with a Geometrics G-816 proton magnetometer and Apex MaxMin II electromagnetic equipment applying the UTEM method (Hendry, 1986). At the Hammers Dal Complex (loc. 1), a conductor was traced down to 400-500 m below the surface (the limit of the method, Hendry, pers. comm, 1985). The conductor is about 500 m wide and seems to be the extension of the surface exposures which are only 40 m wide. At locality 2, a conductor was located 20 m below the surface. No significant anomalies were found at loc. 3 and 4.

In 1987, an electromagnetic ground survey of fifteen line profiles in valleys on Nûgssuaq and a grid on Disko (Fig. 5) was conducted with an Apex MaxMin II and a Geonics EM-16 (Williams, 1987). Five anomalies were recommended for further investigation (Fig. 5, loc. 6-10). The most promising anomaly occurs in sediments in an erosional window through the lavas in the Tunorssuaq valley (loc. 6). On Disko, an iron bearing dyke at Giesecke Dal (at the south-west corner of loc. 4) was covered with a grid. No anomaly was found over the exposed iron cumulate but a weak conductor was located close to the strike of the dyke.

In 1988, a 2 x 2 km grid in Tunorssuaq (Fig. 5, loc. 6) was investigated in detail with a Boliden Mag-87 proton precession magnetometer, a Boliden EM-3 electromagnetic equipment and a Worden prospector gravimeter with the aim of defining a target for drilling (Sundén, 1989). Two conductors were interpreted as coal layers and a magnetic anomaly was ascribed to an exposed dyke. A general increase in the gravity field towards north-west beyond the grid is consistent with the results of Elder (1975). Interestingly, Spector et al. (1985) noticed a broad positive magnetic anomaly in that direction. The results were not found to justify drilling.

In conclusion, serious problems are caused by the severe topography and the difficulty of penetrating picrites and basalts by most of the conventional geophysical methods. So far, the electromagnetic methods have proved most effective in locating anomalies of potential interest. Considering the geological setting, electromagnetic methods with a better depth sensitivity are preferable for future investigations.

GEOLOGICAL INVESTIGATIONS

In 1985, much of the geological field work (Gannicott, 1986) was concentrated on dykes and subvolcanic intrusions on north-west Disko where most of the previously known deposits occur. In particular, the Hammers Dal Complex was remapped. A number of contaminated dykes were discovered in Hammer Dal and Morten Porsild Dal; the length of known dykes were extended by new finds and three new mineralized localities were found. At the anomaly site in Kûgánguaq, contaminated lavas belonging to Asuk and Kûgánguaq Members (Pedersen, 1985a, 1985b) were investigated.

Contaminated lava sequences on Nûgssuaq, known from scattered localities in the Vaigat Formation (Pedersen, 1978 and references herein), were traced over much of the peninsula (Fig. 2). A very dense but thin iron cumulate was (re-)discovered at Saviarqat (in Greenlandic: "small iron grains") in a contaminated lava flow. At Nûk kitdleq on the south coast of Nûgssuaq, thin feeder dykes to a graphite-rich andesite lava were located in the steep cliff. A well-known alkaline ultramafic sill south-east of Qaersut was sampled.

On Ubekendt Ejland, the largest layered gabbro intrusion in the province was sampled as well as some lavas. Svartenhuk Halvø was covered by a brief helicopter reconnaisance up to 72°N; no attention was payed to the sediment contaminated volcanics which occur along the east coast of the peninsula (T. F. D. Nielsen, pers. comm, 1990).

In 1987, the contaminated lava sequences in the Vaigat Formation on Nûgssuaq were sampled systematically in 26 profiles (Christensen, 1988) in order to estimate their economic potential and to locate their eruption sites. At least five stratigraphically different sequences occur within an area of 2000 km^2 (Fig. 2 and 3). Their extent coincides roughly with the area of large sediment thickness (Elder, 1975). With an estimated bulk volume of more than 200 km^3, they represent a significant increase of the contaminated lava volume in the Vaigat Formation (Pedersen, 1985a; 1985b). The extent of the lowermost contaminated lava series is restricted to the westernmost part of the area where it entered the water and formed pillow breccia. The overlying series gradually extends further towards the east before entering pillow breccia facies and the uppermost contaminated lava series rests on gneiss and Tertiary sediments south-east of Qaersut. The middle lava series correlates with the Asuk Member on Disko (Pedersen et al. 1988). The uncontaminated picrite lavas overlying the uppermost contaminated lava sequence is more TiO_2-rich at constant MgO, a characteristic of the upper part of the Vaigat Formation (Fig. 3; Pedersen, 1985a). A second iron cumulate was found at Saviarqat. A lava with a poor iron cumulate extending for more than 300 m in the Vaigat Formation was investigated in Stordal on Disko. Some additional dykes were discovered in Hammer Dal and Morten Porsild Dal; one of the latter contains an iron cumulate.

GEOCHEMISTRY

The collected samples comprise stream sediments (340), soil samples (58) and more than 700 grab or chip samples of rocks.

In 1985, 271 sediment samples were collected during a regional panning programme covering Svartenhuk Halvø, Ubekendt Ejland, Nûgssuaq and northern, central and eastern Disko (Milner, 1985). For each sample about 10 litres of stream sediment was siewed and the -2 mm fraction was panned down to a "heavy" fraction of mainly olivine, pyroxene and some oxides and a small "ultra heavy" fraction dominated by oxides. Metallic iron grains were only recognized in a few samples collected very close to contaminated rocks. A couple of gold grains were found in samples from Kûgánguaq and east Disko; they were probably derived from adjacent sandstone outcrops (M. Millner, pers. comm, 1985). Curiously, only splits of the bulk stream sediment were analysed for Co, Ni and Cu (Table 1). In general, Co shows little variation whereas Ni and Cu reflect the local predominance of either picrites or more evolved tholeiitic lavas. Deviations from this pattern comprise: a) low Ni and Cu in streams cutting the hydrothermal aureole around the gabbro intrusion on Ubekendt Ejland; b) low Co, Ni and Cu near exposures of gneiss or sediments; c) variable Ni and Cu in an area with contaminated lavas on north-west Disko. The only anomalies which could not readily be explained are: d) low Ni and high Cu on the entire south-west coast of Svartenhuk Halvø and e) high Ni (almost "picrite levels") on the entire north-west coast of Nûgssuaq mapped as tholeiitic basalts. The latter may originate from alkaline ultramafic dykes and sills (N. Hald, pers. comm, 1990). Analysis for Cr would probably have helped to identify the sediment-contaminated rocks which do not stand out very clearly in this sample set.

More than 500 grab and chip samples were collected in 1985. Unfortunately, the original sample location maps were lost as well as a number of the samples but most were relocated by the aid of field notes. A set of 270 samples were analysed for Cr, Co, Ni, Cu, Ag, Au, Pt, Pd, Os and Ir; some were also analysed for Pb and Zn (Christensen, 1986). 110 of these samples originate from the Hammers Dal Complex.

Soil samples were collected in 1987 in unexposed fields across the strike of the Hammers Dal Complex and analysed for Cr, Co, Ni and Cu (Christensen, 1988). Across the complex, Cr and Ni show a marked increase to more than twice the background in the solifluction soil whereas the level of Co and Cu is only raised in some of the anomalous samples. No anomaly was noticed in the scree gravel. In a terrain of picrites, a similar deposit would probably appear as a negative anomaly or none. A slight difference in soil chemistry was noted between solifluction soil and scree-type gravel derived from roughly the same tholeiitic lava source. Co and Ni values are identical within statistical error in the two soils but the solifluction soil has a higher Cu and a lower Cr level than the scree gravel.

Another set of bulk sediment samples and pan concentrates was collected at the Hammers Dal Complex, Hareøen and Nûgssuaq (mainly in the area between Tunorssuaq and Anariartorfik). All samples were analysed for Cr, Co, Ni and Cu (Christensen, 1988). Furthermore, the bulk samples were analysed for Au, Pt and Pd - curiously, the reported values are identical for each sample. The sediment samples reflect the picritic background on Nûgssuaq and the more evolved basaltic background on most of Hareøen and the Hammers Dal Complex. On Nûgssuaq, the contaminated lavas show up in the pan concentrates as slightly lower Cr values which reflects the effect of reduction that suppressed crystallization of chrome spinel (Pedersen, 1985a). The effect of Co, Ni and Cu depletion is much more modest than revealed by the rock samples in the following.

Of the 1987 collection, 314 grab and chip samples (264 from lavas on Nûgssuaq and 50 samples mainly from dykes and subvolcanic intrusions on Disko) were analysed for MgO, TiO_2, Cr, Ni and Cu (Christensen, 1988). Complete major element analyses were made of 33 samples but only 18 samples were analysed for Co, Ni, Cu, Pt, Pd, Ir and Ru. About 30% of the samples from Nûgssuaq are uncontaminated picrites and basalts which form a general "evolution" trend (Fig. 6 and 7). The other 70% of the samples are contaminated; most are Ni and Cu depleted to a variable degree: about 35% have lost more than half of their initial Ni and Cu content by precipitation of sulphide or metallic iron. About 60% of the contaminated samples have higher Cr values than the main trend (Fig. 6) which indicates that they are at least mildly reduced (Pedersen, 1985a). Because only a few samples are mildly Ni and Cu enriched, most of the sulphides or metallic iron must have been deposited below the present level of erosion. The depleted lavas diverge in mean by -125 ppm Ni from undepleted lavas with the same MgO content. Assuming, hypothetically, that sulphide precipitation postdated contamination and olivine crystallization, at least 10 million tons of Ni was extracted from the contaminated magmas. Because the three processes most likely cooperated, the amount of extracted Ni would probably be larger.

The PGE data set of 1985 shows variations by three orders of magnitude which is to be expected for variably mineralized rocks. Omitting some of the most erratic values, the data set show some general, positive correlations between Ni, Cu, Pt, Pd, Ir and Au whereas Ag and Os are constantly low (1 ppm and 1 ppb, respectively). For the entire data set, a Pt/(Pd+Pt) ratio of 0.6 and a Cu/(Cu+Ni) ratio of 0.3 agree well with sulphide deposits formed from ultramafic magmas of tholeiitic affinity (Naldrett & Cabri, 1976). It is also noteable that the Ru values (the 1987 data set) are high relative to Pt. In the data sets of 1985 and 1987, samples with at least 15 ppb Pt and 10 ppb Pd were classified as anomalous. On these criteria, 88 anomalous samples were identified - 81 of the samples originated from 17 localities (Table 2; Fig. 8). The remaining 7 samples have a less well known geological provenance and originate from at least 5 different localities.

Naturally, the Hammers Dal Complex was most intensely sampled and analysed; plots of Pt versus Ni and Pd versus Pt are shown in Fig. 9. Data for the other "anomalies" are rather few considering the large scatter but seem to conform with the same trend (Fig. 10). One intrusion that stands out is the Stordal Dyke (Table 2) which shows a consistently higher Pt/Ni ratio than the other "anomalies". A dyke in Morten Porsild Dal may be a segment of the same dyke (Table 2, no. 4).

