DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/11

Projects Aeromag 1995 and Aeromag 1996

Results from aeromagnetic surveys over South Greenland (1995) and South-West and southern West Greenland (1996)

Leif Thorning and Robert W. Stemp

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

G E U S

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

GEUS

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Abstract

After the successful start in 1994 of Project AEM Greenland 1994-1998 in Inglefield Land, North-West Greenland and under the influence of continuing requests from the mineral exploration industry for airborne geophysical coverage of Greenland in general, the need for additional airborne geophysical programmes became increasingly evident. Mainly as a consequence of this, a new regional aeromagnetic survey programme was initiated and financed jointly by the governments of Denmark and Greenland, starting in 1995 with a first survey over South Greenland (Project Aeromag 1995) and followed in 1996 by a survey over South-West and southern West Greenland (Project Aeromag 1996). The Geological Survey of Denmark and Greenland (GEUS) has carried the overall responsibility for the two projects, which are now concluded with the release of the last of the data in March 1997.

Semi-detailed, high resolution aeromagnetic coverage is now available for most of Greenland below latitude 61° 30' on the east coast and over the Inland Ice, and below 63° 45' on the west coast. The surveys were flown separately by two geophysical contractors, Sander Geophysics Ltd (1995) and Geoterrex Ltd (1996). Line spacing is 500 metres and control lines are 5000 metres apart. Line direction is approximately NW-SE with a sensor altitude of approximately 300 metres over terrain (gentle drape). A total of 157 032 line kilometres were acquired during the two projects covering an area of 67 553 km^2.

These data provide a base for the continuous mapping of regional geologic features across exposed geology and over areas covered by ice, water and overburden. All known and - despite this being a well visited and well described area - also many new and interesting geological features have been outlined by the two new aeromagnetic surveys. These will play a major future role in understanding the complex geological setting of the Precambrian in Greenland. Ground geological investigations can now be linked over larger distances than was possible previously; structures connecting the east and west coasts in South Greenland can in several cases be mapped quite accurately.

Digital data, maps and processing reports are available from GEUS.

Introduction

The first aeromagnetic survey financed by public funds and carried out by commercially based geophysical contractors using modern, high resolution equipment was the 1979 survey offshore East Greenland funded by a Danish public Energy Research Programme, Project EASTMAR (Thorning *et al.,* 1982). The first aeromagnetic survey, specifically related to the search for *mineral resources and geological mapping* in general, was Project Aeromag 1992 (Thorning, 1993), flown over a part of the Precambrian of central West Greenland just south of Disko Bay. This was mainly financed by the Mineral Resources Administration, Ministry for Environment and Energy, Denmark, and the Geological Survey of Greenland (GGU).

The successful start of Project AEM Greenland 1994-1998 (Stemp & Thorning 1995a, b) signalled a new level of public involvement in mineral exploration in Greenland. Project AEM Greenland 1994 - 1998 is financed by the Government of Greenland and is concerned with electromagnetic and magnetic surveys over selected areas in Greenland. The project has so far resulted in a GEOTEM transient electromagnetic survey over Inglefield Land in 1994 (Stemp & Thorning 1995a, b), another GEOTEM survey of an area in the Nuuk-Maniitsoq region in 1995 (Stemp, 1996a, b), and helicopterborne frequency domain and multi-parameter surveys over five areas in the Grønnedal region, South-West Greenland in 1996 (Stemp, 1997). The project presently includes definite plans and a signed contract following an EU tender for a GEOTEM survey in central East Greenland in 1997, while the plans for 1998 have not yet been finalised.

This report pertains to the two latest regional aeromagnetic surveys of Project Aeromag 1995 and Project Aeromag 1996, financed jointly by the governments of Denmark and Greenland as part of an agreement between the two governments made in 1994 for the period 1995 - 1997 and aimed at the promotion of mineral and hydrocarbon exploration in Greenland. The programme of regional aeromagnetic surveys will continue in 1997, with a 70 000 line kilometre survey over the Disko Bay - Nuussuaq region of central West Greenland financed by the Government of Greenland. The contract for this has been signed after a public EU tender concluded in March 1997. Plans for 1998 are preliminary and no firm funding is as yet available.

The two regional aeromagnetic surveys from 1995 and 1996 were carried out independently by two geophysical contractors, each selected after an international tender according to the rules laid down by the European Union for public contracts. In both projects many companies put in a bid for the work. The survey of a large area of South Greenland was carried out by Sander Geophysics Limited, Ottawa, from 12 August 1995 to 15 March 1996 (Project Aeromag 1995). A total of 89 755 line kilometres covering an area of 39 187 km^2 were acquired using two geophysically equipped survey aircraft based at Narsarsuaq. Later, a survey of an area on the west coast of Greenland (Project Aeromag 1996) north of the first survey area was carried out by Geoterrex Ltd. from 3 June 1996 to 14 September

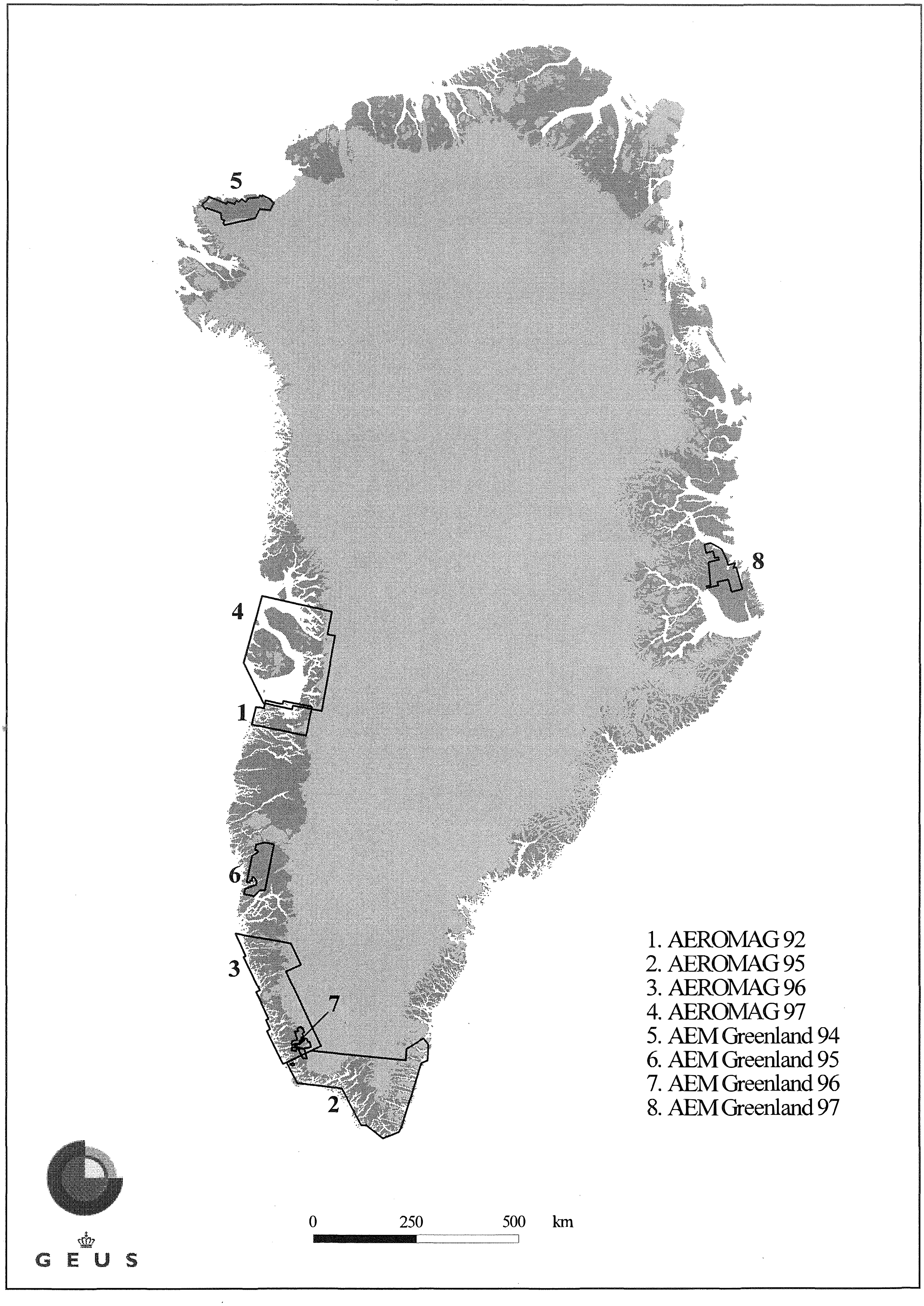
1996 using a single aircraft based at Nuuk, acquiring 67 277 line kilometres over an area of 28 366 km^2. Thus, a total of 157 032 line kilometres covering approximately 67 553 km^2 of Precambrian terrain were acquired in the two projects. After the first of March 1997 all data are released to the public and are now available from GEUS.

The department of economic geology, Geological Survey of Denmark and Greenland (GEUS), has planned and managed all of the government financed surveys mentioned above, until 1995 within the framework of the Geological Survey of Greenland (GGU), and since 1995, after the merger of the two geological surveys (DGU and GGU; Ghisler, 1996), as a part of GEUS. The two projects reported here were under the direction of project leader Leif Thorning and geophysicist Robert W. Stemp.

This report provides an overview of the two projects. Selected aspects of survey parameters and field operations are discussed and a brief description of selected features in the magnetic data is included. Detailed descriptions of the survey aircraft, geophysical and navigation equipment, calibrations and data processing techniques have been presented in separate reports by each of the airborne survey contractors (Meusy, 1996; Allen, 1997). The position of all the mineral exploration airborne surveys mentioned in this introduction can be seen on Figure 1 (see following page).

Figure 1 (Next page): *Aeromagnetic (AEROMAG) and electromagnetic/magnetic (AEM) surveys carried out by GEUS in the period 1992 - 1997*

Airborne geophysical surveys in Greenland 1992 - 1997



Geological setting

The area covered by the two aeromagnetic surveys reported here belongs to the Precambrian craton of Greenland, described in a number of classical papers, to which the reader is referred for a full description of the geology. A comprehensive review can be found in Escher & Watt (1976), which contains complete references to prior relevant publications. More recent reviews discuss revised perceptions of some of the features in the area. Useful overviews of existing geoscience data, including the current information on geology and economic geology, can be found in two issues of the Thematic Map Series compilations of geoscience data (Thorning *et al.*, 1994; Ady & Tukiainen, 1995), although the aeromagnetic anomaly maps in these compilations now have been superseded by the new anomaly maps produced in Aeromag 95 and Aeromag 96. Finally, the still ongoing Project SUPRASYD has resulted in a number of new ideas and discoveries concerning the southernmost part of Greenland, recently summarized in Chadwick & Garde (1996). A complete account of the geology will not be given here, but the following main elements set the geological scene.

The two main geological regions in the combined survey area are the Archaean craton to the north and the Palaeoproterozoic Ketilidian orogen to the south. The boundary between the two is at the west coast placed near 61°30'; north of this is what is usually referred to as 'the border zone', a part of the Archaean craton to varying degrees influenced and overlain by the Ketilidian supracrustal rocks and tectonic events and the later Midproterozoic Gardar events. The border zone is thought to be present under the Inland Ice all the way to the east coast.

The Archaean craton of Greenland is the largest and best exposed craton of the North Atlantic cratons (Brewer, 1996). It consists mainly of granitoid quartzo-feldspathic gneisses probably largely derived from acid or intermediate igneous rocks, but also encompasses rafts of amphibolites, probably derived from metavolcanics, and anorthosites. There are many occurrences of supracrustal rocks of varying age within the surveyed area, however, the Tartoq group in the southern part of the Aeromag 1996 survey area is the best known of the supracrustal sequences. Most of the craton have experienced several phases of folding, faulting and/or metamorphism, often in granulite facies. The well known Fiskenæsset complex is situated within the Aeromag 1996 survey area, near its northern boundary. It is a stratiform intrusion covering an area of approximately 2500 km^2 containing anorthosites, leucograbbro and gabbro with minor amounts of ultramafic rocks and chromitite and has been dated to approximately 2800 MA.

In the southern part of the Aeromag 1996 survey area the Archaean gneisses are at places unconformably overlain by well preserved undeformed and unmetamorphosed Palaeoproterozoic sediments and basic volcanic rocks. Further to the south these sediments become strongly deformed and metamorphosed by the Ketilidian orogen. This is the Border Zone between the Archaean craton and the Palaeoproterozoic Ketilidian orogen. The character of the corresponding zone on the east coast is geologically different.

The most recent description of the Palaeoproterozoic Ketilidian orogenic belt, age approximately 1800 MA, is given in Chadwick & Garde (1996), which contains full references to earlier publications. Adopting here the definitions of Chadwick & Garde (1996), the Ketilidian orogen can be divided into four zones: the Border zone, the Julianehåb batholith, the Psammite Zone and the Pelite Zone, see Figure 2. The southern limit of the Border Zone is usually placed at the Kobberminebugt shear zone on the west coast. The Julianehåb batholith comprises polyphase granites, granodiorites, tonalites, diorites and subordinate metagrabbros and amphibolite dikes. The batholith was, according to Chadwick & Garde (1996), emplaced during sinistral transpression as a result of oblique convergence between the Archaean continental plate to the north and a no longer preserved oceanic plate to the south. It can be interpreted as the roots of a volcanic arc, which became the source for the rocks in the Psammite and Pelite zones. The batholith contains several mylonites and shear zones. The Psammite and Pelite zones are thought to have been deposited in intra-arc basins and the inner part of a forearc between the batholith and an ocean to the south. The sedimentary rocks were later migmatized and deformed prior to the emplacement of rocks of the rapakivi suite.

Approximately 1200 MA another main event, the Gardar period, affected South-West Greenland, resulting in the formation of sedimentary and volcanic rocks as well as intrusions and several generations of dikes, see Emeleus & Upton (1976). This is known to have influenced the western part of South-West and South Greenland, but so far rocks of this age have not been proven to be present on the east coast except for some mafic dikes.