Below, the PGE data are compared with previous analyses and the quality of the PGE data set is discussed.

EVALUATION OF THE PGE DATA SET

The quality of the 'PGE data set' (including Cr, Co, Ni and Cu) is amenable to evaluation by its internal consistency and by comparison with previous investigations. This applies in particular to the Hammers Dal Complex that has previously been investigated in detail (Ulff-Møller, 1977 and unpublished data) and has yielded a large part of the present data set (110 analyses).

Cu, Ni, Pt and Pd values exist for the entire data set and the above mentioned trends are some indication of internal consistency. The Cr data are less complete and show a large variation that is uncorrelated with Cu, Ni and rock type; most of the values for the Hammers Dal Complex are below 350 ppm Cr, the minimum for the contaminated rock suite. The same apply to the Co values; neither Cr or Co are considered further.

The PGE analyses were based on two methods of extraction: Pt, Pd, Os and Ir by lead assay on all samples and duplicate analyses for Pt and Pd by nickel sulphide assay on 180 samples (Gannicott, pers. comm, 1990). In neither case is the method of detection known. The Pt and Pd values obtained by the two extraction methods agree well for the metallic iron free rocks, even for low values, but show a considerable scatter for the metallic iron bearing rocks. Although nickel sulphide is generally considered to be a more efficient PGE extractor than metallic lead, correlation lines with a slope of one are found for both elements when the most extreme values are neglected. Curiously, the highest recorded value of 1000 ppb Pt was obtained on a lead assay whereas the nickel sulphide assay on the same sample yielded 5 ppb!

Independent PGE data for comparison are unfortunately rather scarse. Previous Pt analyses were all made on metallic iron concentrates by optical emmission spectroscopy on lead assays (Goldschmidt & Peters, 1932; Ulff-Møller, 1977) and by neutron activation analysis (Klöck, 1986). Only one set of analyses based on samples from the Hammers Dal Complex (in Ulff-Møller, 1977) is directly comparable to the Greenex data (Fig. 9). As it is seen, the discrepancy between the two sets of values is significant: in terms of the Pt/Ni ratio the divergence is about a factor of 10. The Pt analysis of iron from a locality on south Disko (Klöck, 1986) also fall on the Pt-rich trend. Goldschmidt & Peters reported ppm and sub-ppm values of Pt, Pd, Ir, Os and Rh in iron from this locality. Although Ni was not determined, their Pt values are compatible with the high Pt/Ni trend. Further, Klöck reported Ir and Au values for Hammer Dal iron which are also systematically higher than the Greenex data. If the high Pt/Ni trend represents the true values then the Greenex data correspond more closely to the expected composition of sulphide liquid coexisting with metallic iron. In the few cases where the state of sample alteration is known, the high Pt values were obtained on highly weathered, sulphide-rich samples.

From these observations, it is evident that severe problems are connected with the analysis of metallic iron bearing rocks. The presence of metallic iron is likely to impede:

a) chip sampling because large iron grains affect the fracturing of rocks (large grab samples will probably be more representative),
b) crushing and milling of samples to a fine homogeneous powder (a prerequisite for efficient extraction of the PGE) because the iron is ductile,
c) most preconcentration procedures because metallic iron is a comparatively good extractor.

In an attempt to solve the discrepancy between the data obtained at research laboratories and the Greenex data set, a number of samples from the Hammers Dal Complex were oxidized and analysed as described in appendix A. The analyses made by two commercial laboratories are consistent with the Greenex data set. Analyses made by H. Bollingberg gave significantly higher Pt values although the old high values could not be reproduced. Analyses of reference material (PTC-1 and PTA-1) suggest that the calibration is not in error. However, severe problems were encountered during sample preparation and preconcentration. The problems are connected with the high Fe content of the samples and are likely to cause inefficient PGE extraction. We presume that similar problems may be connected with the commercial analyses. A project to examine these problems is in progress.

CONCLUSIONS

It can be concluded that the West Greenland Basalt Province represents a promising exploration target for Co, Ni and probably also the PGE (platinum group elements). The metallic iron and sulphides occur in contaminated volcanic rocks which were derived from ultrabasic parent magmas by reaction with carbonaceous, sulphurous sediments. Two major prospective areas have been located on north-west Disko and the Nûgssuaq peninsula, respectively. The geological setting of the two areas is shown in Fig. 11. On Disko a number of mineral showings occur mainly in dykes and subvolcanic intrusions whereas a large volume of Ni and Cu-depleted lavas on Nûgssuaq suggest that ore deposits may occur at depth. The apparent difference between the two areas may reflect a difference in the erosion level as well as the intensity of the investigation.

On Nûgssuaq, contaminated lavas with a total volume of more than 200 km^3 occur in the Vaigat Formation. The contaminated magmas erupted in at least five separate events after depositing about 10 million tons of Ni by sulphide or iron metal extraction in magma reservoirs in the underlying sediments - only modest deposits have been seen at the surface. The contaminated lava sequences occur in the lower part of the Vaigat Formation, from 100 to 1000 m above the top of the sediments. The lateral extent of the contaminated lava sequences is quite well known but only few eruption sites have so far been located.

The prospective area on north-west Disko is defined by a swarm of NW-SE to N-S striking contaminated dykes and subvolcanic intrusions. Many of these were probably feeders to extensive contaminated lavas - now strongly eroded but initially exceeding the Nûgssuaq lavas by volume. The intrusions host deposits of metallic iron and sulphides many of which are modest from a direct economic point of view. "Branched iron bodies" (Ulff-Møller, 1977) dominate the iron cumulates and were deposited along contacts sloping up to 70° by a mechanism that is not completely understood. The presence of iron cumulates is thus evidence of considerable magma transport capability whereas the amount of iron typically reflects the local conditions of deposition rather than the general potential of an intrusive system. Considering the transport conditions in volcanic feeder systems, the mineral showings may just be "the top of the iceberg" and improve downwards and towards the source; however, the depth to the underlying sediments may exceed two kilometres (Fig. 11).

The Hammers Dal Complex on Disko belongs to this mineralized dyke swarm and has a number of attractive characteristics: a) it is the richest metallic iron deposit exposed in the province; b) it is accessible to ground geophysics that has revealed a conductor 400-500 m below the present surface with much larger dimensions than the outcrops; and c) the strongest hydrothermal alteration field on Disko occurs just 1 km north-east of the complex which may imply the existence of a larger intrusion at depth.

The Stordal Dyke and a dyke in Morten Porsild Dal stand out among the mineralized intrusions by a markedly higher Pt/Ni ratio that coincides with the trend defined by the research laboratory analyses. However, only modest deposits of iron and sulphides have been found and both dykes are exposed in rugged terrain which is not easily accessible to geophysical prospecting techniques.

A significant divergence exsists between Pt analyses from metallic iron bearing rocks made by research laboratories and commercial laboratories; the values of the latter are seemingly a factor 10 too low. This severe problem is connected with the presence of metallic iron that impedes representative sampling, homogenization by crushing and preconcentration of the PGE.

RECOMMENDATIONS

The exploration targets are sulphide and metallic iron deposits in shallow, sediment contaminated intrusions and craters or feeder dykes to vast lava volumes. Future prospecting will demand 1) a geophysical method suited to track deeply situated mineralization and 2) a solution of the analytical problems connected with routine analysis of metallic iron bearing rocks, and 3) a better understanding of the contamination process that controlled the formation of sulphides and metallic iron.

1) Among the standard geophysical methods employed, electromagnetics proved the most efficient to trace deep mineralization, but a method with a penetration depth of more than 500 m is required. Hendry (1985) came with other recommendations in addition to the UTEM method he used. An exploration version of the magneto-telluric technique might also be worth considering.
2) A solution to the analytical problems connected with iron bearing rocks should preferably comprise a sample preparation technique which allows reliable analysis by various standard techniques. A research project with this objective is under preparation at GGU. The procedure would be facilitated by separate analyses of the sulphide and metallic iron fractions which contain the major part of the Co, Ni, Cu and PGE.
3) A simplified model of the contamination process has been proposed by Ulff-Møller (1990) which can explain the most basic features of the complex zoning patterns of the iron. The study shows that the zoning of iron bodies may reflect conditions in the weakly contaminated part of a magma series which is often poorly represented in the subvolcanic intrusions but probably more important at depth. An investigation of chrome-spinel bearing olivine phenocrysts and cognate gabbro and norite nodules may be of further help to elucidate the concentration processes.

The majority of the mineral showings in the West Greenland Basalt Province occur in subvolcanic intrusions on Disko and have been investigated in detail in the field. Most of the deposits are represented in hand specimen collections gathered by the author. An analytical reconnaissance programme based on this sample material and a compilation of existing data about the intrusions would be useful to select intrusions for detailed investigations.

The knowledge of the prospective area on Nûgssuaq is only of a reconnaissance nature. If the present picture of a few mineral showings and a large volume of Ni-depleted lavas holds, then the selection of sites for detailed geophysical surveys will depend on locating feeders and lava eruptions centers. This can be done with various means:

1) The most acute needs could be covered by a detailed chemical and stratigraphical interpretation of Greenex's lava profile data; however, the profiles are most closely spaced along the western and northern edges of the prospective area.
2) A more accurate contribution can be obtained by a photogeological interpretation based on a new stereoscopic technique using photographies taken with an ordinary hand-held camera from a helicopter. This technique provides orders of magnitude more information than what can be obtained visually during the closest helicopter fly-by. A project of this type is in progress on Nûgssuaq (A. K. Pedersen and L. M. Larsen), but increased assistance is needed in order to complete the regional coverage within the first couple of years.
3) The most efficient way to locate mineral showings and eruption sites, according to previous experience from Disko, is still traditional fieldwork.

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APPENDIX A

by I. Sørensen and H. Bollingberg

The large number of Pt analyses made during Greenex's prospecting, the small number of analyses made in research laboratories and the divergence of the Pt/Ni ratio by a factor of 10 between the two data sets calls for a critical examination of the latter although the results of the three research laboratories agree semi-quantitatively.

The analysis of metallic iron bearing rocks poses a classic chemical problem which may be overcome by disintegration of the metal phase - for example by sulphidation and subsequent roasting (Goldschmidt & Peters, 1932) or by direct oxidation of the iron. We decided to proceed along the line - followed earlier by one of us (HB in Ulff-Møller, 1977) - which seemed fruitfull in order to increase the number of directly comparable analyses and to test the calibration of the earlier spectrographic analyses.

The iron was removed by hand magnet during crushing of the rocks and oxidized separately in porcelain boats in an electric muffle furnace. The first batches were oxidized at 950^{o} C which caused strong sintering and even melting of a sulphide-rich sample. The next batches were then oxidized at 700^{o} C, the same temperature used with the earlier analyses. The oxidation of the iron appeared to be much more sluggish than we recall. So, a flow of oxygen was led through the furnace and several steps of heating and crushing were needed to speed up the process (Fig. 12).

Aliqots of the oxidized iron were analysed by two commercial laboratories, lab A and B and ourselves (lab C, Table 3). Lab A made silver assays which were dissolved and analysed by plasma spectroscopy (ICP). Lab B used instrumental neutron activation analysis of nickel sulphide assays. We used lead acetate/sodium borate assaying and optical emmission spectrographic analysis of the lead button as described by Goldschmidt & Peters (1932). Lab A and B obtained values for Pt, Pd and Au which are consistent with the Greenex data (Fig. 13). Three iron concentrates, analysed in triplicate by us, gave values for two samples consistent with the Greenex data whereas the third sample yielded intermediate values between the two trends. Our analyses of two noble metal standards (PTC-1 and PTA-1) gave values somewhat lower than the recommended values which indicate that our calibration is not seriously in error.

As an additional experiment, 1 g aliqots of metallic iron were dissolved in warm 6N hydrochloric acid. In one case, the solution was evaporated to dryness and the bulk was mixed with the lead acetate/borate flux in a porcelain crucible. An additional (chloride ?) liquid phase was formed during the lead assaying. In spite of that, the spectrographic analyses (175958-06, Table 3) are comparable to the previous ones. In two other cases, the solution was filtered and the filter with remnant was ashed at 300° C in the electric furnace before lead assaying. The analysis gave much lower values which indicate that a substantial amount of the noble metals was lost in the filtrate because no precipitation with hydrogen sulphide was carried out.

During the oxidation and preconcentration of the samples, we encountered a number of problems which may also have played an important role in the procedures employed at the commercial laboratories. The repeated steps of heating and crushing caused an unsatisfactorily large sample loss. Furthermore, the lead assaying of the FeO-rich samples progressed in a non-quantitative manner and was very sensitive to reduction by the flame of the gas burner. Our Pt determinations for the standards included in the investigation are somewhat low compared to the recommended values and show a systematic variation (Fig. 14) which suggests that the recovery of Pt (and the other noble metals ?) may be strongly dependant on the Fe content of the sample. Presumably due to the recovery problems this time, we were not able to confirm our previous high Pt values (in Ulff-Møller, 1977).

We do not know what precautions may have been taken by the laboratory producing the analyses for Greenex. Similar problems with sluggish oxidation of the metallic iron and incomplete PGE extraction would most likely have been effective in the procedures of the commercial laboratories. If metallic iron survived the oxidation, this would further decrease the recovery of PGE (Beamish, 1966). Because our PGE estimates are too low in spite of many efforts, we believe that the Greenex PGE values are probably also too low.

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Table 1. Stream sediment chemistry and related source rocks

		Co ppm	Ni ppm	Cu ppm
Picrites	mean	85	1018	90
	N	157	158	157
	s.d.	17	245	30
	max	117	1917	220
	min	24	500	34
Basalts	mean	54	150	186
	N	42	43	42
	s.d.	8	69	55
	max	74	387	328
	min	41	82	98
FeTi-basalts	mean	50	76	202
	N	19	19	19
	s.d.	8	11	42
	max	60	97	303
	min	32	61	133
Gneiss and sediments	mean	20	28	41
	N	8	8	8
	s.d.	11	11	21
	max	45	40	61
	min	11	12	17

Analyses of the -2 mm fraction by atomic absorption spectrophotometry (Milner, 1985). N: number of samples; s.d: one standard deviation; max and min: maximum and minimum values.

Table 2. Platinum-palladium anomalies in the West Greenland Basalt Province.

Year of collection:		1985					1987						
		Ni ppm	Cu ppm	Au ppb	Pt ppb	Pd ppb	Co ppm	Ni ppm	Cu ppm	Pt ppb	Pd ppb	Ir ppb	Ru ppb
Disko:													
1) Hammers Dal Complex	mean	2675	1048	14	47	25							
	N	40	40	18	25	38							
	s.d.	3376	1208	5	66	22							
	max	18000	6400	25	350	110							
	min	180	110	10	15	10							
2) Hanekammen Complex	mean	140	160	10	20	10							
	N	1	1	1	1	1							
3) Kitdlît dyke	mean	2883	1153	14	55	31	655	4543	2603	37	20	20	253
	N	6	6	5	4	6	3	3	3	3	3	3	3
	s.d.	1032	645	3	41	18	845	4730	3289	29	0	0	110
	max	4200	2400	16	100	57	1630	10000	6400	70	20	20	340
	min	1700	720	10	20	15	134	1620	620	20	20	20	130
4) M. Porsild Dal dyke	mean						750	2130	1750	300	40	40	40
	N						1	1	1	1	1	1	1
5) Point 440 dyke	mean	1230	330	10	60	44							
	N	2	2	2	2	2							
	s.d.	806	42	0	14	4							
	max	1800	360	10	70	46							
	min	660	300	10	50	41							
6) Giesecke Dal W dyke	mean	1630	793	5	37	18	1560	5900	860	60	20	20	190
	N	3	3	3	3	3	1	1	1	1	1	1	1
	s.d.	404	291	0	29	7							
	max	2000	1000	5	70	25							
	min	1200	460	5	20	12							
7) Stordal dyke	mean	8480	1844	27	368	154							
	N	5	5	5	5	5							
	s.d.	10312	3220	40	366	255							
	max	26000	7600	99	1000	610							
	min	1000	300	5	70	14							
8) Point 882, volcanic neck	mean						27	121	159	20	20	20	180
	N						1	1	1	1	1	1	1
9) Ametystskrænten lava	mean						79	775	267	28	20	20	253
	N						6	6	6	6	6	6	6
	s.d.						57	504	87	20	0	0	94
	max						164	1350	360	40	20	20	430
	min						26	141	234	20	20	20	190
10) Kûganguaq, lava, Asuk M.?	mean	160	165	10	15	-							
	N	1	1	1	1								
Nûgssuaq:													
11) Saviarqat, lava	mean	1583	364	5	40	21	2784	4434	624	110	30	24	248
	N	6	6	4	3	6	5	5	5	5	5	5	5
	s.d.	796	54	0	17	13	4267	5101	743	152	14	9	206
	max	3000	420	5	60	40	10000	10000	1800	380	50	40	590
	min	800	280	5	30	10	24	50	43	20	20	20	40
12) Agatdal, lavas	mean	460	140	10	15	-							
	N	1	1	1	1	-							
13) Anariartorfik, lava	mean						42	188	112	20	20	20	180
	N						1	1	1	1	1	1	1
14) Auvfarssuaq, boulders	mean	751	335	8	19	12							
	N	8	8	8	4	5							
	s.d.	665	330	3	5	2							
	max	2200	1100	10	25	15							
	min	70	55	5	15	10							
15) Qaersut, sill	mean	2350	555	14	90	46							
	N	2	2	2	1	2							
	s.d.	1485	629	6	-	40							
	max	3400	1000	18	-	74							
	min	1300	110	10	-	17							
16) Sarqâta qáqâ, gabbro intrusion	mean	297	565	10	51	46							
	N	3	3	3	1	2							
	s.d.	240	589	6	-	1							
	max	560	1200	16	-	47							
	min	90	36	5	-	45							

Samples with at least 15 ppb Pt or 10 ppb Pd were classified as anomalous.
N: number of anomalous samples; s.d: one standard deviation;
max and min: maximum and minimum values.

Table 3. Platinum group elements in samples from the Hammers Dal Complex.

GGU no	ppb	Pt	Pd	Au	Os	Ir	Ru	Rh	Ag
Lab A:									
175954-03		330	179	147	-	-	-	-	-
175958-03		110	83	68	-	-	-	-	-
176020		8	3	17	-	-	-	-	-
Lab B:									
175954-03		338	195	1417	<65	24	<325	22	-
175958-03		<235	<138	130	<55	7	<276	<7	-
Lab C:									
175954-03		130	130	tr.	-	-	-	-	900
175954-05		650	<100	130	-	-	-	-	900
175954-05		<100	260	130	-	-	-	-	1200
175958-03		550	tr.	<100	-	-	-	-	600
175958-05		510	tr.	140	-	-	-	-	400
175958-05		370	tr.	<100	-	-	-	-	300
175958-06		250	tr.	tr.	-	-	-	-	200
176004-05		610	tr.	tr.	-	-	-	-	500
176004-05		470	<100	tr.	-	-	-	-	300
175954-01		<80	<100	<100	-	-	-	-	800
176020		80	tr.	tr.	-	-	-	-	400

– : not analysed

GGU no.	sample description	Fe wt%	Ni wt%	corr. factor
175954	sulphide-rich iron cumulate in basalt	12		
-01	rock, magnetic fraction removed	0		1.00
-03	magnetic fraction	85	2.8	1.30
-05	magnetic fraction, new batch	85	2.8	1.30
175958	sulphide-poor iron cumulate in basalt	32		
-03	magnetic fraction	>99	1.2	1.38
-05	magnetic fraction, new batch	>99	1.2	1.38
-06	magnetic fraction, acid digestion	>99	1.2	1.00
176004	iron bearing andesite	2.2		
-05	magnetic fraction	>99	0.5	1.35
176020	graphite-rich andesite, iron-free	0	~0.02	1.00

Correction factors were estimated from the weight change by oxidation.

Methods:
All samples were oxidized except 175958-06.
Lab A: lead assay extraction on 5 g samples, analysis by ICP.
Lab B: nickel sulphide assay extraction on 10 g samples, analysis by INAA.
Lab C: lead assay extraction on 0.5 g samples, spectrographic analysis.
The nickel content of metallic iron was measured by microprobe.