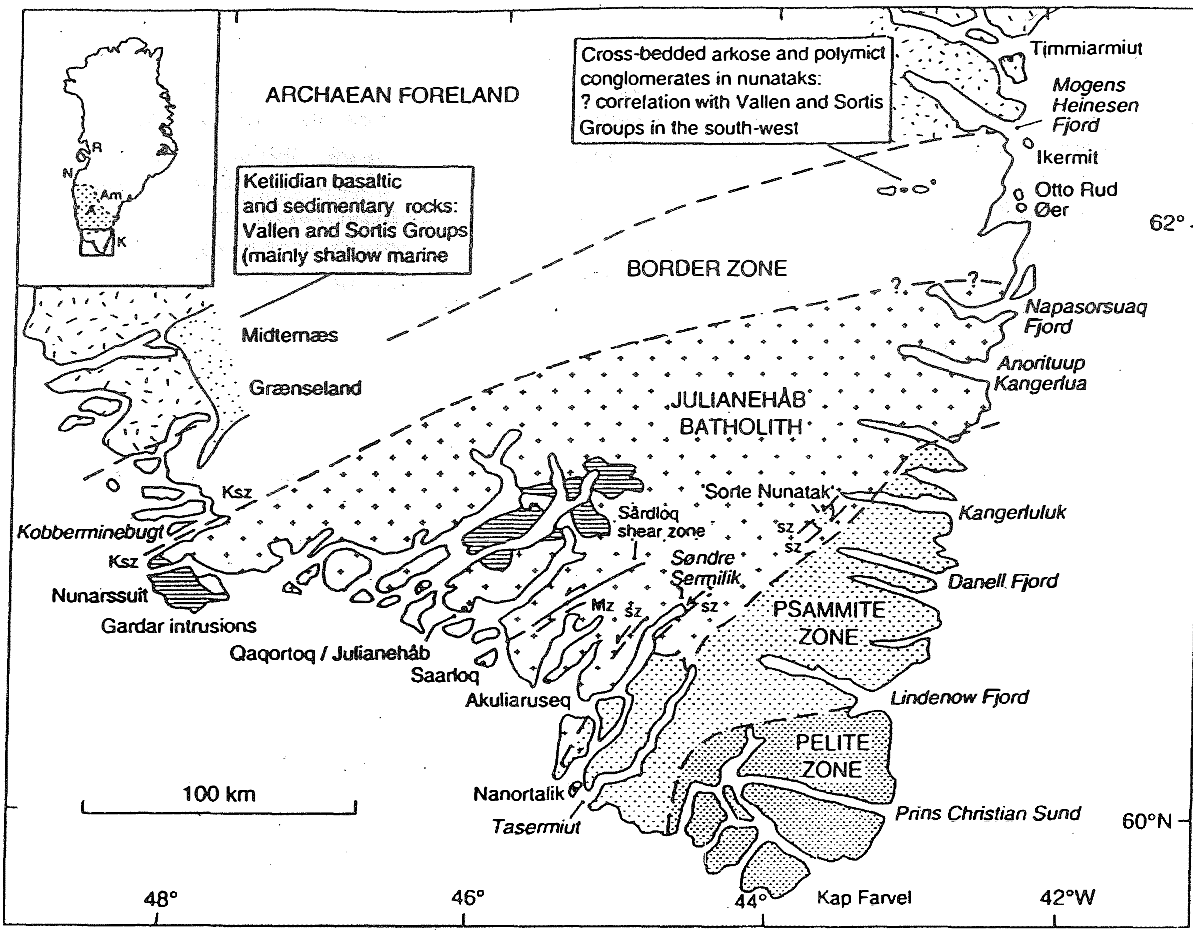


Fig. 1. Summary map of the Ketilidian Orogen, South Greenland, showing the principal divisions: Archaean foreland, Border Zone, Julianehåb batholith, Psammite Zone and Pelite Zone. Much of the orogen is covered by the Inland Ice. Ksz, Kobberminebugt shear zone; sz, shear zone; Mz; Matorssuaq zone of high-strain orthogneisses; horizontal ruling: Gardar sedimentary and volcanic rocks and intrusions. Inset map of Greenland shows the area of the summary map, the Archaean block (A), and the Palaeoproterozoic Ketilidian (K), Ammassalik (Am), Nagssugtoqidian (N) and Rinkian (R) orogenic belts.

Figure 2: *Summary of geology taken from Chadwick & Garde (1996)*

Survey parameters and statistics

The survey parameters for the two aeromagnetic surveys were intentionally kept similar. Regular survey lines were spaced at 500 metres intervals and oriented N30W, perpendicular to the regional geological strike. Control or tie lines were flown at 5000 metres intervals in an orthogonal direction to the regular survey lines. Survey terrain clearance was set at 300 metres using a gentle drape and best effort basis. Accurate navigation and positioning were provided by differential GPS systems. Video cameras were also on board each aircraft as a backup, but the recorded videos were used primarily for photogeological purposes.

Diurnal tolerance was set at a maximum of 10 nT from a chord of 1 minute in length. All control lines were flown during "quiet" diurnal periods and without line breaks, whenever possible. Line spacing was not allowed to exceed 1.5 times the nominal spacing over a distance greater than 3 kilometres. The nominal absolute positioning is in both surveys better than 25 metres.

The airports used for these surveys were Narsarsuaq, main base of operation for Sander Geophysics Ltd during Project Aeromag 1995 and Nuuk, main base of operation for Geoterrex Ltd during Project Aeromag 1996. Narsarsuaq has a good paved runway (1900 metres) but the surrounding hills necessitate visibility of six km. and a ceiling of 500 metres. The airport at Nuuk is also paved, but shorter (950 metres). The main problem for this airport is the occasionally prolonged periods of foggy weather. Normal airport operating hours at both airports are nine hours per day, six days per week, although extended hours can be arranged for at additional cost, a service it was necessary to use in both surveys.

Although different aircraft were used for the two surveys, all aircraft were operated at a normal survey flying speed of 160 knots (82 metres per second) allowing the recording of magnetic anomaly wavelengths less than 50 metres (approximately 8 metres sampling distance). Ambient wind and topography of course resulted in significant local deviations from this norm.

Aeromag 1995: South Greenland

The Aeromag 1995 survey was laid out to cover most of the Ketilidian mobile belt of South Greenland and as much as possible of the boundary to the older Archaean rocks to the north in as detailed a manner as possible using fixed-wing aircraft. Alpine terrain with elevations ranging from sea level to over 2000 metres was a major obstacle. In the flying a unique and new option was used for the first time, a computer assisted drape flying program designed and successfully implemented by Sander Geophysics Ltd. during this project. This enabled the flight crews to maintain an optimal drape position at all times, thus minimising problems usually associated with terrain clearance in mountainous regions, and consequently producing both a better and a safer survey. The method is based on a digital elevation model combining the terrain of the region with slopes adjusted to the optimal rate of climb and descent of the aircraft used for the survey. The aircraft auto pilot uses this model to position the aircraft on the optimal drape surface, which ensures better continuity both along lines and across lines.

Each survey aircraft was identically equipped with a caesium magnetometer mounted in a 2.5 metre tail stinger and using a magnetic compensator manufactured by RMS Instruments. Magnetometer sensitivity was 0.01 nT with a recording rate of 10 Hz. The figure of merit of each aircraft was calculated based on manoeuvres in the field area and gave the results included in Table 1.

Table 1. *Key dates and figures of merit for Project Aeromag 1995*

Aircraft 1	**Cessna 402B (registration C-GCKB)**
08 Aug.	arrival in Narsarsuaq from Africa
12 Aug.	calibration & first production flight
13 Aug.	start of major maintenance in Narsarsuaq
21 Sept.	production resumed
29 Sept.	Figure of merit: 1.58 nT
02 Dec.	Figure of merit: 1.45 nT
13 Dec.	Christmas break
10 Jan.	return to Narsarsuaq
17 Jan.	Figure of merit: 1.92 nT
15 Mar.	final production flight
Aircraft 2	**Beechcraft Queenair B80 (registration C-FWZG)**
12 Aug.	arrival in Narsarsuaq from Canada
13 Aug.	calibration & first production flight; Figure of merit: 0.65 nT
25 Oct.	to Canada for engine change/major maintenance
06 Feb.	return to Narsarsuaq
08 Feb.	Figure of merit: 1.32 nT
14 Feb.	engine failure on survey; no further use of aircraft for this project

Table 2. *Production per calendar month, Project Aeromag 1995*

Month	Available aircraft days	Line kilometres flown	Line kilometres flown per day
Aug 95	20	7,201	360
Sept	40	10,622	266
Oct	55	41,688	758
Nov	30	7,592	253
Dec	12	3,723	310
Jan 96	21	4,292	204
Feb	37	9,184	248
Mar	15	5,453	364
Total	**230**	**89,755**	**390**

Survey flight crews consisted of two licensed pilots in the aircraft cockpit to share the flying duties as well as operate all geophysical and navigational equipment. Survey flights were on average about 4.3 hours in duration. Two flights per day per aircraft were flown when weather and daylight conditions were adequate. A total of 137 production flights were needed to finish the survey over seven months. The survey operations of Project Aeromag 1995 were originally planned to start in Narsarsuaq in early May 1995 using a single geophysically equipped aircraft with an estimated average production rate of approximately 550 kilometres per day. This estimate was based on a study of weather and diurnal statistics in South Greenland. For reasons beyond the control of the contractor and GEUS, survey production did not commence until early August. To overcome this late start the contractor made a second aircraft available at no additional cost to the project.

Airborne geophysical surveying in Greenland can be difficult and unpredictable, especially so in South Greenland. To illustrate this, actual production figures are shown in Table 2. Seven months were required to complete the total survey, because the originally estimated production rate was only achieved in the month of October 1995, during which approximately 46% of the survey was flown. Note that two aircraft were not always available due to required maintenance. Also, there was a break in the operations over the Christmas period (see Table 1).

During the survey, rigorous safety precautions were maintained. Using two aircraft up to four flights could be obtained per day, although available daylight hours allowed only one flight per day per aircraft during the winter period. No suitable alternate airstrip was available so weather conditions in Narsarsuaq had to be constantly monitored. One potentially dangerous engine failure occurred on 14 February 1997, while aircraft C-FWZG was at survey altitude. Fortunately the aircraft was able to gain altitude and return to base on one engine.

Of all the limitations for a swift execution of the survey operation, weather was the key obstacle for production. This can be seen by the fact that production per flight over the entire field operation averaged 611 km. accepted data including aborted and non-productive flights. This is an excellent production figure.

Aeromag 1996: South-West and southern West Greenland

The survey grid of this project was laid out to continue the 1995 survey to the north along the west coast of Greenland over Precambrian (Archaean) geology. Though desirable from a scientific point of view it was not possible to continue the Greenland Inland Ice coverage from coast to coast. However, the survey area was widened as much as possible to include near coastal areas offshore and a significant part of the western margin of the Inland Ice in order to ensure sufficient lateral mapping of structures. Also, it was decided to decrease the number of line kilometres to be flown in order to minimise the risk of a prolonged field period.

Survey parameters were similar to those for the survey flown in 1995 over South Greenland: 500 metres line spacing, 5000 metres between control lines, a line direction of N37W,

and 300 metres altitude in a gentle drape. Specifications for diurnal magnetic variation and positioning were also the same.

The survey aircraft was equipped with a caesium magnetometer mounted in a tail stinger and using a magnetic compensator manufactured by RMS Instruments. Magnetometer sensitivity was 0.001 nT with a recording rate of 10 Hz. The figure of merit of the aircraft was calculated based on manoeuvres in the field area on three separate occasions and the results were found to be very good: 1.611 nT (5 June 1996), 0.933 nT (12 August 1996), and 1.306 nT (3 September 1996).

The method of computer assisted drape flying was also used, this time by use of a system developed by Geoterrex Ltd for the aircraft used, a Cessna Titan 404 (C-GGTA). As in South Greenland, the survey area for 1996 encompasses severe topography. Operations were logistically a little more convenient because there are airports situated both north and south of the survey area (Nuuk and Narsarsuaq).

The weather was also for this survey the major obstacle for a fast and smooth operation. On a few flights an unexplained noise signal from an external source caused serious problems for the recording of the magnetic data and the flight had to be abandoned and the lines in question re-flown at a later time. In Table 3, the survey statistics for the Aeromag 1996 survey compiled by Geoterrex Ltd is given. The average production of 646.9 line kilometres per flight is an excellent figure testifying to a very efficient operation. The high number of days lost to bad weather is also worth noticing. It is probably typical for operations in the southern part of Greenland, which is susceptible to variable front weather with high winds and precipitation. Further north the weather in general becomes more stable and usually fewer days are lost to bad weather.

Table 3. *Survey statistics for Aeromag 1996*

Total production:	67,277.1 km
Number of production flights:	90
Hours of production flying:	338.1 hours
Km flown per production hour:	199.0 km
Km flown per average production flight:	646.9
Days in the field:	104
Days lost to equipment and testing:	4
Days lost to weather:	52

Processing of data

For both surveys a significant amount of processing was done in the field, in Narsarsuaq in 1995/1996 by Sander Geophysics Ltd, and in Nuuk in 1996 by Geoterrex Ltd.

In the field office, after each survey flight, analogue profiles are produced from digital flight data if not already produced in flight for each survey line. The following traces are usually plotted: magnetometer at several resolutions, calculated 4th difference for the magnetics, barometric altimeter, radar altimeter, GPS latitude, GPS longitude, time, date, flight number and line number. The ground station magnetometer data is also plotted on the same chart record to permit immediate identification of any diurnal effects on the airborne data. There are differences in the detailed methods used by each of the two contractors. Within 24 hours of each flight a differentially corrected flight path plot is also produced.

These two preliminary products provide a means for quality control of the data by the geophysical contractor and on-site GEUS personnel to ensure that all specifications of the contract are adhered to or if reflights are required.

Following the quality control procedures and when sufficient data are available, preliminary magnetic contour maps are produced in the field. Together with the multi-parameter profiles, the contour maps are examined by GEUS geophysicists as an initial step of the interpretation.

The final processing and production of deliverable items took place at the respective processing centres of the two geophysical contractors, both located in Ottawa, Canada. The processing encompassed careful levelling of the magnetic data, checks of navigation and other accessory data, production of digital archives of line data and grids, production of final maps and profile plots, and the writing of the processing reports. Details in the processing of the two data sets can be found in Meusy (1996) and Allen (1997).

When the data and other items are received at GEUS, the digital data are entered into the GEUS database of airborne geophysical data and simultaneously undergoes a final data quality control. The digital data is then available for internal use in GEUS. When the data are officially released, the data become available for the public and may be used by anyone interested.

Summary of products

In this section is given a summary of the products of the two surveys. Discussion of some of the results can be found in a subsequent section of this report.

In the authors' judgement, the data acquired in these surveys are of excellent quality. The computerised drape flying has significantly improved (minimised) the cross-over errors of line - control line intersections. The new maps and the digital data make up very important new sources for all geoscientific studies of the region.

Aeromag 1995: South Greenland

This survey consists of 89 755 line kilometres acquired on 656 lines oriented N30W and 58 orthogonal control lines. Line data archives are stored on CD-ROM, which also contains the calculated grids of total magnetic intensity and vertical gradient of the total magnetic intensity in Geosoft GXF or GRD format (100 m by 100 m calculated grid).

The compiled data are delivered as maps in two scales, 1:50 000 (38 map sheets) and 1:250 000 (2 map sheets). The maps contain coastlines and other major topographical features from a digital map of Greenland supplied by GEUS and Kort- og Matrikelstyrelsen, Denmark (UTM zone 22, WGS84).

In Figure 3 an index map of the 1:50 000 maps is show. To illustrate the results three maps in scale 1:2 000 000 prepared by Sander Geophysics Ltd as part of the delivery, are included in this report: in Figure 4 the composite of Total Magnetic Intensity in colour and shadow, in Figure 5 the corresponding map in a shaded grey-scale version, and in Figure 6 the map of the calculated vertical magnetic gradient.

The basic data package available from GEUS consists of the Sander Geophysics Ltd acquisition and processing report and the CD-ROM with all digital data. Maps are also available, but are not part of the basic package.

Table 4. *Map products from Project Aeromag 1995*

1 : 50 000	Flight lines
	Total Magnetic Intensity contour map
	Total Magnetic Intensity contour and colour map
	First vertical derivative
1 : 250 000	Total Magnetic Intensity contour and colour map
	First vertical derivative
	Total Magnetic Intensity shadow (330 , 35)
	Composite colour and shadow

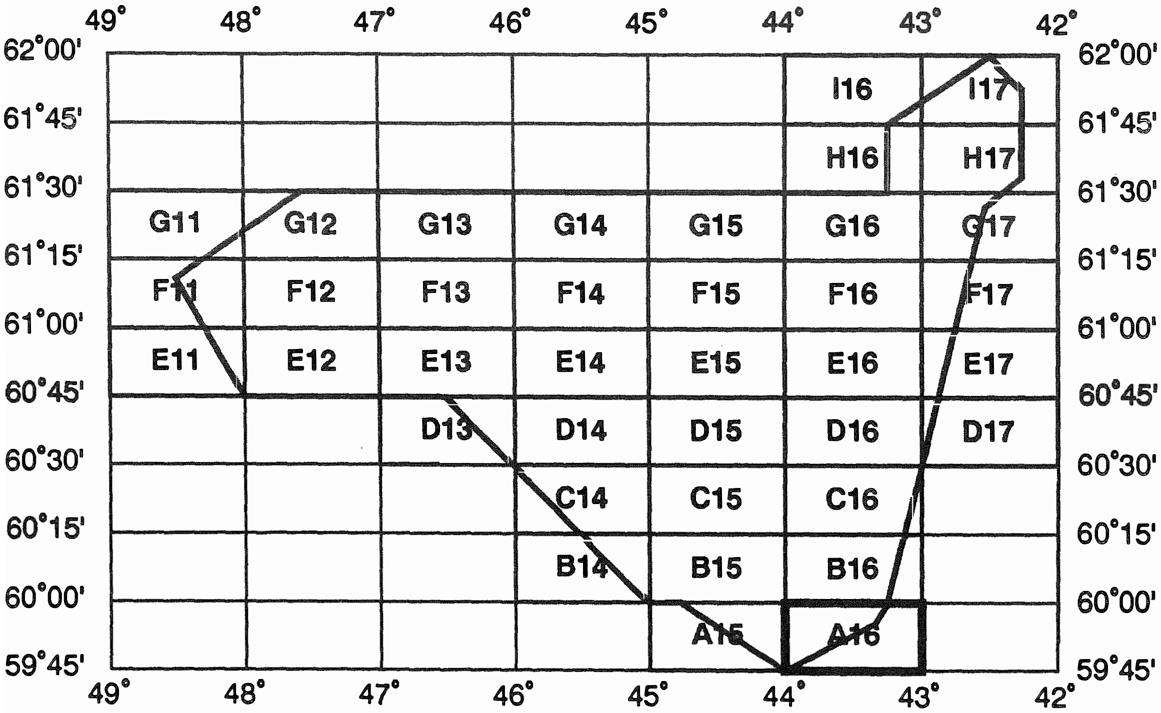
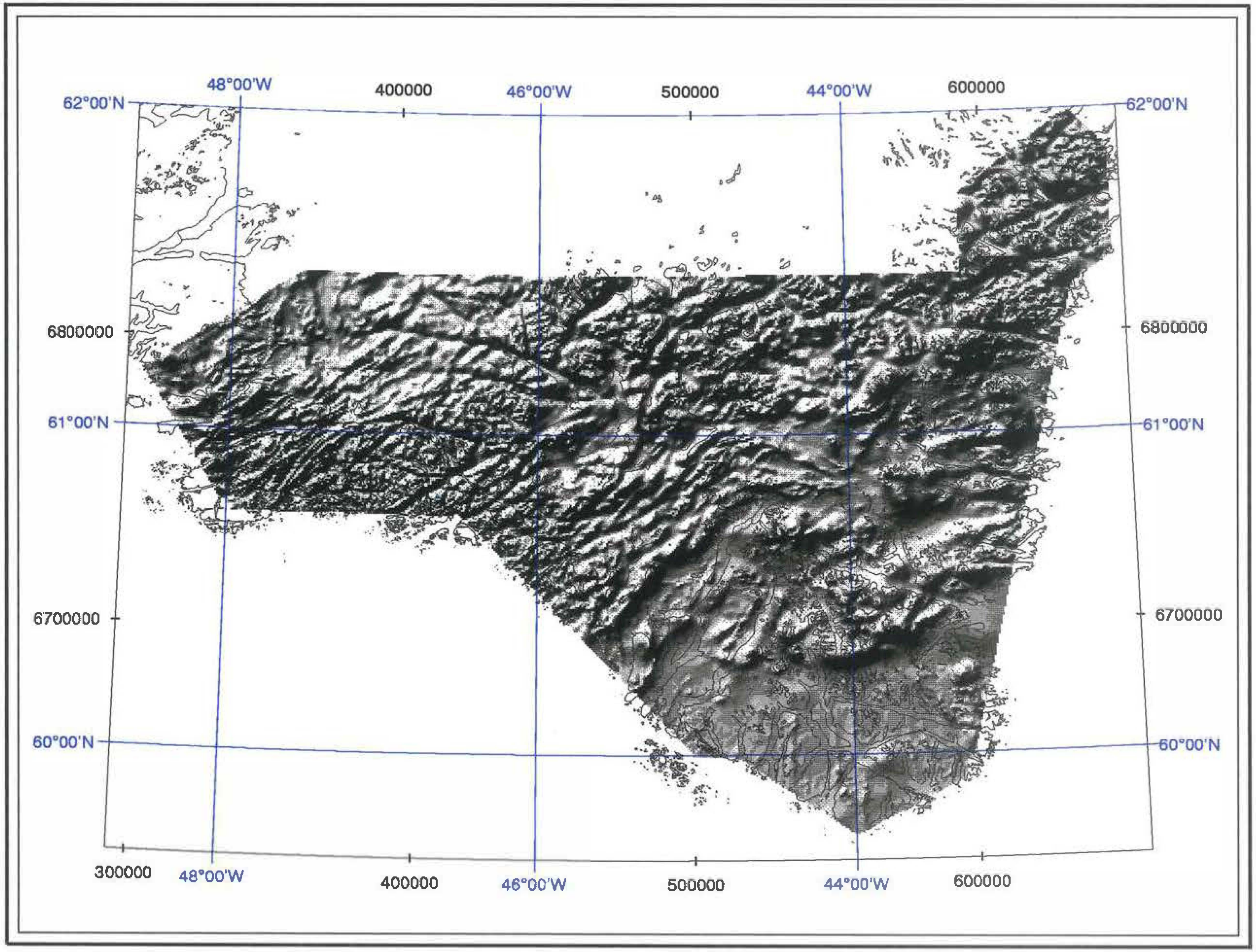


Figure 3: *Map sheets for the survey of Project Aeromag 1995*

Figures 4, 5 and 6 (following three pages): *Total Magnetic Intensity (4 and 5) and vertical gradient (6) anomaly maps.*



GEUS

PROJECT AEROMAG 1995
SOUTH GREENLAND

SHADED RELIEF OF THE TOTAL MAGNETIC INTENSITY

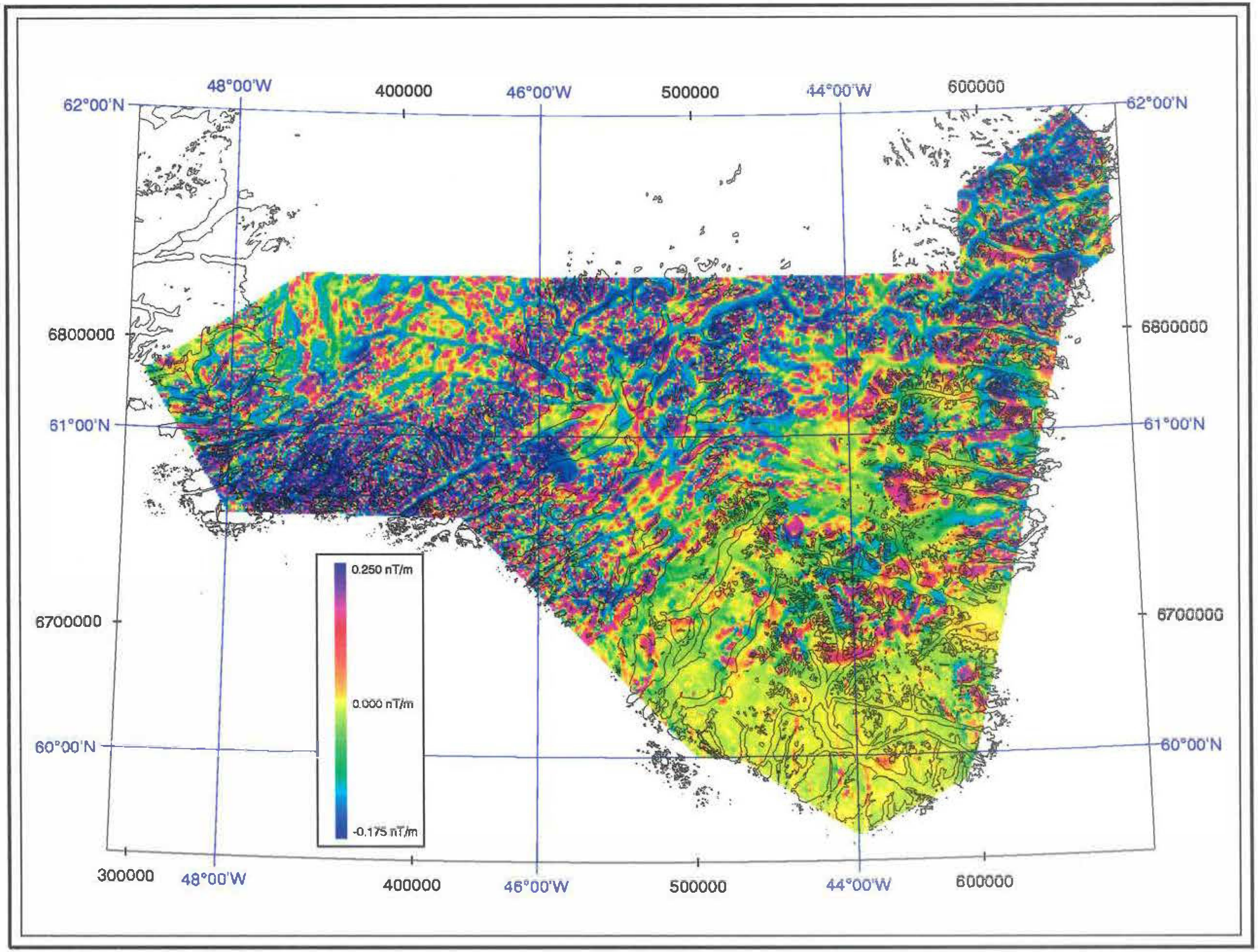
ILLUMINATION
DIRECTION: 330°
INCLINATION: 35°

Project AEROMAG 1995
is jointly funded by
the Governments of Denmark and Greenland
(Mineral Resources Administration
for Greenland
and Minerals Office, respectively).
The project is managed by
the Geological Survey of
Denmark and Greenland (GEUS).