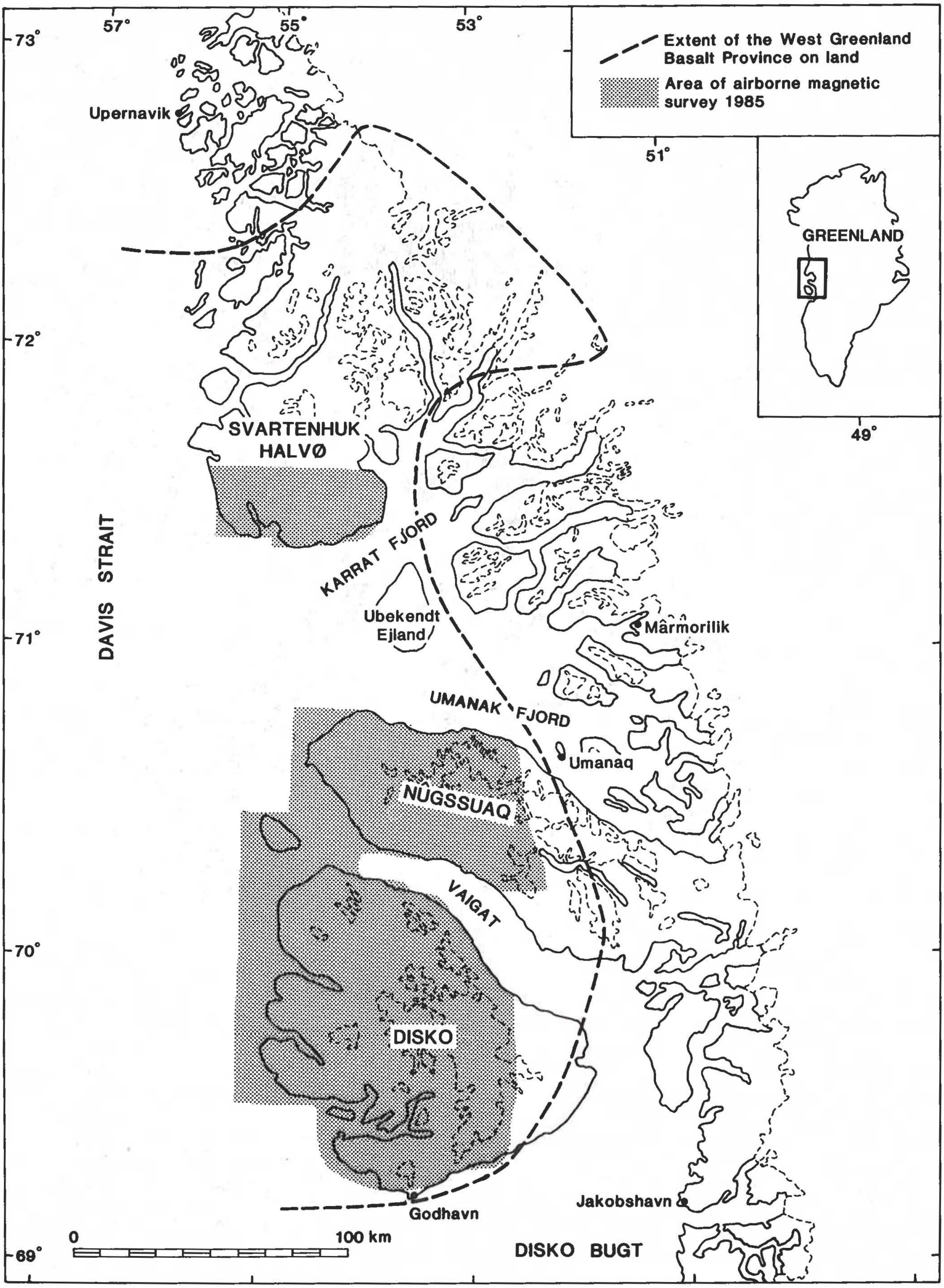


Fig. 1. Present extent of the West Greenland Basalt Province.

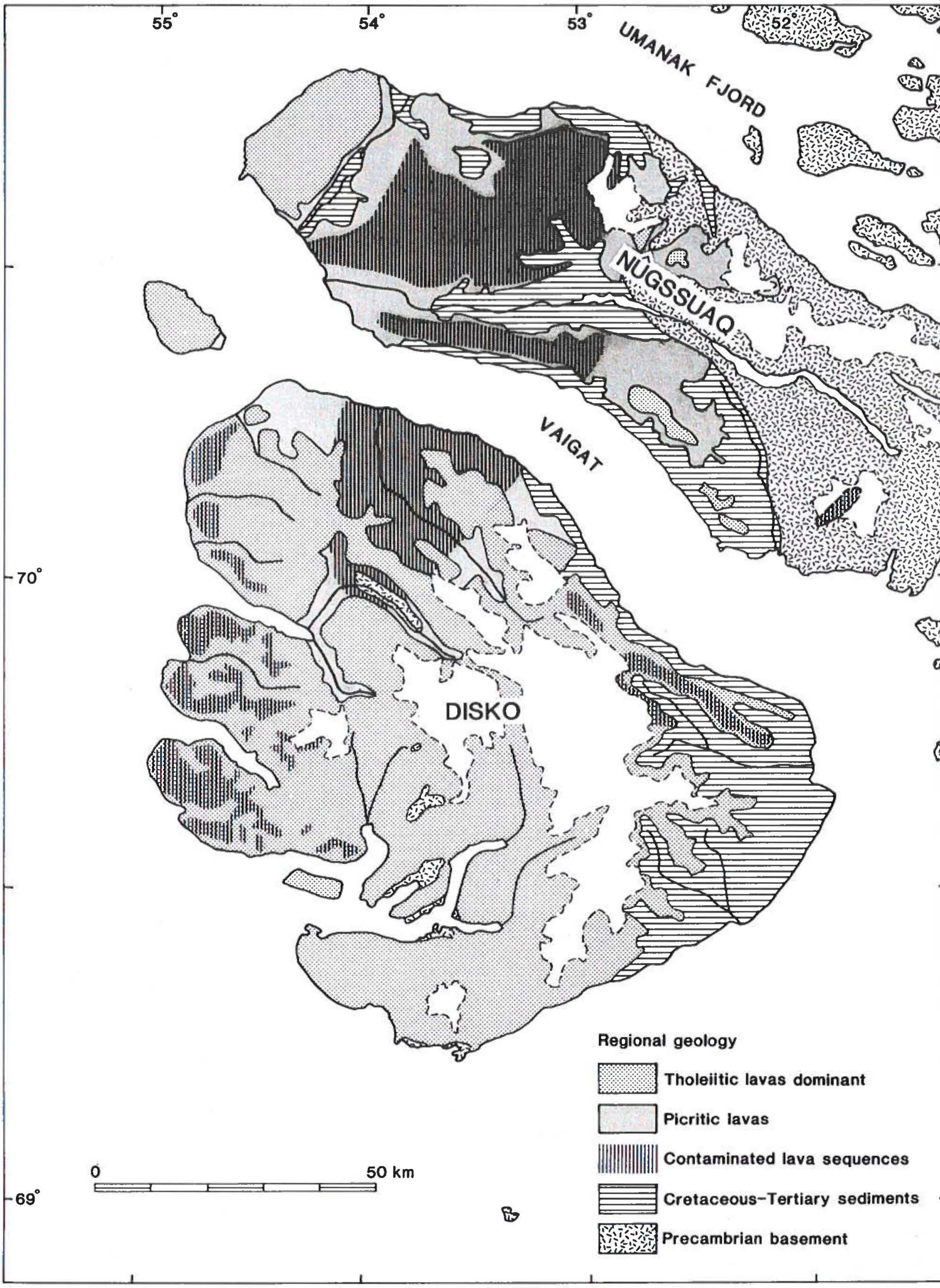


Fig. 2. Geological map of the Disko - Nûgssuaq area.

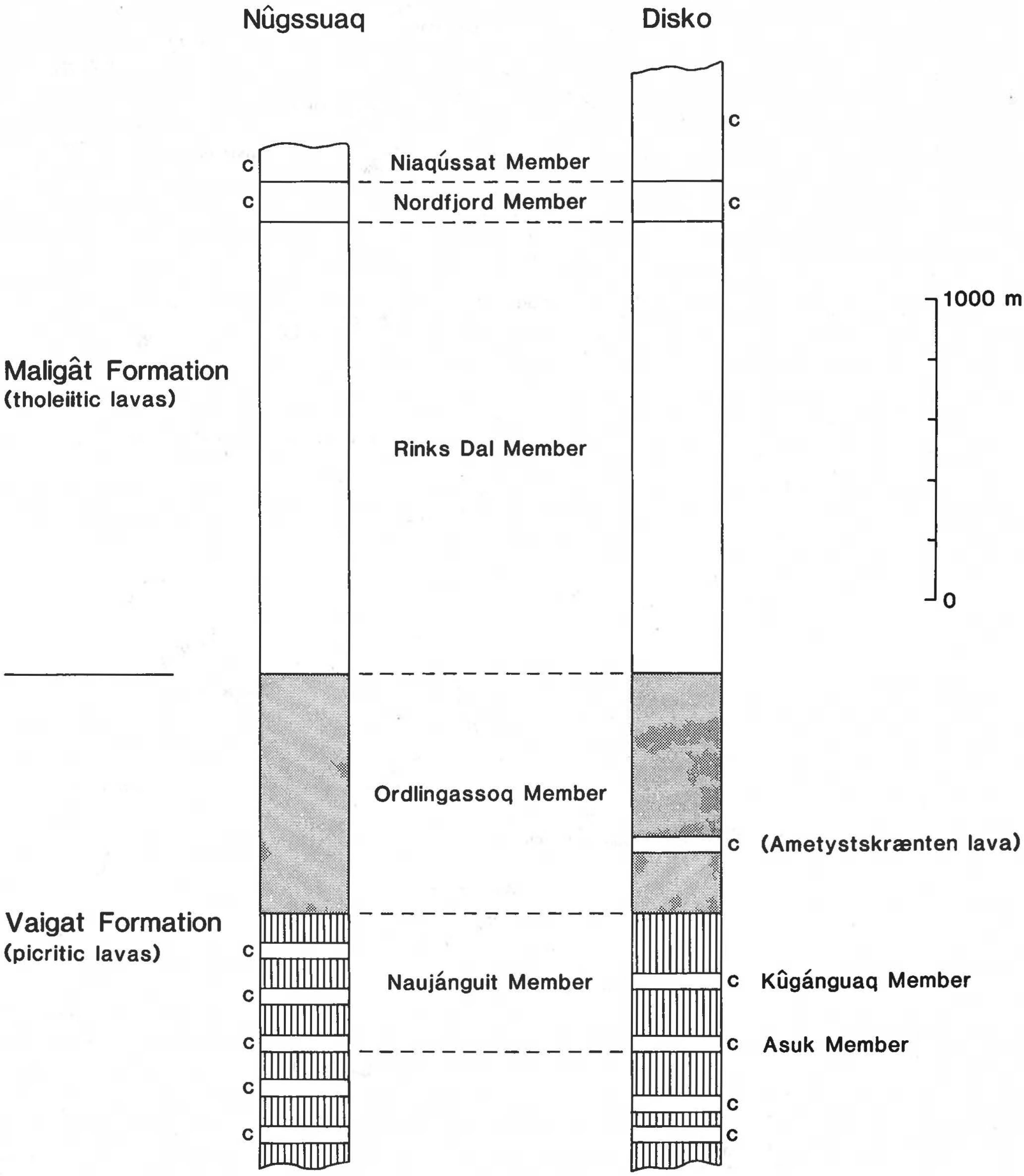


Fig. 3. Lava stratigraphy of Nûgssuaq and Disko (based on data from Hald & Pedersen, 1975; Pedersen, 1975a, 1985b and Pedersen et al. 1989).