Topographic base from 1: 250.000 maps
supplied by
Kort- og Matrikelstyrelsen (KMS),
Denmark (A200/87)

SCALE 1: 2,000,000

Flown and compiled by
Sander Geophysics Limited



GEUS

PROJECT AEROMAG 1995
SOUTH GREENLAND

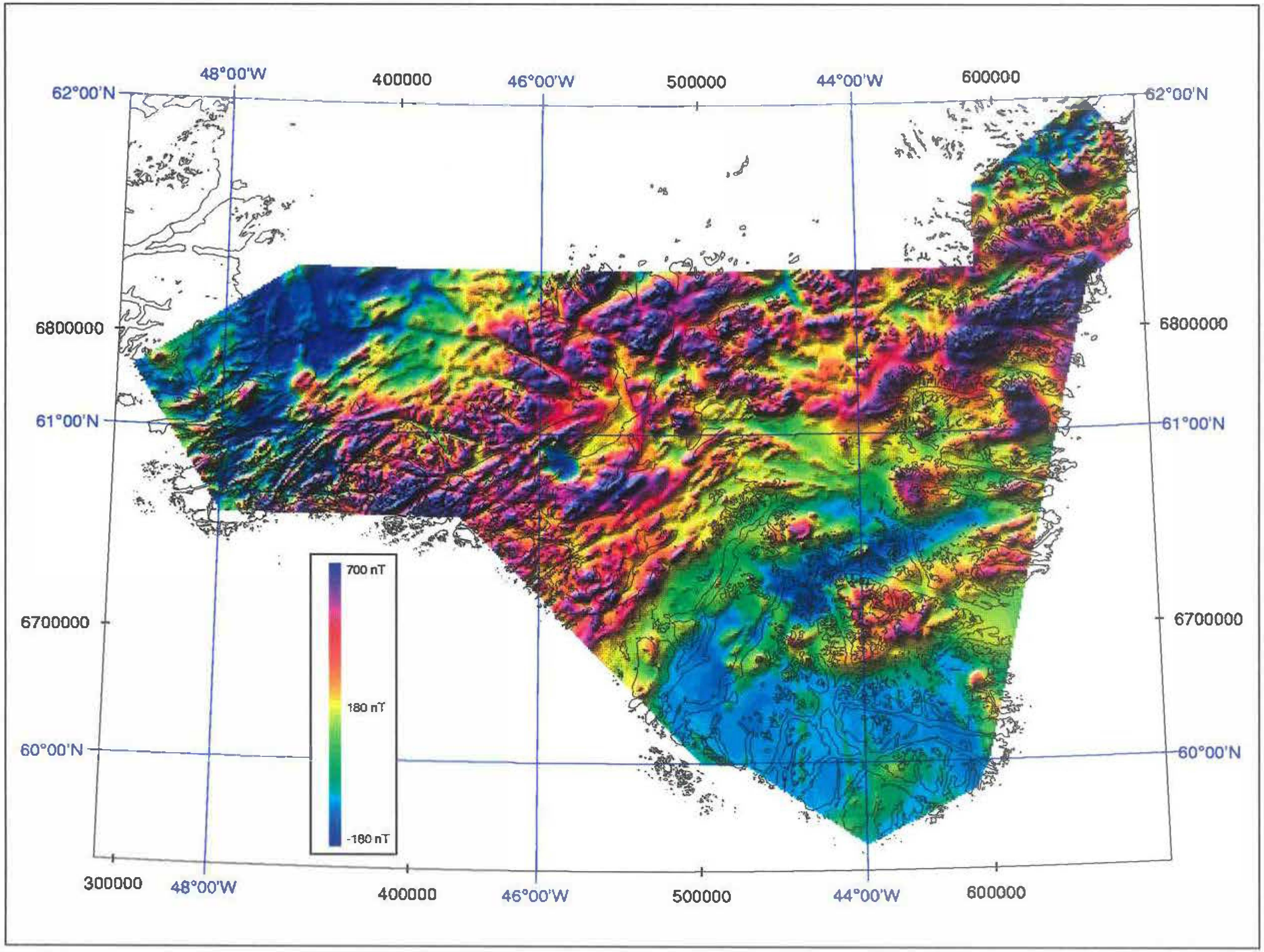
FIRST VERTICAL DERIVATIVE OF THE TOTAL MAGNETIC INTENSITY (nT/m)

Project AEROMAG 1995
is jointly funded by
the Governments of Denmark and Greenland
(Mineral Resources Administration
for Greenland
and Minerals Office, respectively).
The project is managed by
the Geological Survey of
Denmark and Greenland (GEUS).

Topographic base from 1: 250.000 maps
supplied by
Kort- og Matrikelstyrelsen (KMS),
Denmark (A200/87)

SCALE 1: 2,000,000

Flown and compiled by
Sander Geophysics Limited



GEUS

PROJECT AEROMAG 1995
SOUTH GREENLAND

COMPOSITE OF THE TOTAL MAGNETIC INTENSITY COLOUR AND SHADED RELIEF

ILLUMINATION
DIRECTION: 330°
INCLINATION: 35°

Project AEROMAG 1995 is jointly funded by the Governments of Denmark and Greenland (Mineral Resources Administration for Greenland and Minerals Office, respectively). The project is managed by the Geological Survey of Denmark and Greenland (GEUS).

Topographic base from 1: 250.000 maps supplied by Kort- og Matrikelstyrelsen (KMS), Denmark (A200/87)

SCALE 1: 2,000,000

Flown and compiled by Sander Geophysics Limited

Aeroromag 1996: South-West and southern West Greenland

This survey consists of 67 277 line kilometres covering 28 366 km^2 acquired in lines oriented N37W with orthogonal control lines. Line archive data are stored on CD-ROM together with calculated grids of total magnetic intensity and the vertical gradient.

The compiled data are delivered as maps in two scales, 1:50 000 (35 map sheets) and 1: 250 000 (2 map sheets). The maps contain coastlines and other major topographical features from a digital map of Greenland supplied by GEUS and Kort- og Matrikelstyrelsen, Denmark (UTM zone 23, WGS84).

Figure 7 from the Geoterrex processing report (Allen, 1997) gives the location of the sheets in the detailed map series. Figures 8 and 9 illustrate the data from Aeromag 1996, shown by Geoterrex Ltd. in the form of Total Magnetic Intensity as shaded colour anomaly map and Calculated Vertical Magnetic Gradient anomaly map.

Table 5. *Map products from Project Aeromag 1996*

1:50 000	Flight path maps
	Total Magnetic Intensity contour maps
	Vertical Gradient contour maps
	Total Magnetic Intensity colour maps
	Vertical Gradient colour map
1:250 000	Total Magnetic intensity colour map
	Vertical Gradient colour map
	Total Magnetic intensity as grey-scale shadow relief map
	Total Magnetic Intensity pseudo-colour, shadow relief map

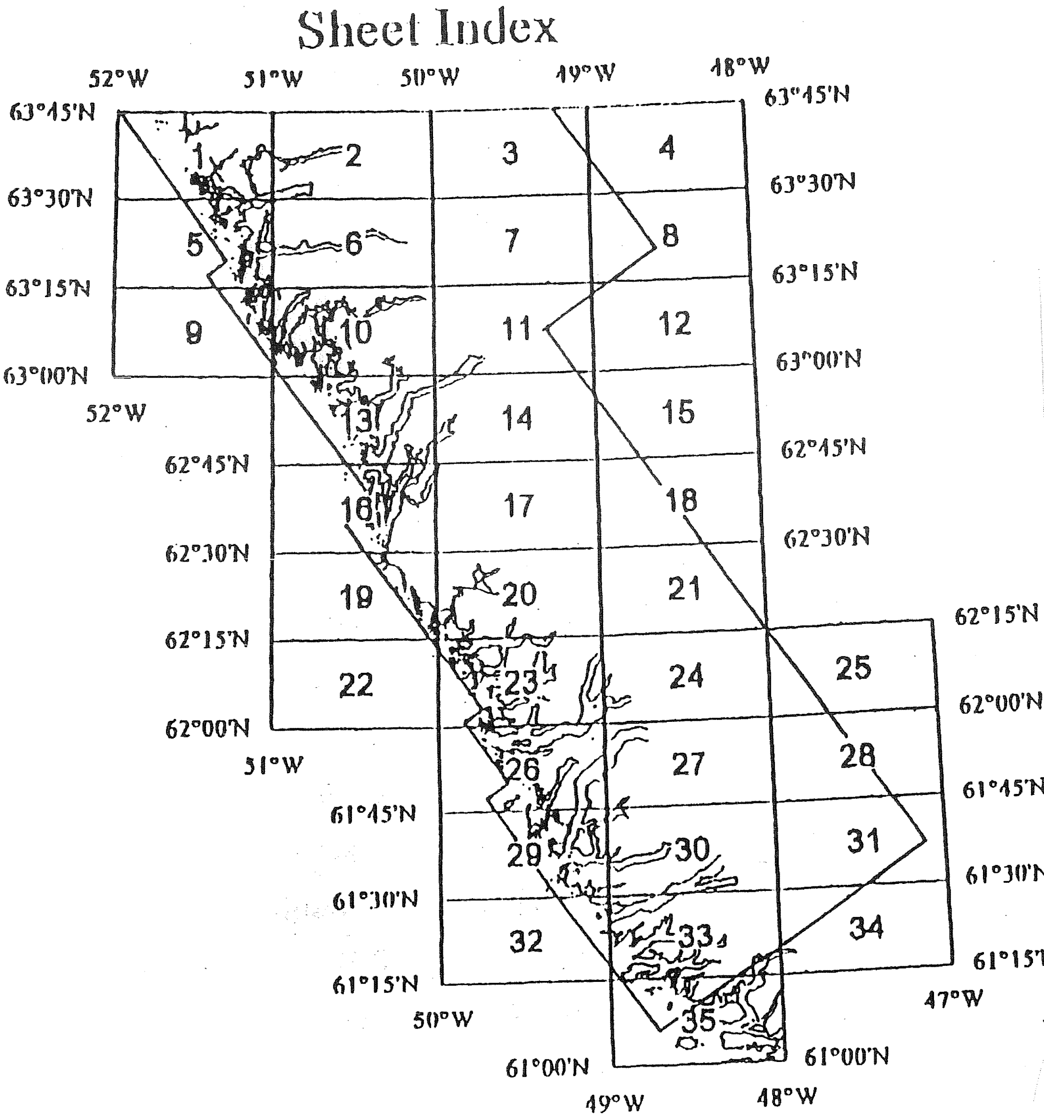
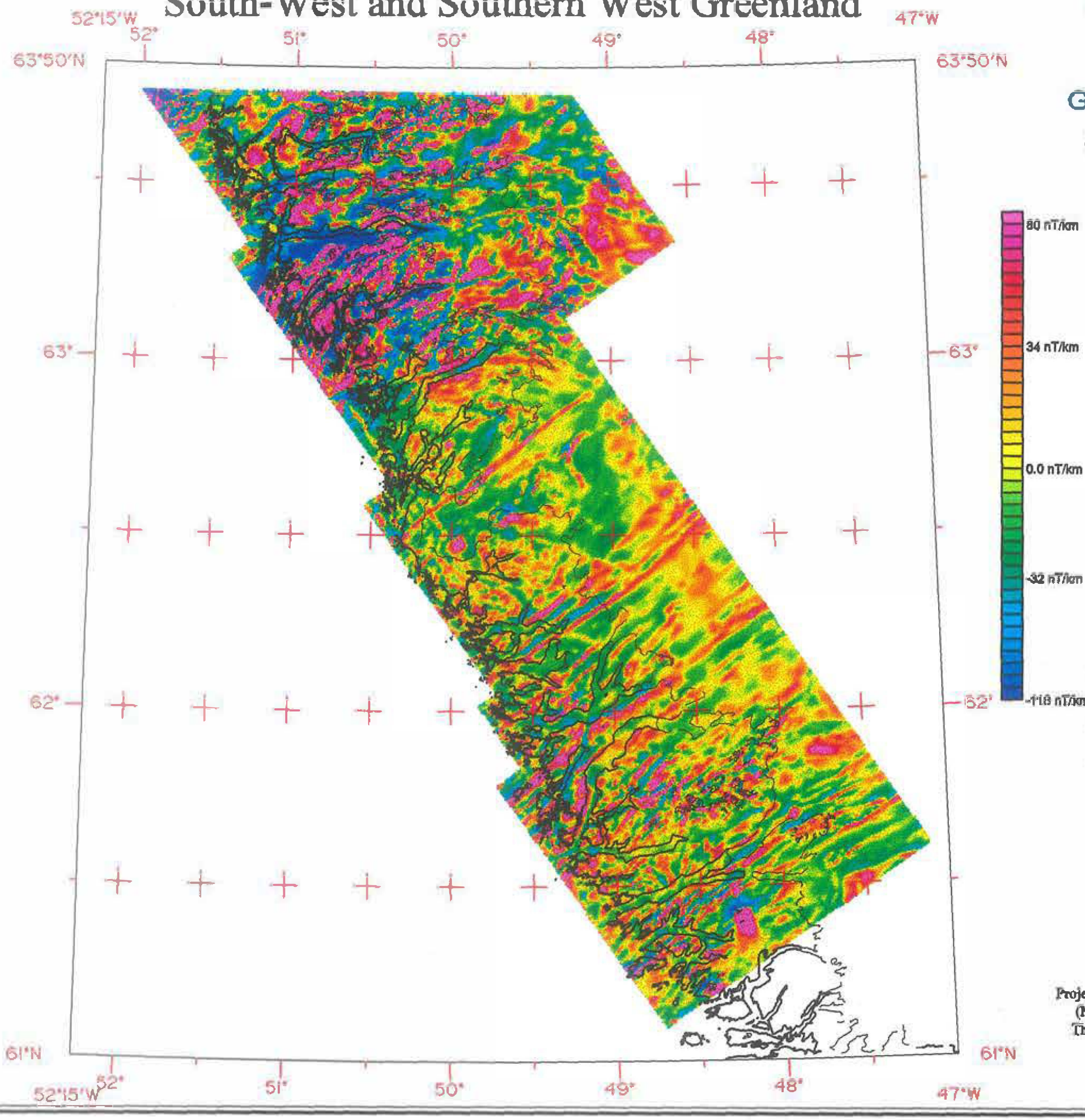


Figure 7: *Index map of sheets in the Aeromag 1996 survey*

Figures 8 and 9 *(following two pages): Total Magnetic Intensity (6) and vertical gradient (7) anomaly maps*

Project AEROMAG 1996
South-West and Southern West Greenland



GEUS

Calculated Vertical Gradient of Magnetics

LEGEND

Coast Line..............................

Sea Water/Ice Cap Boundary.......

Land/Ice Cap Boundary...............

GEODETIC INFORMATION

Projection	UTM	False Easting	500,000 m
Spheroid	WGS84	False Northing	0 m
Central Meridian	51°W	Scale Factor	0.9996

Survey Parameters

Magnetic Data Recording Interval..............0.1 seconds (approximately 8 m)
Traverse Line Spacing..500 m
Traverse Line Direction..N 37° W
Control Line Spacing...5000 m
Control Line Direction..N 53° E
Aircraft Altitude..300 m drape
Dates Flown.......................................May 1996 to September 1996
Magnetic Inclination..78°N
Magnetic Declination...36°W
IGRF Correction...1996.5 @ 650 m A.S.L.