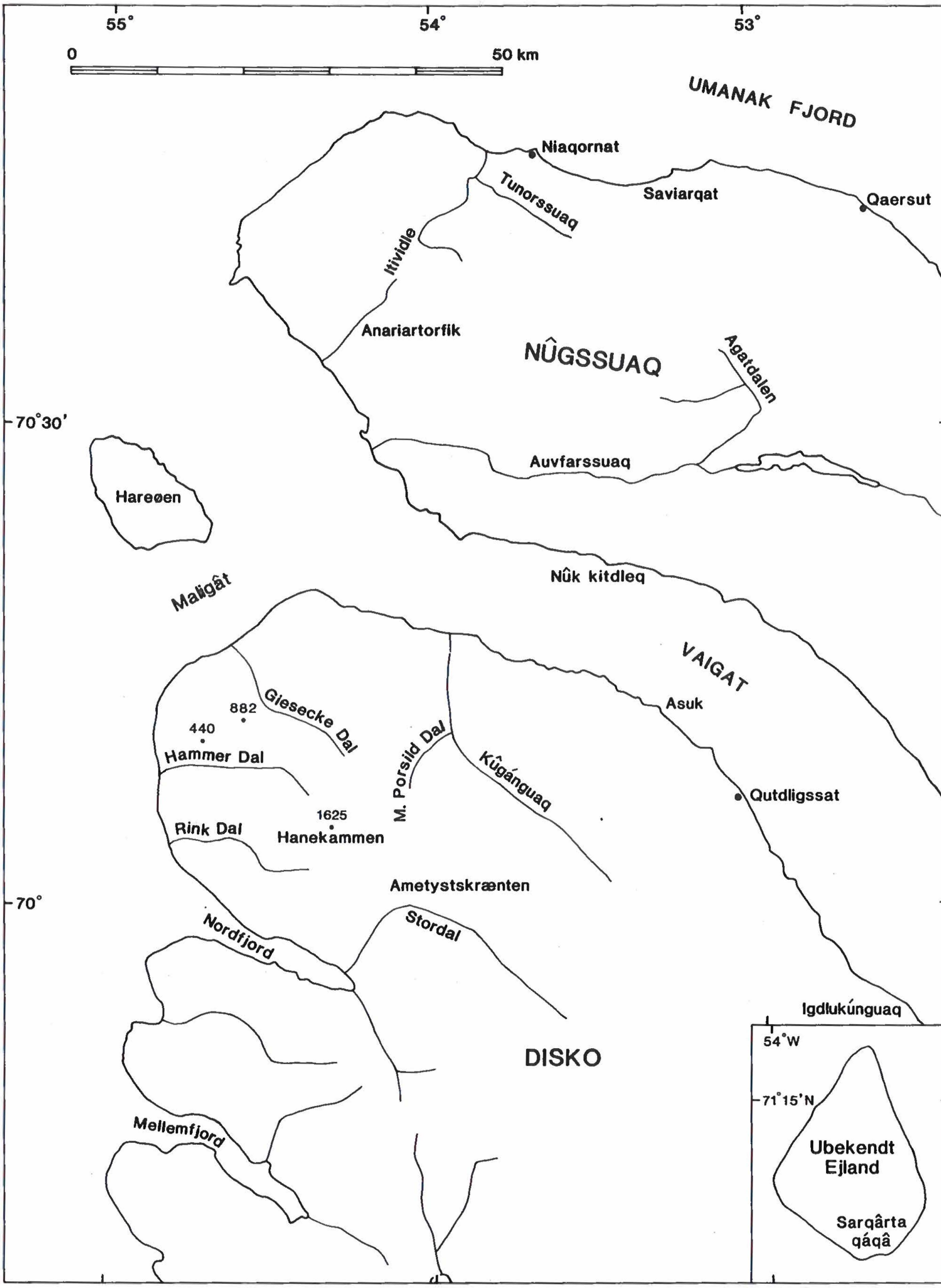


Fig. 4. Geographical names cited in the text.

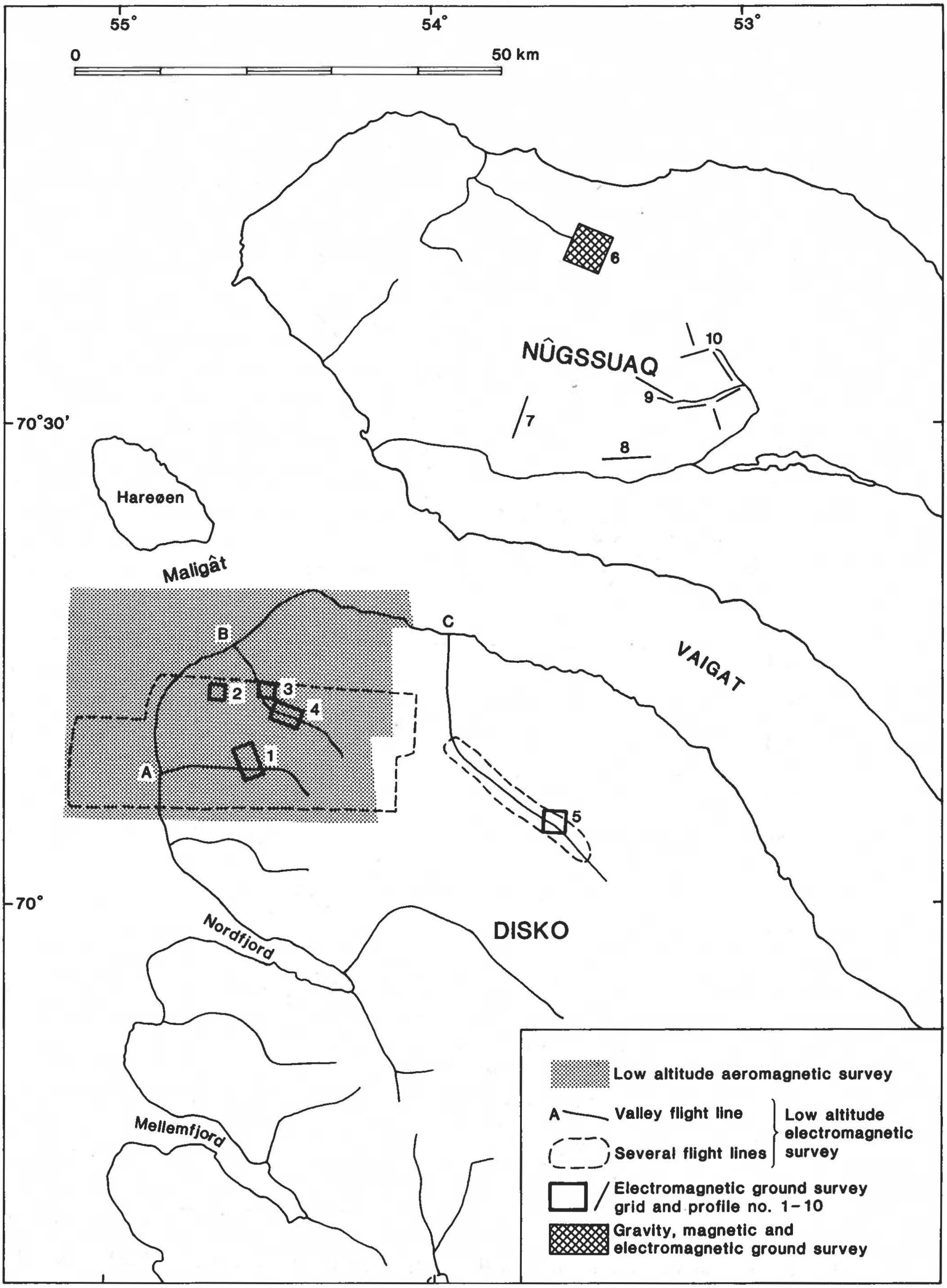


Fig. 5. Geophysical surveys on Disko and Nûgssuaq 1985, 1987 and 1988.

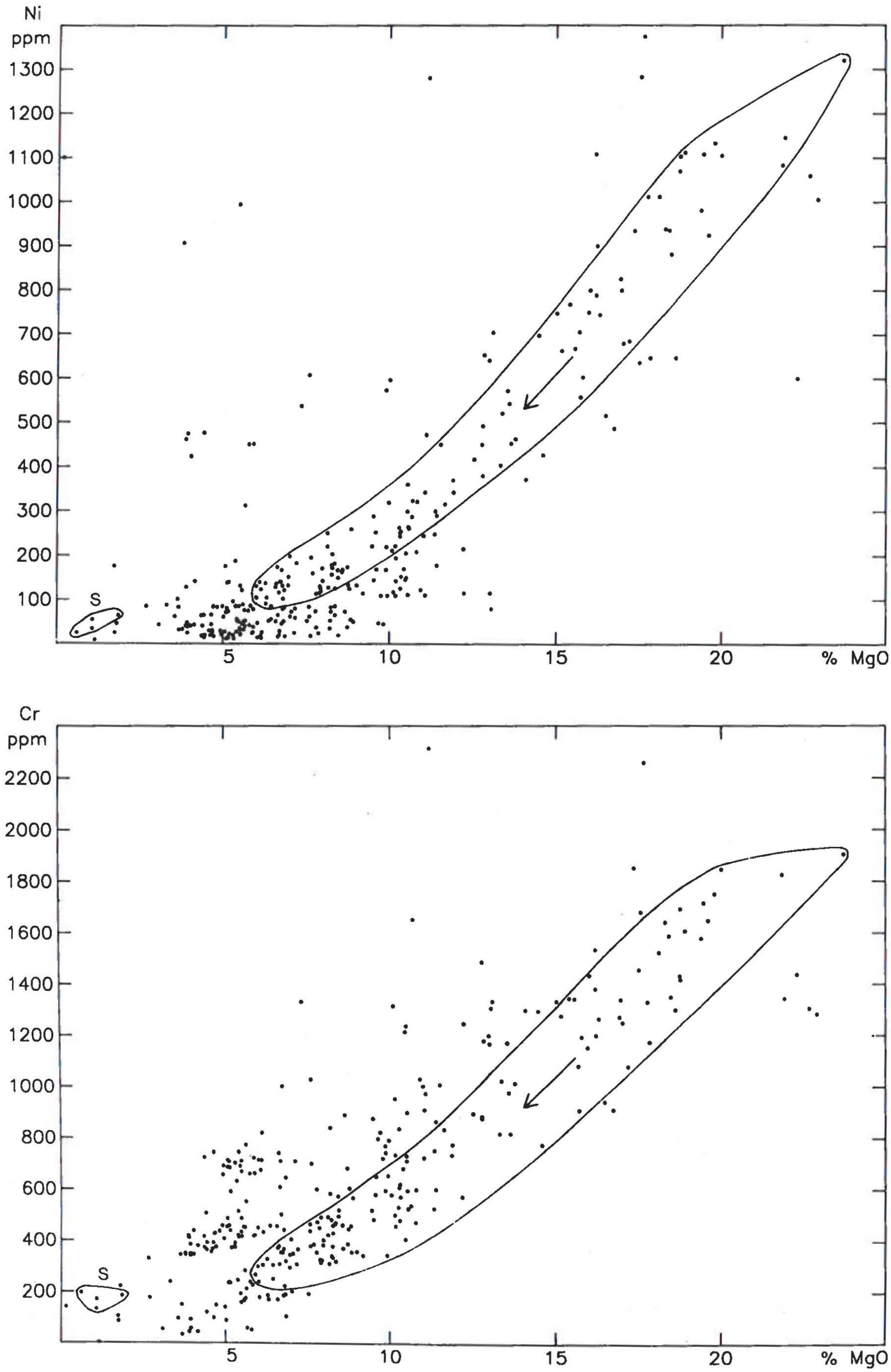


Fig. 6. Ni and Cr versus MgO in Nûgssuaq lavas. The encircled field contains typical uncontaminated rocks; an arrow shows the evolution trend by olivine (+ Cr-spinel) fractionation. S: composition of shale.