Acquisition Equipment

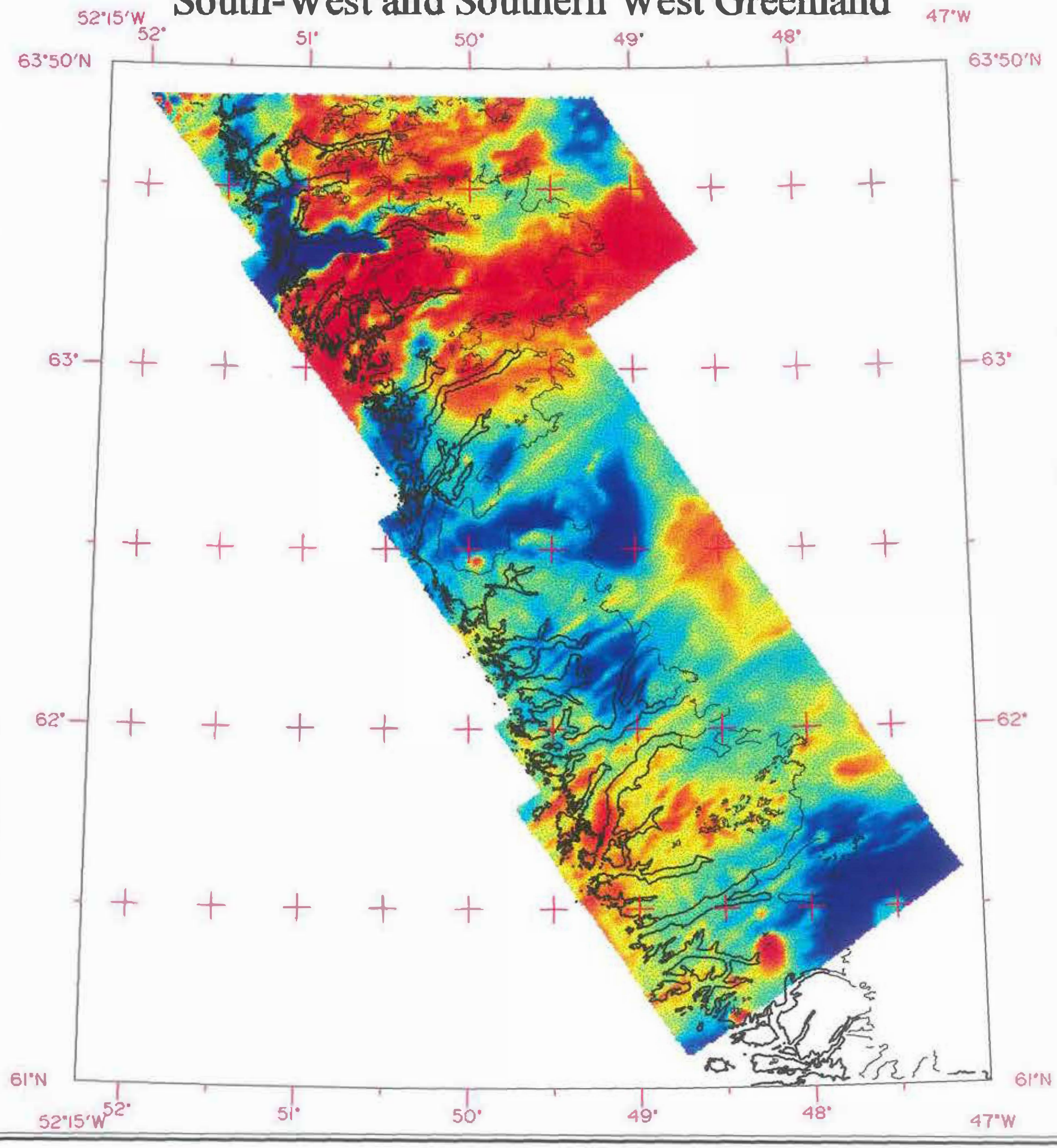
Survey Platform...Cessna Titan 404
Magnetometer..................................Scintrex CS-2 Cesium Vapour
Dynamic Compensator.......................................RMS AADC 27 Term
Data Acquisition System..............................Geoterrex GEODAS 486
GPS Receiver..Sercel NR103 10 Channel
Video Camera...Panasonic WV C1302
Video Recorder...Panasonic AG-2400

Topographic base from 1:250,000 maps supplied by
Kort- og Matrikelstyrelsen (KMS), Denmark (A200/87)

Project AEROMAG 1996 is jointly funded by the Governments of Denmark and Greenland (Mineral Resources Administration for Greenland and Minerals Office, respectively). The project is managed by the Geological Survey of Denmark and Greenland (GEUS).

0 50 Kilometres 100 150

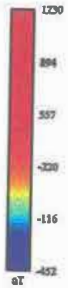
Project AEROMAG 1996
South-West and Southern West Greenland



GEUS

geoterrex

Total Field Magnetics



LEGEND

Coast Line..................................

Sea Water/Ice Cap Boundary......

Land/Ice Cap Boundary..............

GEODETIC INFORMATION

Projection.............................UTM	False Easting..................500,000 m
Spheroid...........................WGS84	False Northing.........................0 m
Central Meridian...................51°W	Scale Factor........................0.9996

Survey Parameters

Magnetic Data Recording Interval...............0.1 seconds (approximately 8 m)
Traverse Line Spacing..500 m
Traverse Line Direction...N 37° W
Control Line Spacing..5000 m
Control Line Direction..N 53° E
Aircraft Altitude...300 m drape
Dates Flown.......................................May 1996 to September 1996
Magnetic Inclination...78°N
Magnetic Declination..36°W
IGRF Correction...1996.5 @ 650 m A.S.L.

Acquisition Equipment

Survey Platform...Cessna Titan 404
Magnetometer...Scintrex H8 Cesium Vapour
Dynamic Compensator..RMS AADC 27 Term
Data Acquisition System...................................Geoterrex GEODAS 486
GPS Receiver...Sercel NR103 10 Channel
Video Camera...Panasonic WV C1302
Video Recorder...Panasonic AG-2400

Topographic base from 1:250,000 maps supplied by
Kort- og Matrikelstyrelsen (KMS), Denmark (A200/87)

Project AEROMAG 1996 is jointly funded by the Governments of Denmark and Greenland (Mineral Resources Administration for Greenland and Minerals Office, respectively). The project is managed by the Geological Survey of Denmark and Greenland (GEUS).

0 50 Kilometres 100 150

Discussion

Regional aeromagnetic surveys of the type presented here contain a wealth of information, which will become available in detail when the data are used in studies of specific or regional features within the survey area. It is not feasible to discuss all aspects of the new data within the framework of the projects, but some main results immediately interesting from a qualitative evaluation of the aeromagnetic anomaly maps are pointed out. First, some general observations are discussed in the first four subsections. After that follows a number of further subsections dealing with selected geographical areas.

All aeromagnetic anomaly maps displayed on the figures in this main section of the report are based on a 100 by 100 metres grid formed by the merger of the two original grids produced by the geophysical contractors. Apart from ensuring the use of comparable reference fields (IGRF) and the correct positioning of the two grids in UTM zone 23, no further treatment has been carried out. In the overlapping zone between the two original surveys the aeromagnetic field has been calculated as a straight average. There are no serious errors, although a more careful final merger of the two grids is possible. The area covered by the combined grid is shown in Figure 10, which can be used for easy reference if the topography is obscured by the aeromagnetic anomalies on the following figures. In order to facilitate overview and comparison between figures, they all use the same colour classification of the magnetic data fitted to the entire range of the data using the method of 'equal area', so that the colour scale of Figure 11 fits all figures. The anomaly map is displayed as a shaded colour map with a light source to the north at 45 degrees inclination. The subsequent figures showing parts of the survey area are prepared by a simple zoom of the map and grid in Figure 11. Consequently, the scale may differ from one figure to the next, and a fifty kilometre scale bar has been placed on all figures of this type to compensate for this. All calculations, plots etc. have been produced in the Geosoft Oasis package and the plots have been prepared on a NovaJet III Jet ink plotter. The topographical base is from a digital version of the printed KMS 1:250 000 topographical maps produced in a joint project between KMS, the Minerals Office and GEUS (A200/87).

The combined grid of the vertical gradient, corresponding to the combined grid of Total Magnetic Intensity (TMI), is also useful to study, but only Total Magnetic Intensity maps have been included in this section.

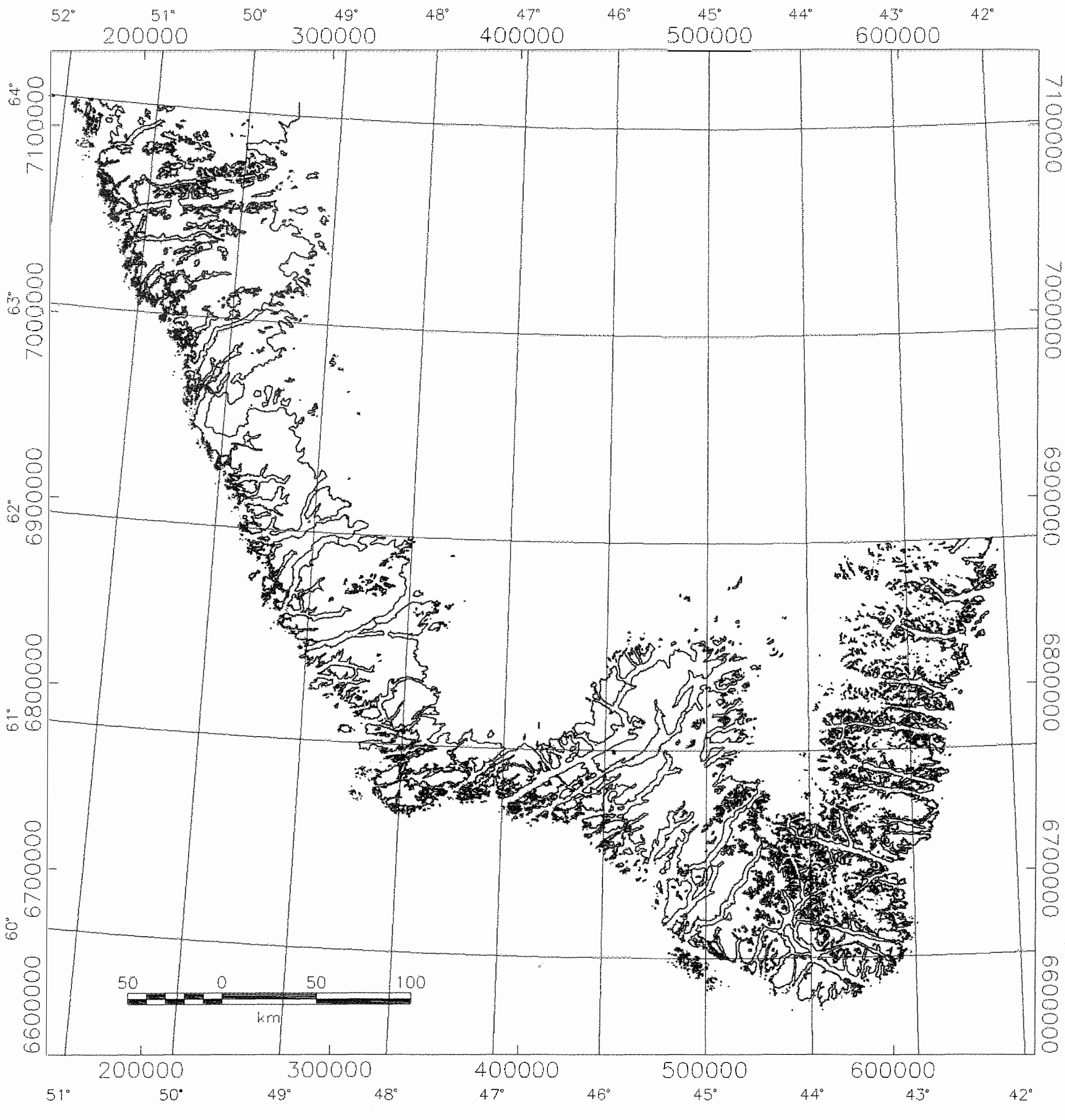


Figure 10: *The area covered by the surveys of Aeromag 1995 and Aeromag 1996*

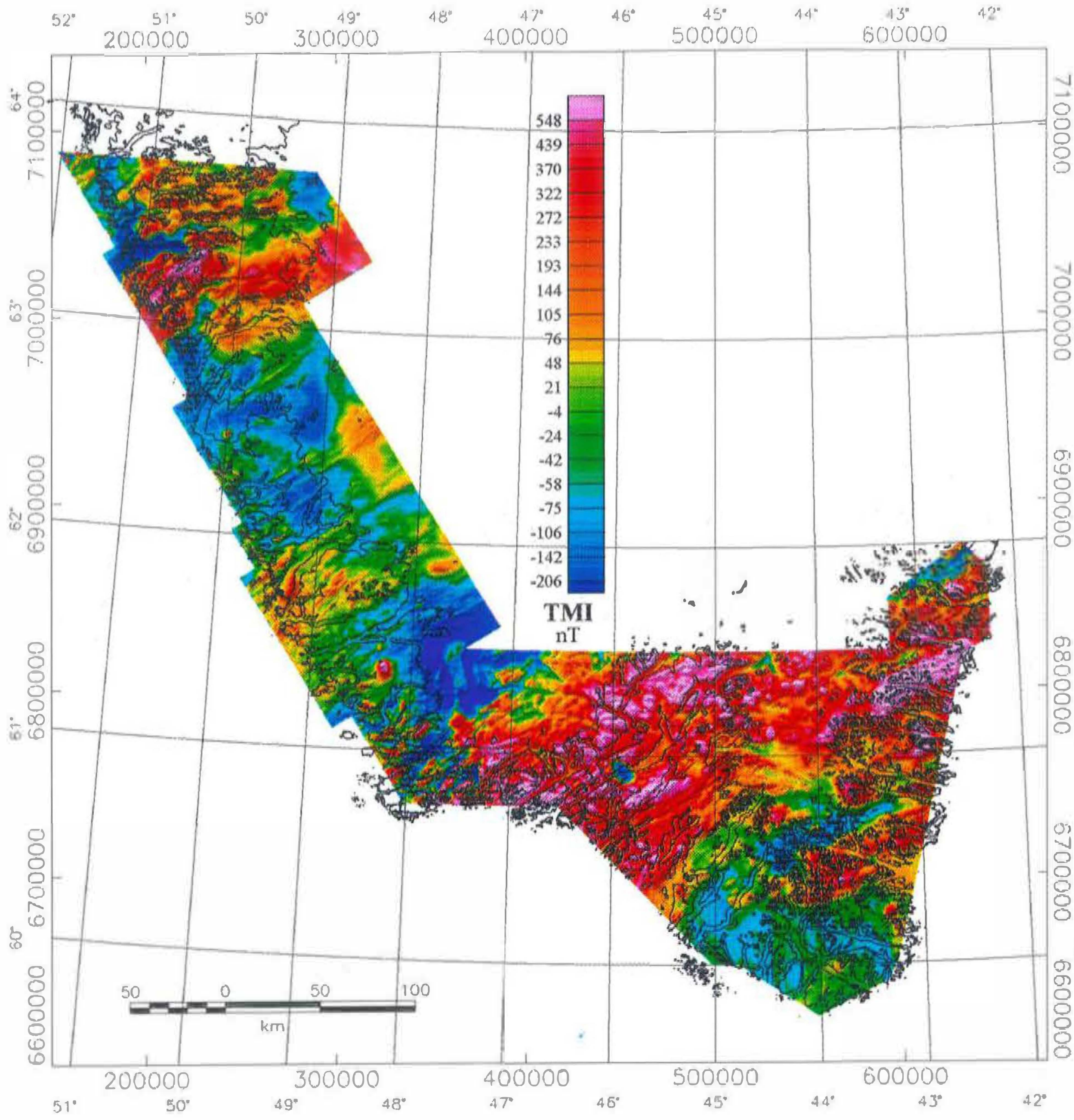


Figure 11: *The combined Total Magnetic Intensity anomaly map of Aeromag 1995 and Aeromag 1996*