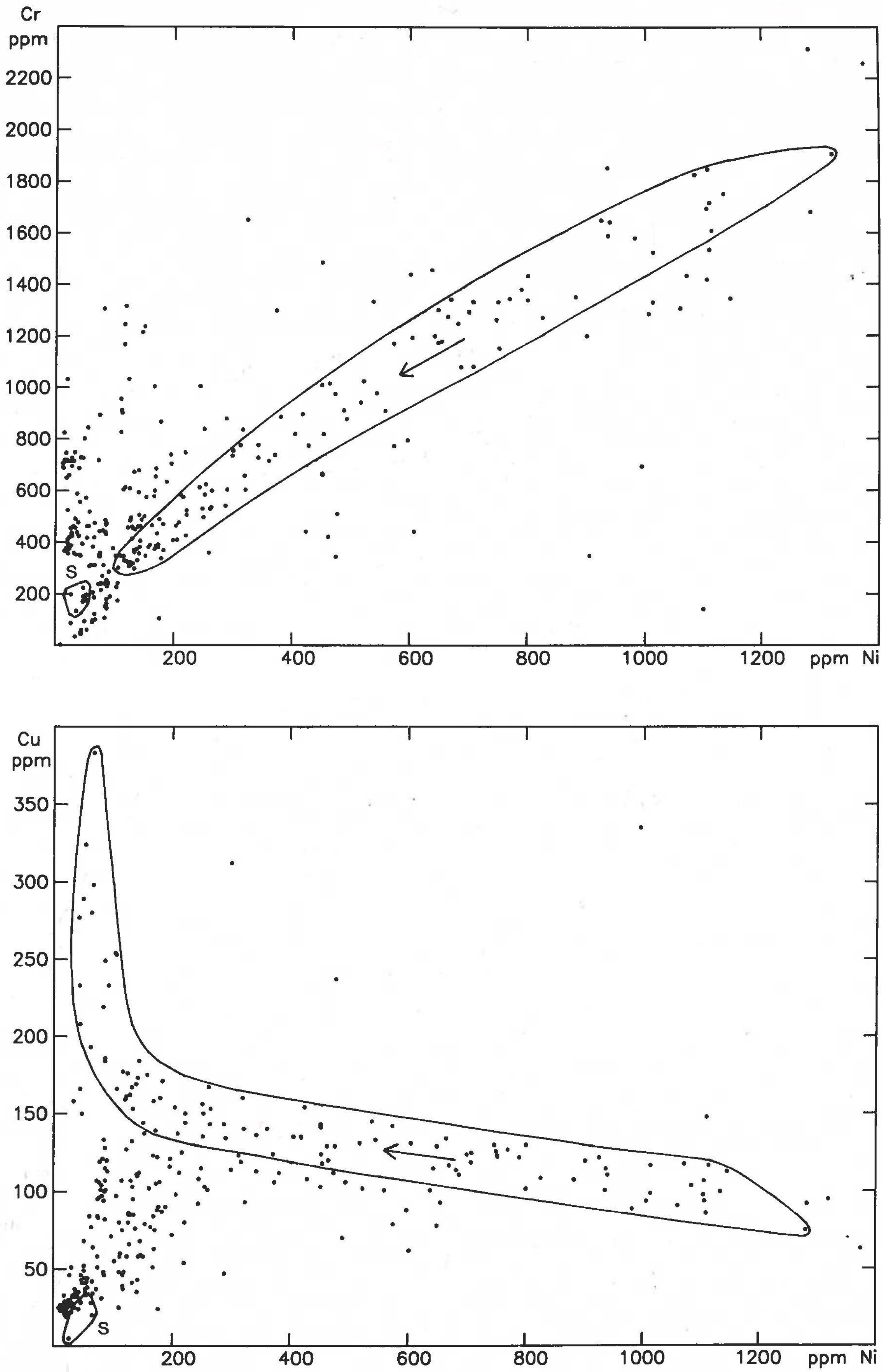


Fig. 7. Cr and Cu versus Ni in Nûgssuaq lavas (same signature as in Fig. 6).

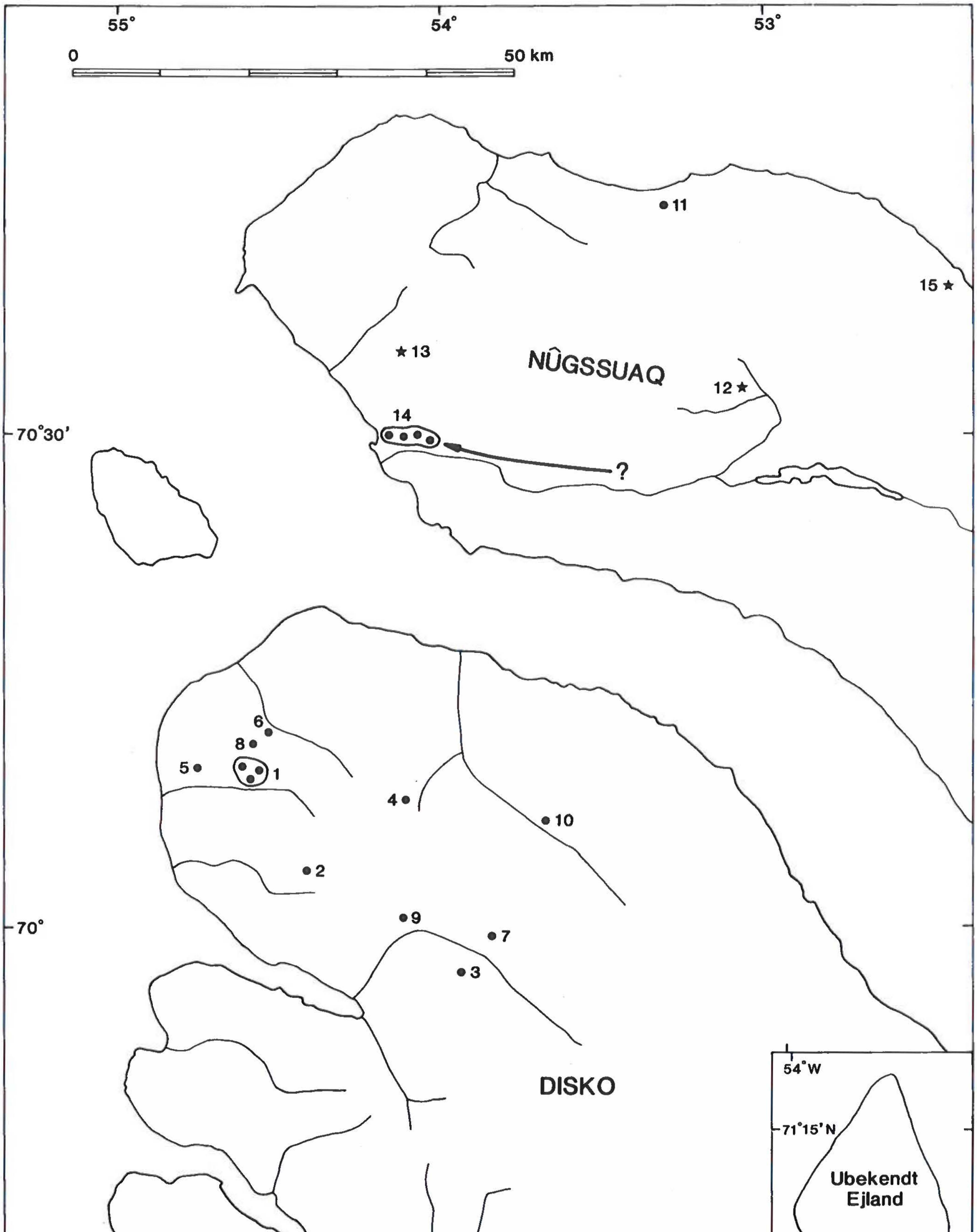


Fig. 8. Platinum anomaly map of Disko and Nûgssuaq. Dots: localities with metallic iron; stars: iron not observed.

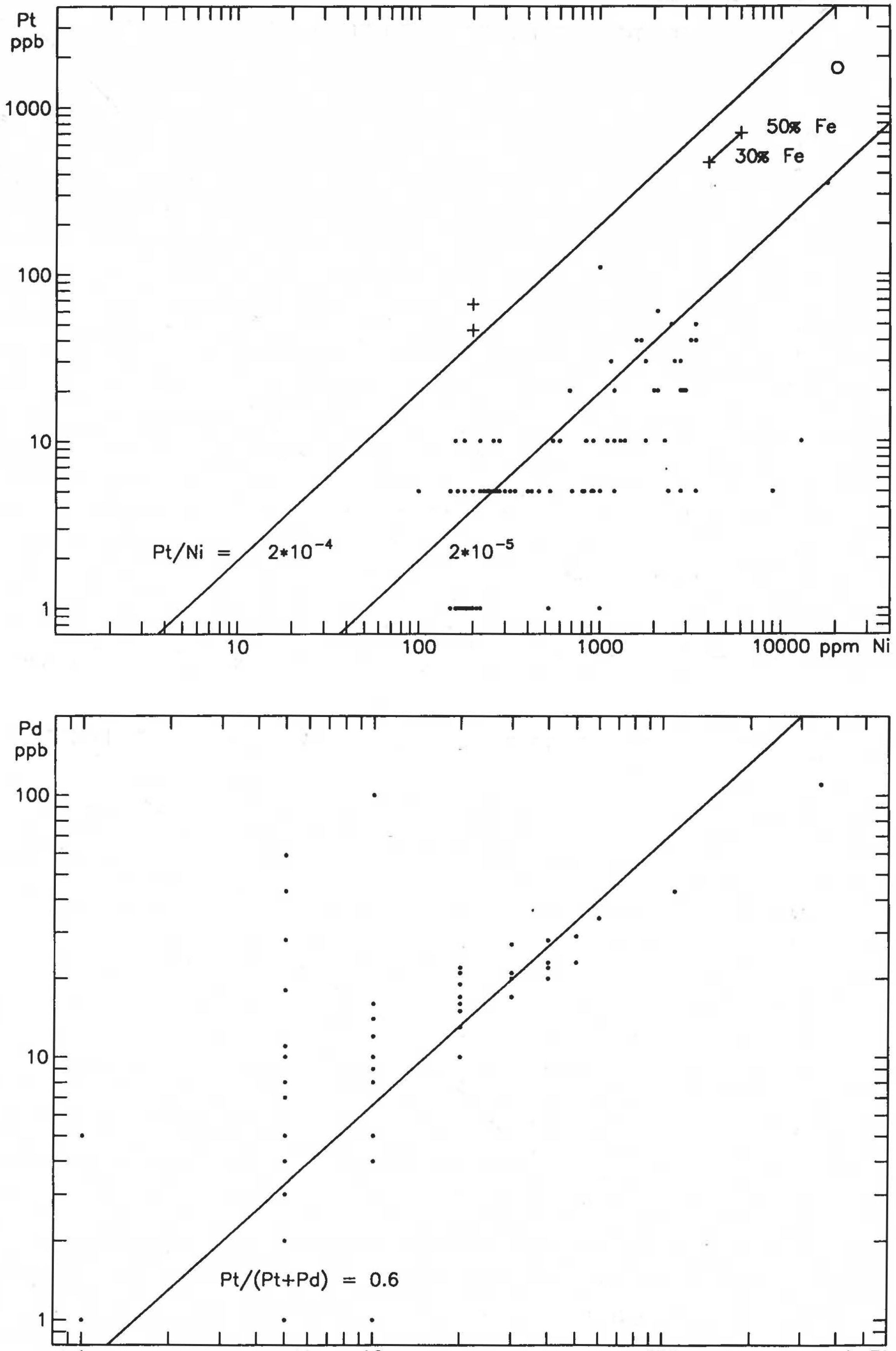
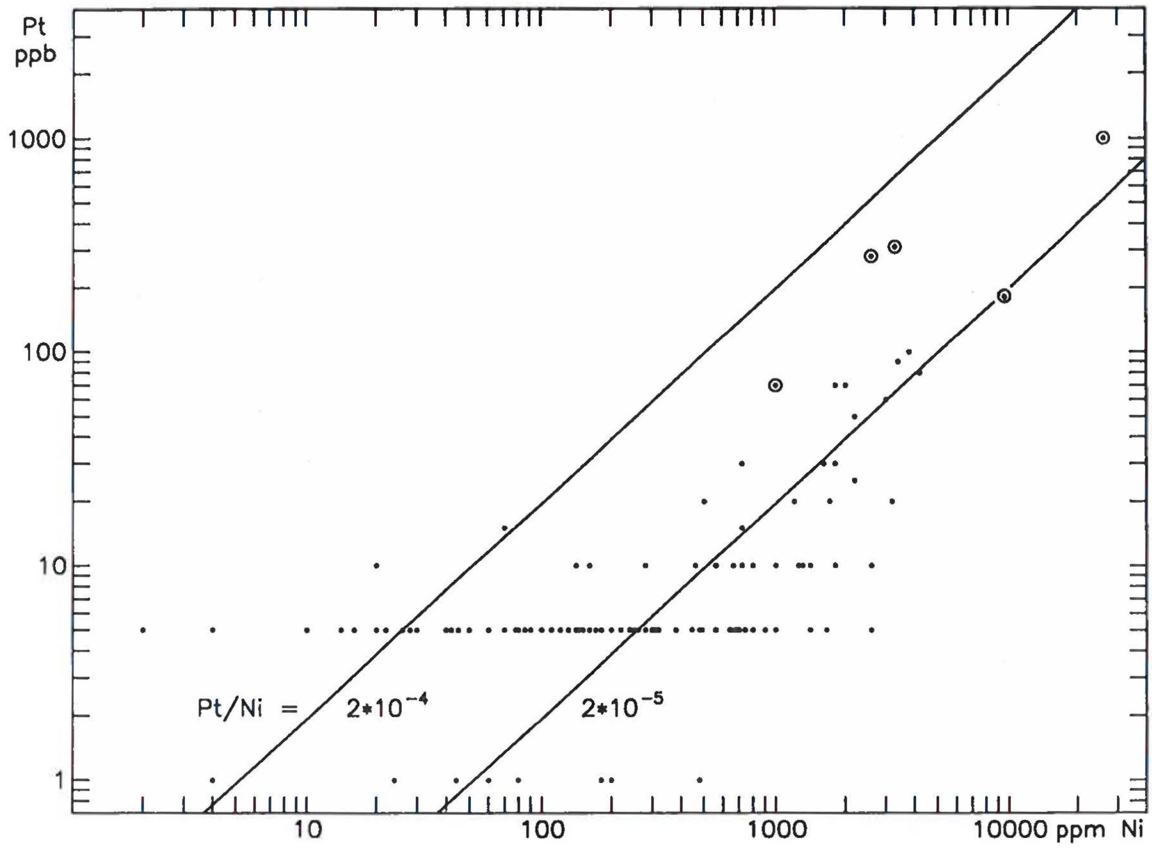


Fig. 9. Pt, Pd and Ni in rocks from the Hammers Dal Complex. Dots: Greenex data; crosses: data from Ulff-Møller (1977) recalculated to bulk rock compositions (30 to 50% Fe in iron cumulate); circle: metallic iron from south Disko (Klöck, 1986).



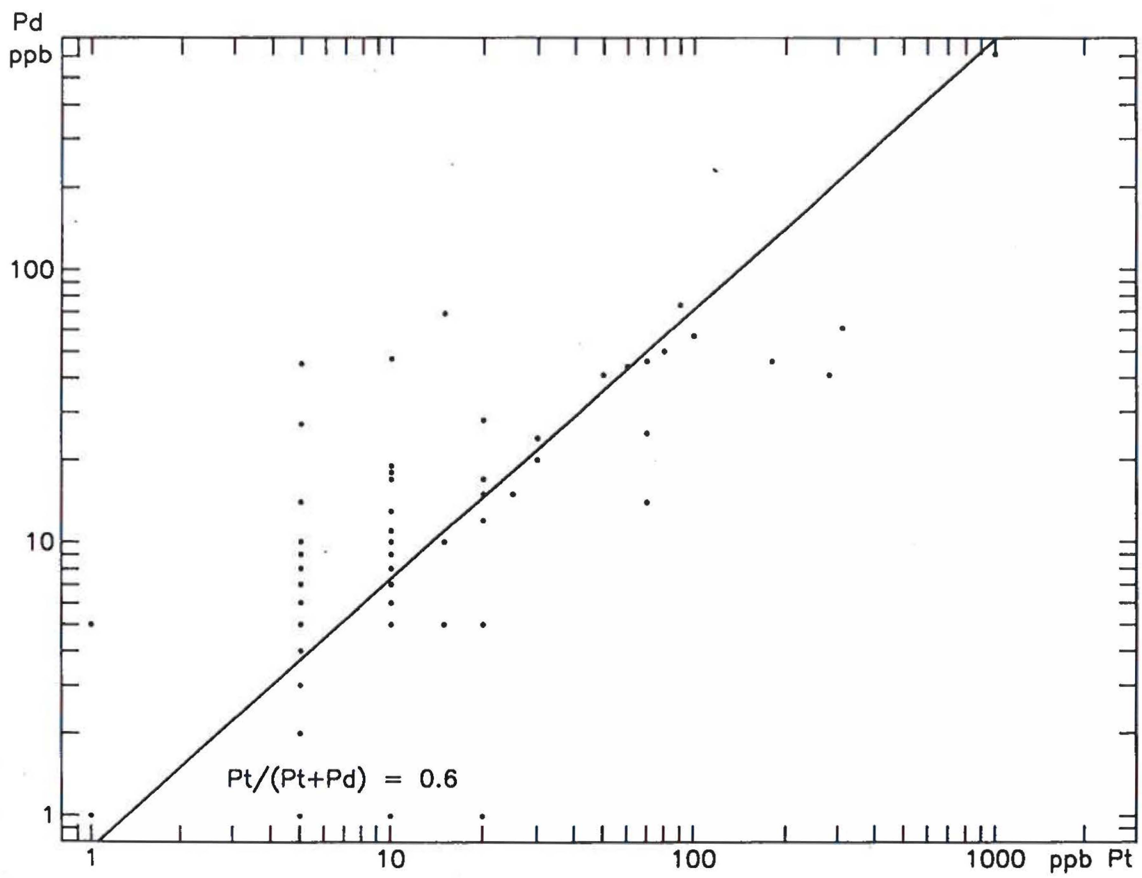


Fig. 10. Pt, Pd and Ni in other mineral occurences (excl. the Hammers Dal Complex). The Stordal Dyke: encircled dots. Reference lines as in Fig. 9.

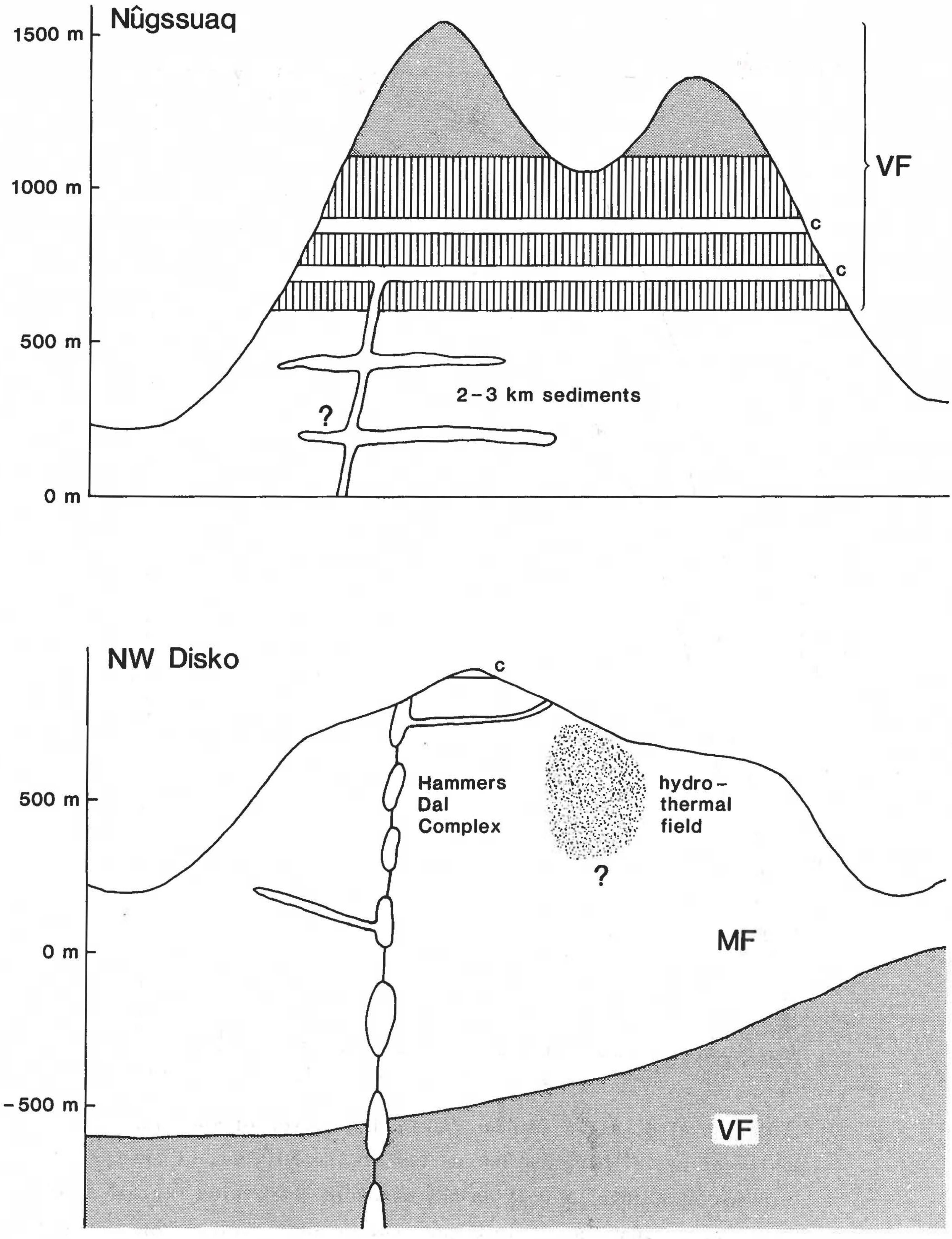


Fig. 11. Geological setting of mineralized intrusions on Disko and Nûgssuaq (scematically).