Existing data superseded

The new surveys presented here completely supersede and replace older existing data over the same area, which have previously been available from GEUS' open files. All of these previous regional surveys should now be discarded and replaced with the new regional surveys, which will allow a much more detailed analysis. This includes the regional survey flown in 1967-68 by Finprospecting Ky for Kryolitselskabet Øresund ('the Cryolite Company'), a few reconnaissance lines flown over the Fiskenæsset region by Thorning (1984), and the western and southern parts of the GICAS surveys flown by Thorning *et al.* (1986, 1988). New versions of the aeromagnetic anomaly maps will be included in planned future digital versions of Thorning *et al.* (1995) and Ady & Tukiainen (1995).

Regional and detailed geophysical surveys

Comparisons with older aeromagnetic data clearly show how much better quality recent regional aeromagnetic data possess. However, it should also be remembered that regional aeromagnetic surveys, such as Aeromag 1995 and Aeromag 1996, in no way provide the ultimate tool, when it comes to unravelling geological structures using airborne geophysical data. This can be illustrated by a comparison with the very detailed, helicopterborne geophysical surveys carried out in five areas near Grønnedal, South-West Greenland, in Project AEM Greenland 1996 (Stemp 1997), an area also covered by Project Aeromag 1996. Using line separation of 200 metres and sensor heights of a few tens of metres, these surveys are much more detailed, as can be seen in Figure 12 showing two anomaly maps of the area of Midternæs produced from the two projects at the same scale. The geological structures only hinted at in the regional aeromagnetic data coverage, can be seen in complicated detail in the more detailed data. The helicopterborne survey furthermore produces many different types of data, e.g. magnetics, electromagnetics, radiometrics, and VLF. This type of surveying is clearly superior in quality, but it is also more expensive, and therefore not feasible to carry out for all of Greenland. Thus, an important role for regional data is to provide the regional framework for the positioning of more detailed surveys: both types of surveys have a role to play in the future.

Surveying of ice-covered regions

The numerous glaciers in Greenland and especially the enormous Inland Ice provide a challenge for the mapping and understanding of regional geology in Greenland. This was among the reasons for previous attempts to obtain aeromagnetic data over the Inland Ice in the GICAS project (Thorning *et al.* 1986, 1988). The aeromagnetic maps in Ady & Tukiainen (1995) and Thorning *et al.* (1994) are partly based on these data, which are also included in the compilation of Verhoef *et al.* (1995). They can only be used for very large scale features because of a wide line spacing of 8 to 12 kilometres.

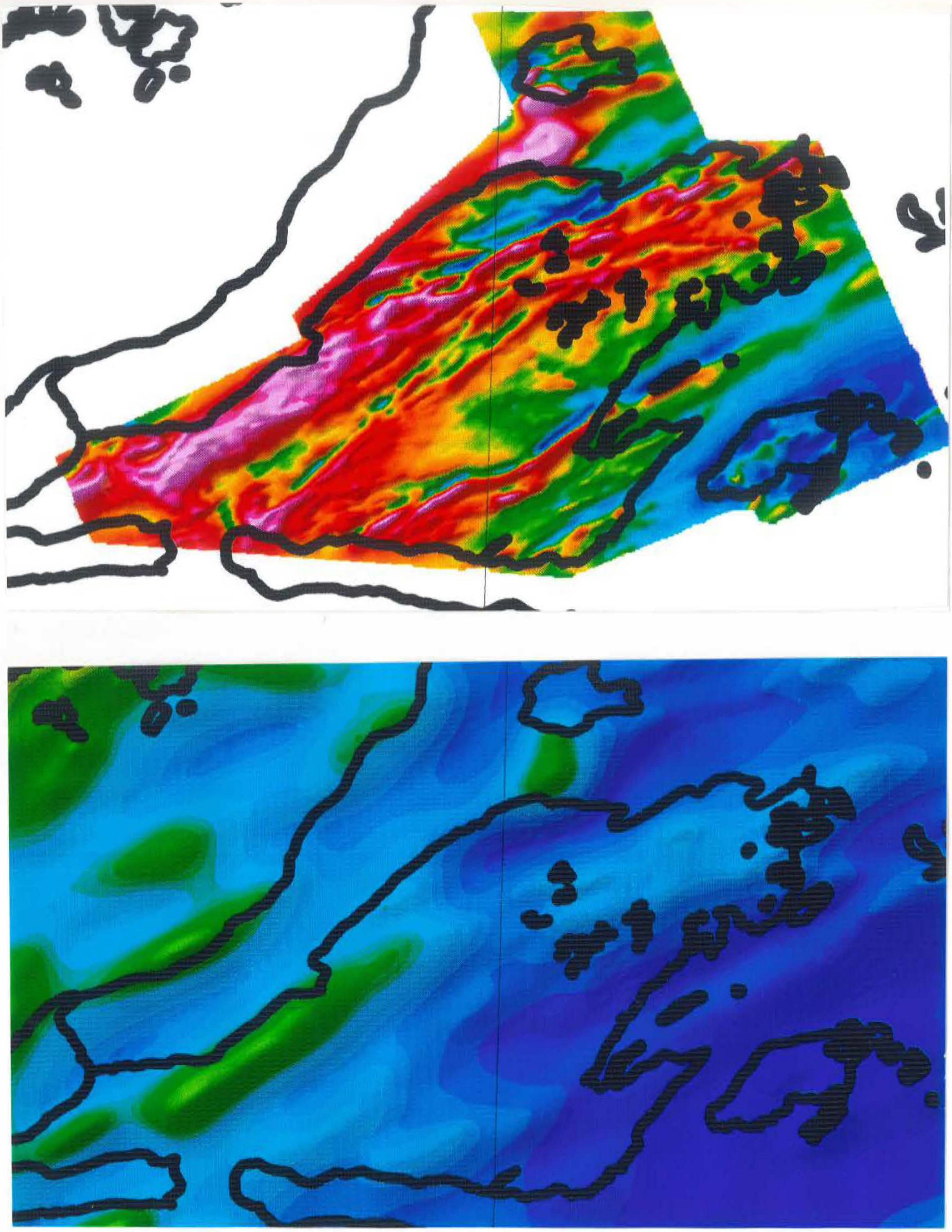


Figure 12: *Two aeromagnetic surveys partly covering the same area. Top: from the detailed helicopter-borne survey of AEM Greenland 1996; Bottom: from the regional AEROMAG 1996 survey.*

The results of Aeromag 1995 and Aeromag 1996 clearly demonstrated how much better modern, more detailed aeromagnetic surveys map the geology hidden by the Inland Ice. In South Greenland it has for many years been a point of discussion how to relate the geology observed at the two coasts, and how to interpolate the geological structures under the Inland Ice Cap. Therefore, it was decided to let the aeromagnetic survey of South Greenland cover both the ice-free margins and the ice-covered area in between, using the same survey parameters throughout. This has resulted in the first detailed aeromagnetic map totally ignoring the distribution of ice cover and therefore revealing the underlying geology in a degree of detail not seen before. North of the Aeromag 1995 survey area, Greenland widens significantly and therefore the same could not be done in the Aeromag 1996 area. However, the knowledge of lateral extent of geological structures in this area of the west coast has also been improved by including major ice-covered regions along the western margin of the Inland Ice. If a better understanding and mapping of large scale structures, as e.g. the border zone between the Archaean and the Ketilidian, is required, a very good argument can be put forward for extending the regional coverage of Aeromag 1995 north to at least 62° N using similar survey parameters as in Aeromag 1995 and Aeromag 1996. This would greatly facilitate attempts to reconstruct Precambrian geology in the North Atlantic region by mapping the expected full extent of and details in this important boundary between major Precambrian crustal blocks.

Topographical effects

The topography in Greenland is a major obstacle for airborne surveying. In certain areas flat topography is present, and detailed fix-winged surveys can be flown, as e.g. in Inglefield Land in 1994. However, in most of Greenland the problems of flying over rough topography and interpreting data affected by topography must be overcome. In the survey areas discussed here, the topography is mostly alpine in character, and consequently the computer assisted methods of draped flying described above, were very important for obtaining good results. By controlling the aircraft altitude in this way, the continuity of the measured aeromagnetic field both along lines and from line to line is ensured, providing for smaller cross-over errors between lines and tie lines, and thus producing better anomaly maps and better digital data for further use.

The influence of topography on the measured aeromagnetic field should be taken into account when using the data and the anomaly maps. To some extent the effects have been minimized by the method of computer assisted drape flying, but the effects of fjords and other major topographic features can still be seen in many places. Often, however, the fjords, deep valleys, etc., coincide with, and may actually be formed because of, major tectonic features, so anomaly patterns lined up along valleys cannot just be discarded without further thought. Detailed analysis may show that the topographical effect from the valley itself may not be enough to account for the anomaly, and that other effects have to be considered. There are exceptions, where practically no topographic effect can be seen, e.g. the southern tip of Greenland (Figures 4 - 6 and 13), which is magnetically very flat despite the alpine character of the topograhy. Apparently here most of the magnetic sources are so deeply buried, and the near surface rocks so nonmagnetic that neither affects the aeromagnetic field to any great extent.

When evaluating anomaly patterns over ice covered regions this becomes especially important. Studies of the sub-glacial terrain below the margin of the Inland Ice using radio-echo sounding, e.g. Thorning & Hansen (1987, 1988), have shown how fjords can continue for large distances underneath the ice cover. It is then not possible to directly observe the relationship between the topography and the aeromagnetic field, because the surface of the (non-magnetic) ice forms a smooth surface hiding the real (magnetic or non-magnetic) topography of the subglacial rock surface from the radar altimeter. Such effects must be expected to be present at places in South Greenland with its many deeply incised fjords. Thus, care must be taken, especially when modelling from the profile data.

The region from 60°N to 61°N

The southernmost part of the Total Magnetic Intensity map is shown in Figure 13. It may also be useful to refer to Figures 4 - 6 and 11 for a regional overview.

The southernmost tip of Greenland is magnetically very flat, with a few exceptions probably attributable to intrusions, possibly related to the rapakivi suite. Only faint indications are visible on Figure 13, but closer examination of the real data show without doubt that there are several N-S trending narrow magnetic highs of moderate intensity indicating the presence of dike like structures. These have not yet been explained geologically.

The southern boundary of the Julianehåb batholith is clearly defined magnetically at the west coast, with an indication of at least two boundaries, which in a general way correlates with the shear zones separating the Psammite zone from the Julianehåb batholith. The northernmost of these two boundaries separates the strongly magnetized rocks (magnetic anomalies red on the Figure) from rocks of intermediate magnetization (yellows and greens) which again is separated from the low magnetization region (blue) to the south by another linear boundary. However, the magnetic anomaly map shows that there are complications with the north-eastern continuation of these boundaries below the Inland Ice. At least some of them seem to terminate against another NW-SE linear trend, which intersects 61°N at 44° 40'W. The details of this cannot be discussed here, but clearly the southern boundary of the batholith as it is expressed in the magnetic data, does not follow the mapped and inferred position as it has been summarized in e.g. Figure 2 of this report. Rather, there seems to be some indication of a right lateral dislocation along the NW-SE trend in one or more places under the Inland Ice, e.g. just south of latitude 61°N, 44°30'W (see also Figure 4 - 6 and 11). Thus, in brief, the magnetic data indicate the necessity of a more detailed study of the southern boundary of the batholith.

The Psammite and Pelite zones are dominated by sedimentary rocks at the surface, but the triangular area of highly magnetic rocks south of the linear low is situated entirely within these zones, and is obviously from a different source than the sediments. The northern boundary of these highly magnetized rocks cuts across severe topography without showing

much effect in the magnetic data, indicating that the sources are at least partly at depth. It may be intrusions or various granites similar to those of the batholith.

The Ilimaussaq intrusion, one of the Gardar intrusions, is very clearly seen in the magnetic data just south-east of 61°N, 46°W as a well defined magnetic minimum. The other Gardar intrusions do not exhibit similar lows, but seem to correlate with magnetic highs (see Figure 14).

The region from 61°N to 62°N

As can be seen on Figure 14 this region is almost totally dominated by highly magnetized rocks of the Julianehåb Batholith. This is clearly seen to be continuous across the entire region from coast to coast. Topographic effects are present at many locations, but only as second order anomalies not affecting the main conclusion. The precise position of the northern boundary is not straight forward to establish. The magnetic low (in deep blue) visible at both coasts lies entirely within the Border zone, but the traditional boundary of the Ketilidian, which is usually placed at Kobberminebugt on the West coast (just south-east of 61°N, 48°W), coincides with only one of several linear trends. The western region (Figure 15) is characterized by many linear trends in various directions, but the SW-NE direction seems to dominate here and throughout much of the border zone. Two similar, clearly defined magnetic highs stand out in the otherwise mostly non-magnetic border zone. The one to the south-west correlates with the Pyramide Fjeld granite intrusion of Palaeoproterozoic age. The sources of other individual magnetic anomalies must be sought among faults, dikes and intrusions of both Archaean, Ketilidian and Gardar age. The supracrustals in the border zone do not have any noticeable effect on the anomaly pattern of this regional survey, but many details are visible in the much more detailed, low-level helicopterborne survey of Project AEM Greenland 1996 (Stemp, 1997).