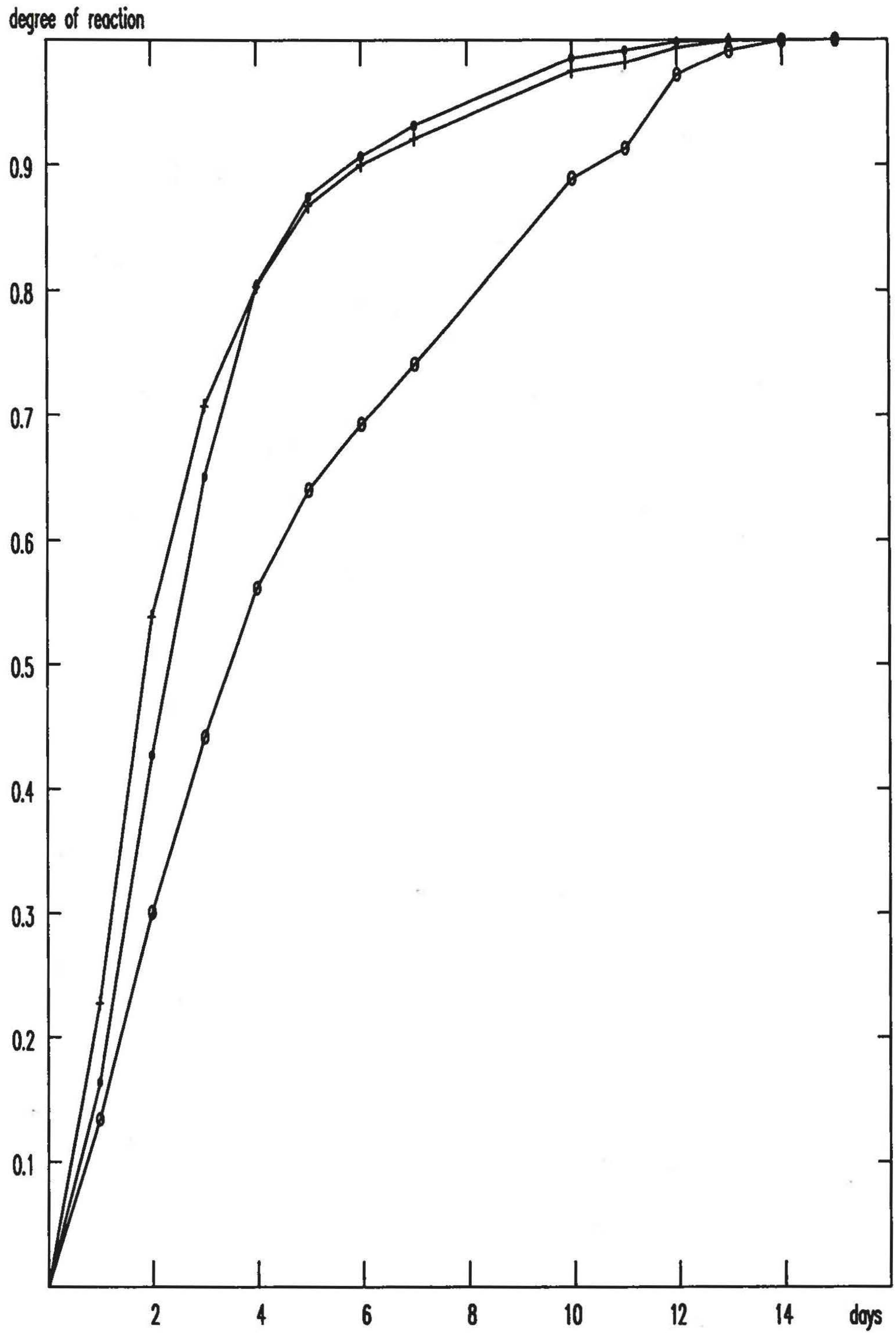
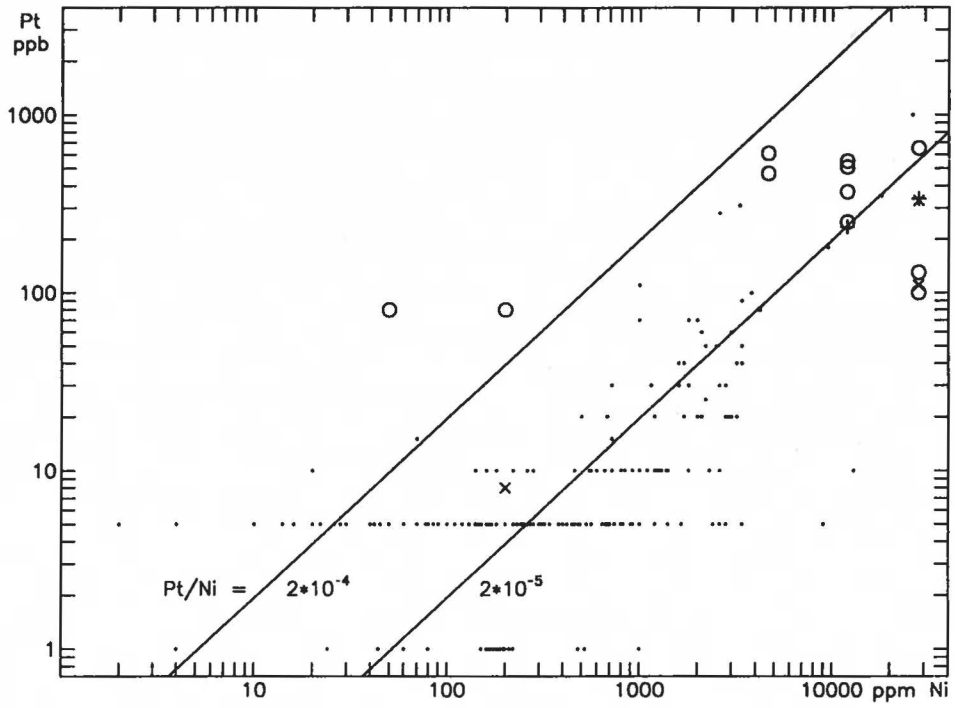


Fig. 12. Oxidation of metallic iron at 700oC. The degree of reaction was monitored by weighing and normalized to the bulk weight change. The bulk weight change as well as the magnetic properties suggest that the final product is mainly magnetite. Crosses: 175954-05; circles: 175958-05; dots: 176004-05; c: crushing. Oxygen was led over the samples after the 5th day.



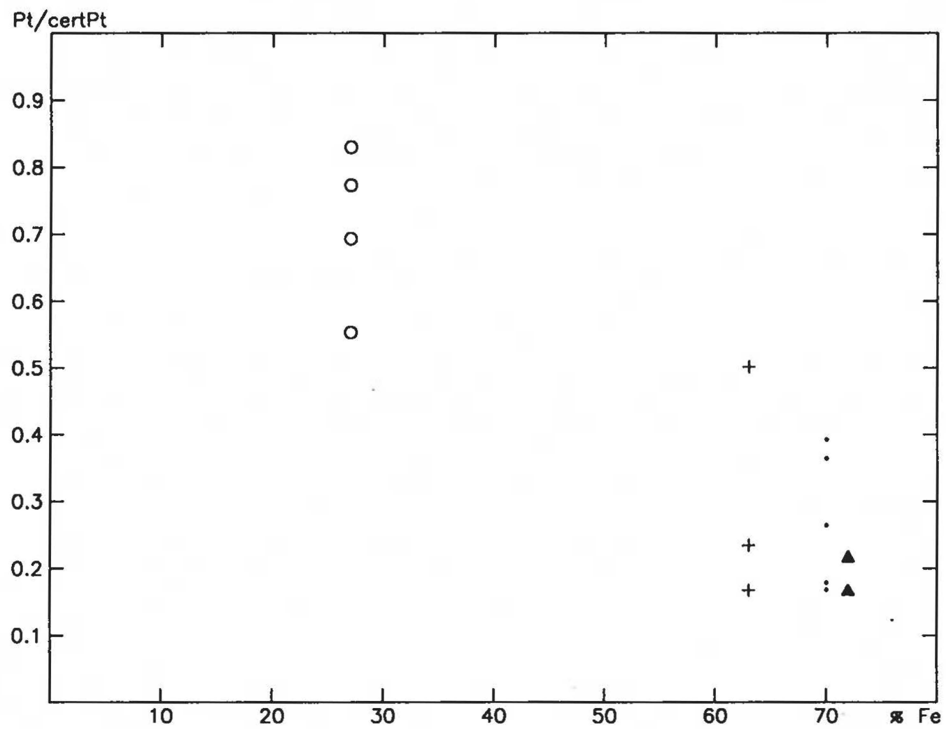


Fig. 13. Pt analyses of iron concentrates from the Hammers Dal Complex (x: lab A; +: lab B; circles: lab C) compared with the Greenex data (dots). Reference lines as in Fig. 9.

Fig. 14. Pt recovery as a function of the Fe content of the sample. Our determinations for the reference materials PTC-1 (circles) and PTA-1 (crosses) were normalized to the certified values. The analyses of the reference materials suggest that the Pt recovery is strongly dependant on the Fe content. For comparison, data for the iron samples (175958: dots; 176006: triangles) are normalized to our previous values (in Ulff-Møller, 1977) which is, of course, tentative.

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