Figure 16 shows an enlargement of the anomaly map of the westernmost part of the region. Though based on the same grid as Figure 11, in this version of the anomaly map the shadows have been produced by a light source to the NE. This emphasises several parallel, slightly curved anomalies striking almost NS, most likely caused by four to five coast parallel dikes, some of which can be followed over approximately 100 km before they exit the survey area. They are also visible on Figures 7 and 8. No certain explanation is known, but a guess could be that the dikes may have to do with the opening of Davis Strait. These features warrant further investigation.

The region from 62°N to 63°N

The character of the aeromagnetic field in this region is quite different from the areas to the south. As can be seen on Figure 17 the dominating feature is a large number of linear anomalies striking NNE. Most of these are positive and must arise from dikes, but they also in some cases seem to separate different rock types giving the impression that there may also be faults involved, perhaps with large lateral displacements.

Several other trends can be seen in the area, some of them with a strike to the E or ESE similar to what can be seen further south in the Ketilidian, some with an almost N-S strike. The relative age of these can be studied.

The northernmost of the linear anomalies is at least 100 km long and seems to be placed entirely beneath the Frederikshåbs Isblink. Also covered by the glacier just south of the 0dike there is a circular anomaly high indicative of a plug like intrusion.

The blocky nature of the anomaly pattern in this region is remarkable. The anomaly pattern is definitely not the result of bad levelling of the magnetic data. Apart from the NNE striking assumed dikes mentioned above, at least two other important directions can be seen. These three linear trends seem to form the boundaries of many blocks of variable degrees of magnetization i.e. consisting of different rock types and maybe also showing the results of different histories.

Note, that many of the features described in this section are only discernible because the survey covers a part of the Inland Ice margin, thereby extending the lateral extent of the anomaly pattern.

The region north of 63°N

The aeromagnetic field exhibits quite different features in this area, see Figure 18. It is dominated by strongly magnetized rocks indicated by the strong anomalies (in red) most likely related to some of the rock types associated with the Fiskenæsset complex. As was pointed out in Ady & Tukiainen (1995) the complex continues for a significant distance under the Inland Ice. As was pointed out by Thorning (1984) the distribution of granulite and amphibolite metamorphic facies rocks in this area plays an important role for the anomaly pattern, granulite rocks being stronger magnetized.

Figure 13: *Enlargement of the Total Magnetic Intensity map of Figure 11, covering the region from 60°N to 61°N; for discussion see text.*

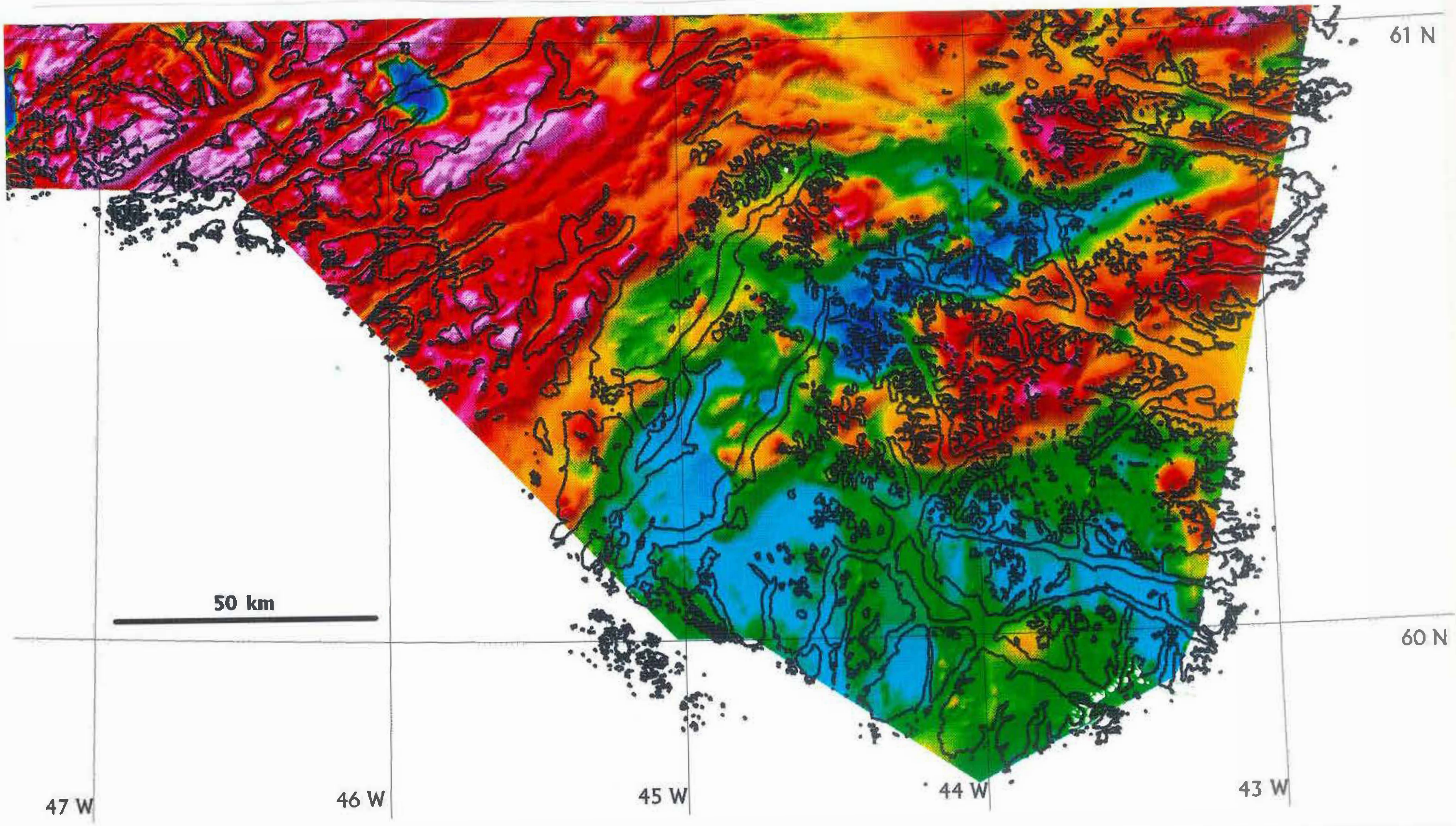
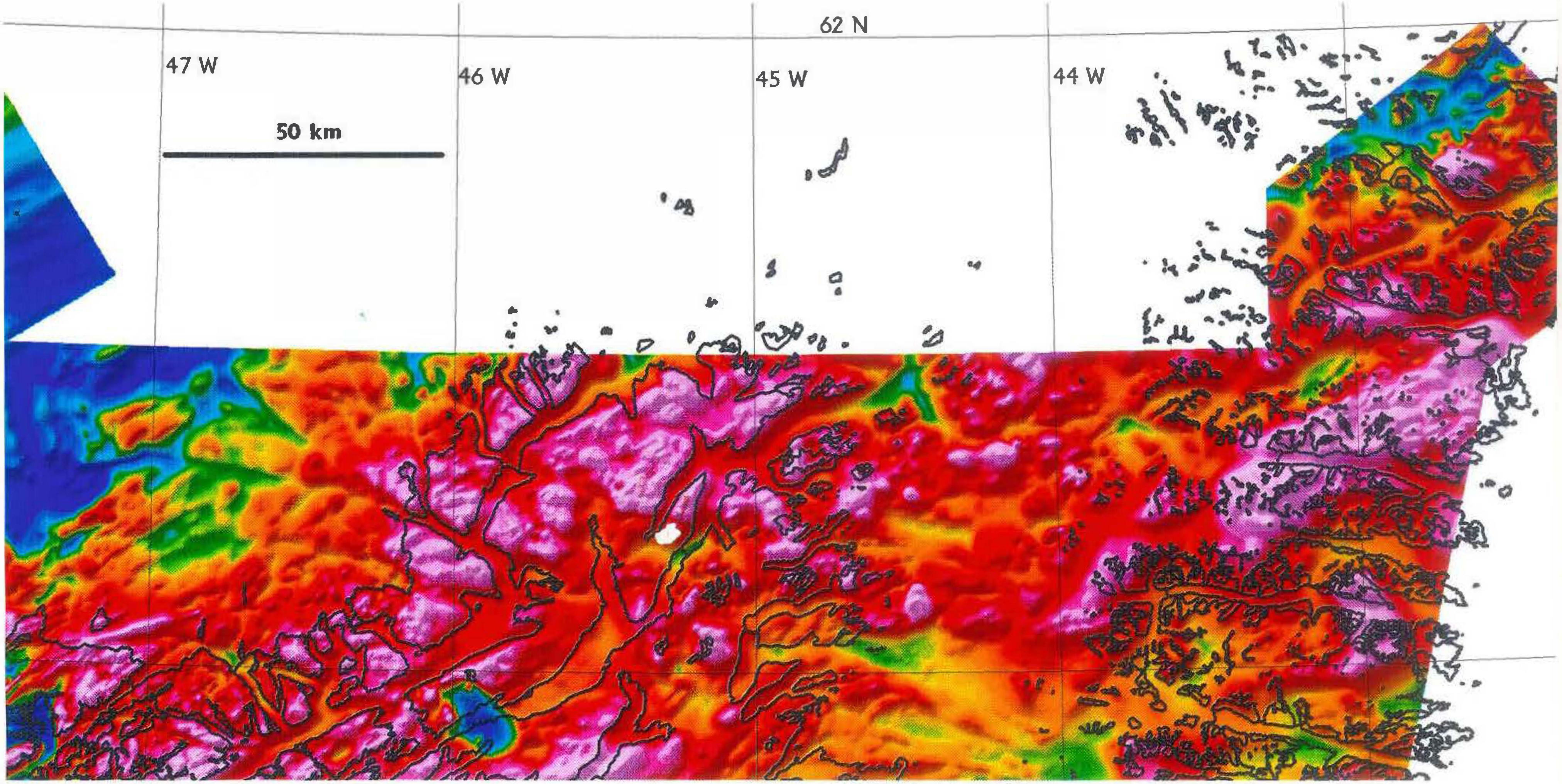


Figure 14: *Enlargement of the Total Magnetic Intensity map of Figure 11, covering the region from 61°N to 62°N, eastern part; for discussion see text.*



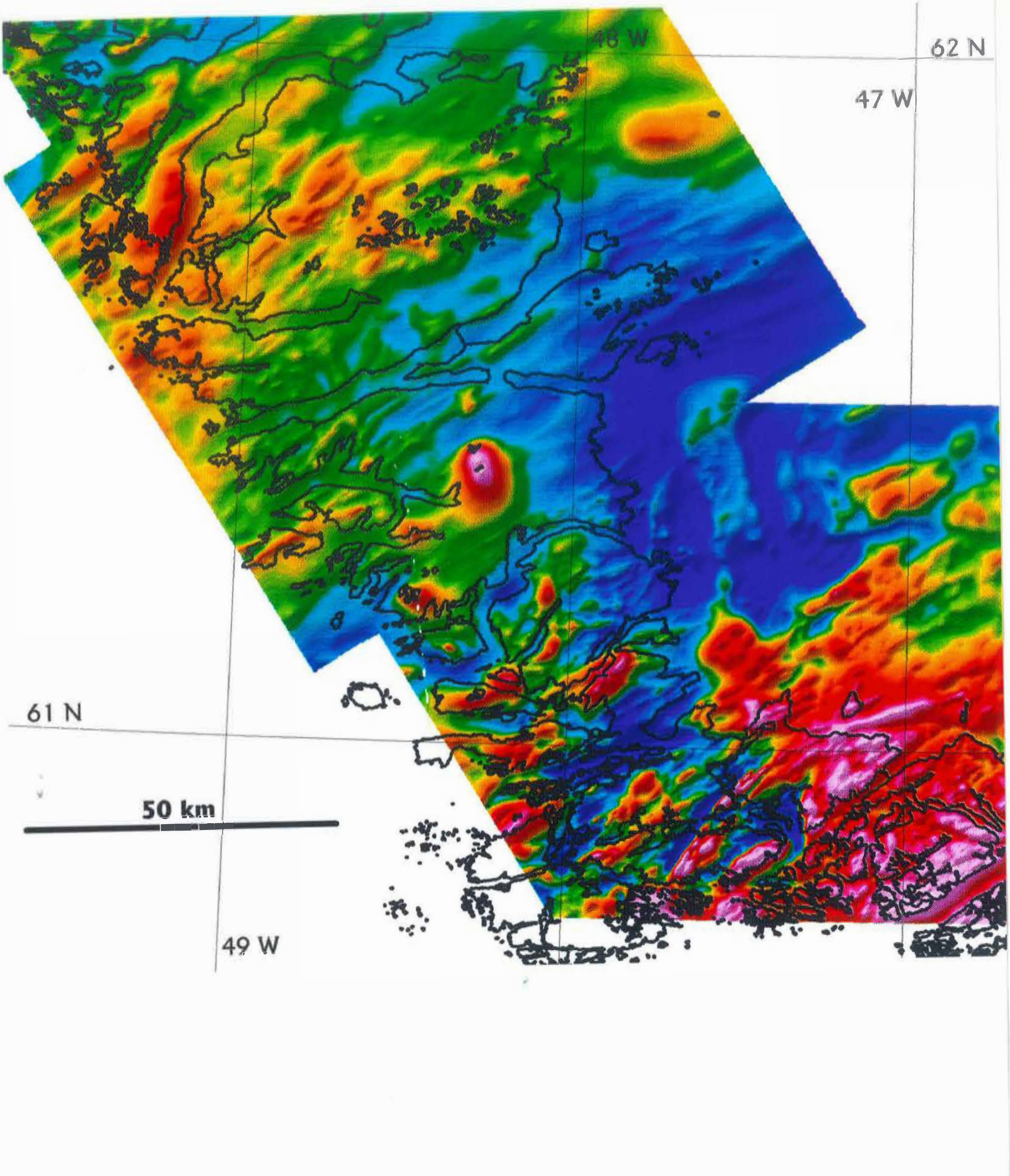


Figure 15: *Enlargement of the Total Magnetic Intensity map of Figure 11, covering the region from 61°N to 62°N, eastern part; for discussion see text.*

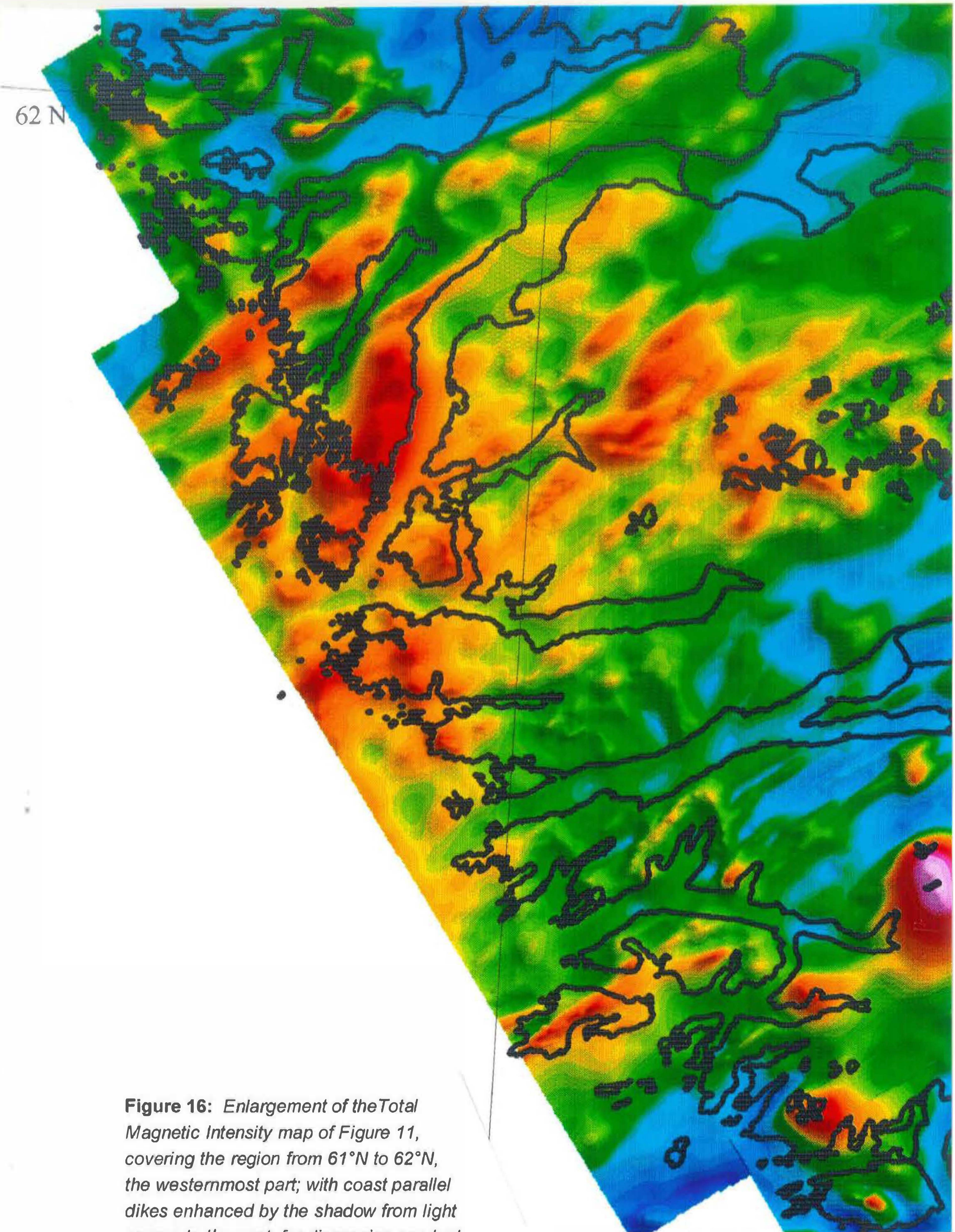


Figure 16: *Enlargement of theTotal Magnetic Intensity map of Figure 11, covering the region from 61°N to 62°N, the westernmost part; with coast parallel dikes enhanced by the shadow from light source to the east; for discussion see text.*

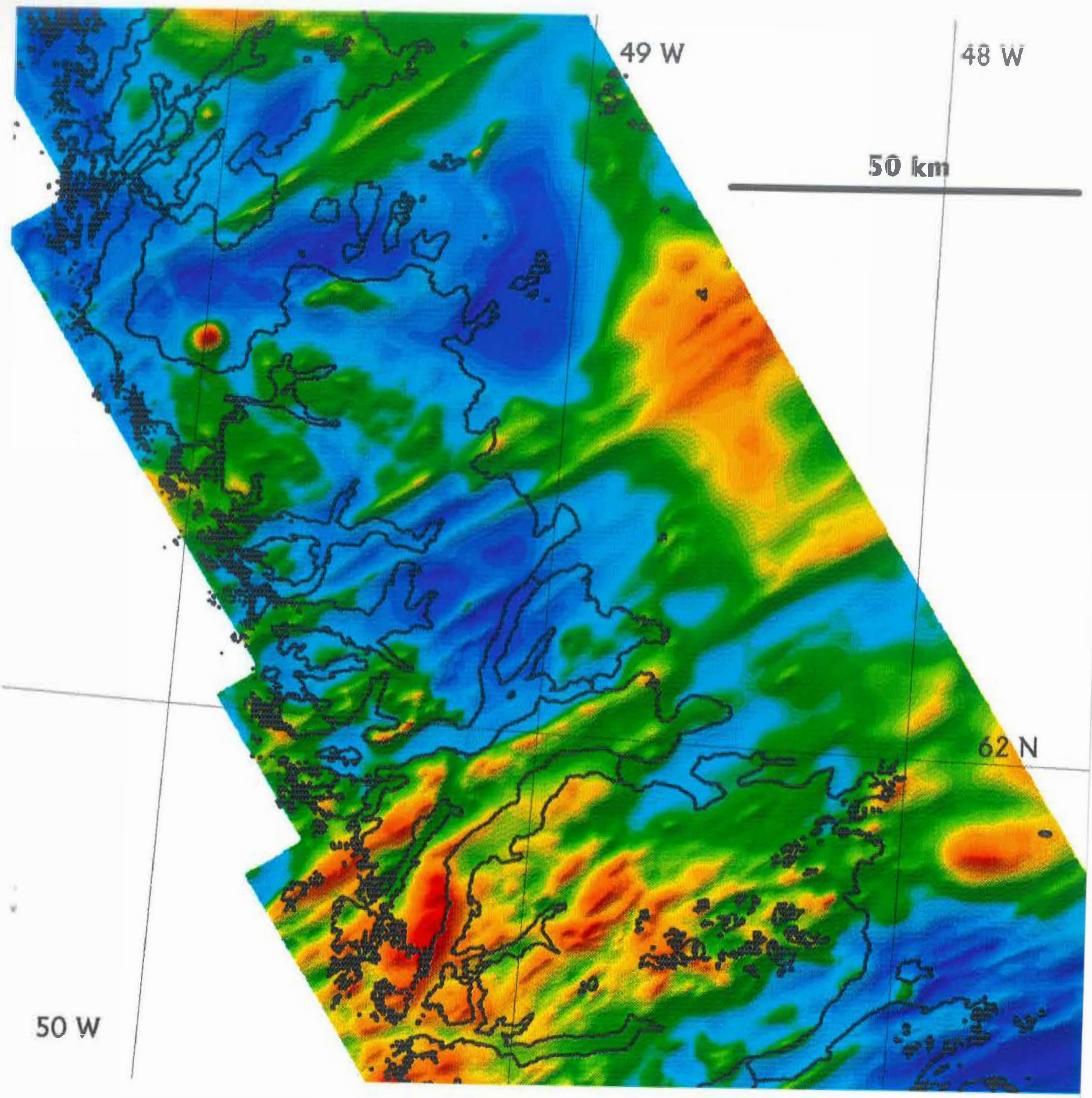


Figure 17: *Enlargement of the Total Magnetic Intensity map of Figure 11, covering the region from 62°N to 63°N; for discussion see text.*

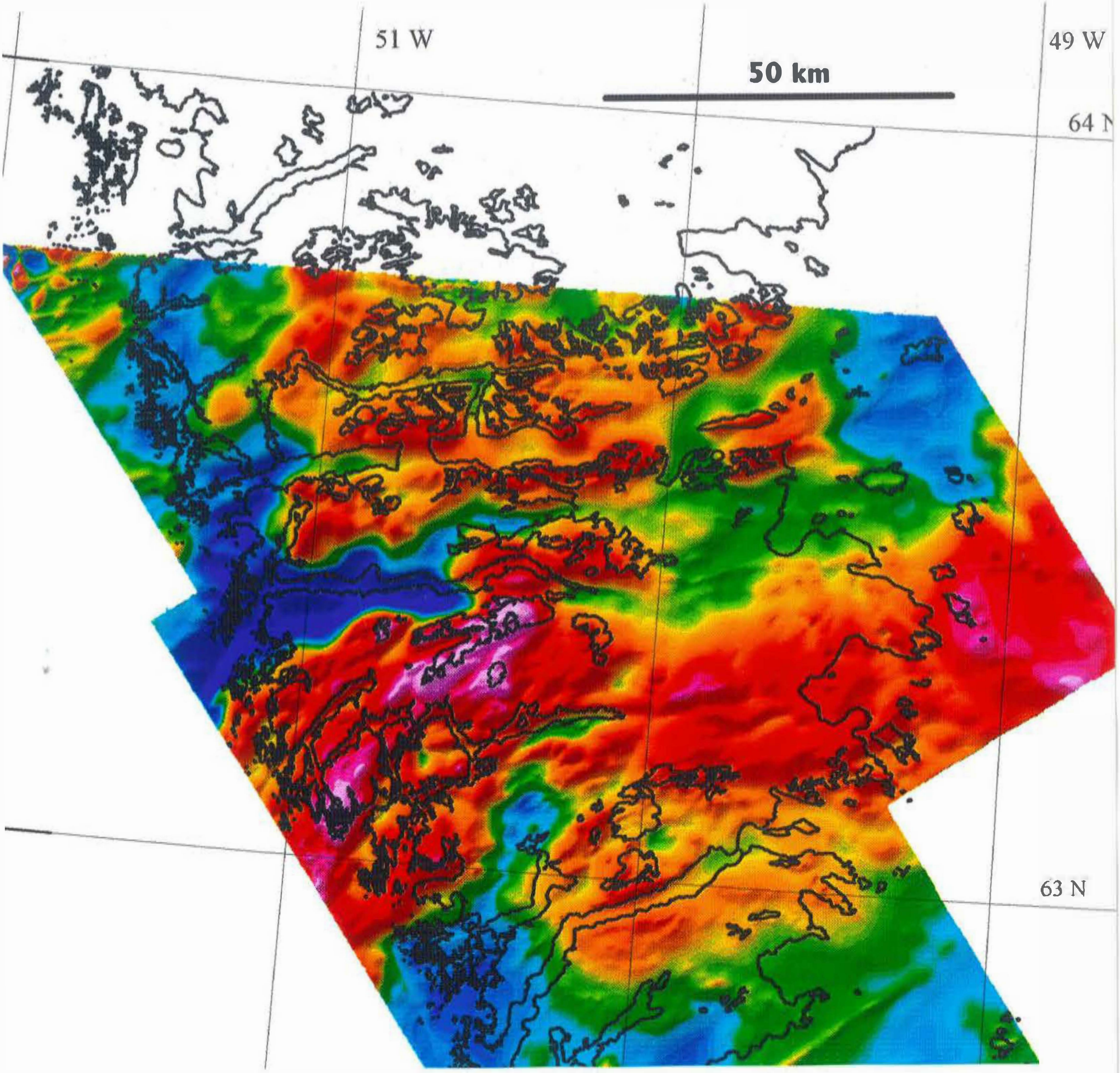


Figure 18: *Enlargement of the Total Magnetic Intensity map of Figure 11, covering the region from 63°N to 64°N; for discussion see text.*

Conclusions

In the authors' opinion the two new aeromagnetic data sets are of very good quality and will be extremely useful for further geoscience work in the area. The plans for Projects Aeromag 1995 and Aeromag 1996 did not include detailed interpretation of the new data; that will be something to do in relation with various future geoscience projects in the area. One such project, SUPRASYD, is already using the data for both detailed studies and more regional work.

At the present time a number of general conclusions from Projects Aeromag 1996 and Aeromag 1997 can be summarized:

- The use of digital terrain model to control the altitude of the aircraft is very important for the acquisition of good quality aeromagnetic data.
- The only real hindrance for a fast execution of airborne surveys in Greenland is the weather.
- The survey parameters used for these surveys proved adequate for a good resolution of regional features, but more detailed surveys over local areas may often be necessary in addition.
- The new aeromagnetic data reflect the 'hidden' geology below the Inland Ice in a detail not seen before in Greenland. Boundaries and trends can now be followed rather than just inferred.
- A number of features have been revealed by the two surveys; a few of them are briefly described in the preceding section.
- In several cases the aeromagnetic data point to the necessity of a geological re-evaluation involving both known and new structures.
- It is strongly recommended to continue the aeromagnetic coverage of the Greenland Precambrian craton to the north.

Availability of data

It is a fundamental objective of the public airborne geophysics projects to make the data generally available at modest prices as soon as possible to allow mining and exploration companies to use the data according to their own tradition and modelling ideas and in this way promote mineral exploration in Greenland. The cost of the available products represents only the cost of reproduction and does in no way recoup the expense incurred during the projects.

The digital data on CD-ROM with a copy of the relevant processing report from the geophysical contractor can be obtained from GEUS at a fixed price of 18 000 DKK exc. of VAT (subject to change without notice). This is the standard price for any of the surveys carried out under the Aeromag or AEM Greenland projects. The delivery time is usually under three weeks (no stock; the items are produced when ordered).

Copies of maps on paper, laminated paper or mylar can also be obtained from GEUS. Price varies depending on number and type of maps; please ask GEUS for a quote for a required set of maps. The maps are produced on demand by the geophysical contractors, and delivery time may be more than three weeks.

Acknowledgements

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