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Aeromagnetic study of the continental crust of northeast Greenland

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Abstract. A reconnaissance-type aeromagnetic survey of northeast Greenland was undertaken by the Alfred Wegener Institute for Polar and Marine Research between 1993 and 1996. These data were compiled in a regional magnetic anomaly map at 3700 m altitude, covering the Caledonian orogen of east Greenland and parts of the Precambrian shield of north Greenland. The survey area was divided into regions with distinct magnetic anomalies. The interpretation of the magnetic anomalies is based on comparison with exposed geological structures and is locally supported by in situ measurements of magnetic susceptibilities. Middle Proterozoic magmatic rocks determine the magnetic character of the Precambrian shield of north Greenland. Rifting and downfaulting of the Precambrian basement at its northern and eastern margin are reflected by gradients in the magnetic field. The Caledonian fold belt of east Greenland could be subdivided into a northern only weakly magnetic part, where pervasive Caledonian reworking probably demagnetized the crust, and a southern part, where isolated positive anomalies occur. Magnetite survived Caledonian metamorphism in these areas. The sensitivity of magnetite to Caledonian metamorphism was recognized in several places in the Caledonides of east Greenland. This observation might be useful in determining the much debated degree of Caledonian reworking of the crystalline complexes of east Greenland.

1. Introduction

Northeast Greenland shares with Scandinavia the traces of the Arctic Caledonian orogen. In contrast to Scandinavia, architecture and evolution of northeast Greenland's continental crust are relatively unknown. Exploring the structure of the continental crust of northeast Greenland is vital for a deeper understanding of the geological framework of the present North Atlantic region.

The Alfred Wegener Institute for Polar and Marine Research (AWI) undertook, as part of an extensive geophysical program in east Greenland (V. Schlindwein and W. Jokat, Structure and evolution of the continental crust of northern east Greenland from integrated geophysical studies, submitted to Journal of Geophysical Research, 1998), a regional aeromagnetic reconnaissance survey (Figures 1 and 2). The survey covers the Caledonian orogen of east Greenland and the Precambrian shield of north Greenland and thereby supplements preexisting aeromagnetic data which focus on the shelf areas offshore east Greenland [*Larsen,* 1990; *Thorning,* 1988] and north Greenland [e.g., *Riddihough et al.,* 1973; *Coles et al.,* 1976].

Whereas seismic investigations of east Greenland [e.g., *Larsen and Marcussen,* 1992; *Weigel et al.,* 1995; *Fechner and Jokat,* 1996; Schlindwein and Jokat, submitted manuscript, 1998] provide locally detailed information on the crustal structure, this aeromagnetic study has the advantage of yielding an overview over large-scale geological units like the Caledonian orogen and the Precambrian shield of north Greenland (Figure 1). The magnetic properties of these units are examined and subareas with characteristic magnetic anomalies identified. Owing to the lack of other geophysical data in most of the survey area, the interpretation of these magnetic anomalies is based on relating the anomalies to exposed geological structures. Locally, ground magnetic studies [*Schlindwein,* 1998a] allow direct correlation of magnetic anomalies and surface rocks. The main part of this paper is dedicated to the description and the discussion of the correlation between aeromagnetic anomalies and geological structures.

Emphasis is placed on the analysis of magnetic anomalies over the Caledonian fold belt of east Greenland. The degree of Caledonian reworking of the crystalline complexes of east Greenland is a key question in the understanding of the Caledonian orogeny [*Haller,* 1971; *Henriksen and Higgins,* 1976]. This study offers a new way to address this problem: Having recognized the sensitivity of magnetic source rocks in the study area to Caledonian metamorphism, the magnetic data can be used to distinguish areas which experienced the same petromagnetic evolution. When combined with petrological studies, this can contribute in future to map the varying intensity of Caledonian reworking of the continental crust of east Greenland.

2. Data Acquisition

The aeromagnetic surveys of the AWI were designed to provide a regional overview over the magnetic anomalies of northeast Greenland north of 70°N (Figure 1). The aeromagnetic data were acquired during four survey campaigns, called AEROMAG93-96, which were flown between 1993 and 1996. With line spacings of 10-40 km and flight levels up to 3700 m, the surveys have only reconnaissance character. The limited range of the aircraft and large distances between suitable airfields imposed logistic constraints on the scientific program. For example, the N-S tie lines could not be flown independently from the E-W profile lines but had to be incorporated in the regular survey flights, with less than optimum attention to magnetically quiet periods. Figure 2 shows the resulting total of about 55,500 km of aeromagnetic profiles.

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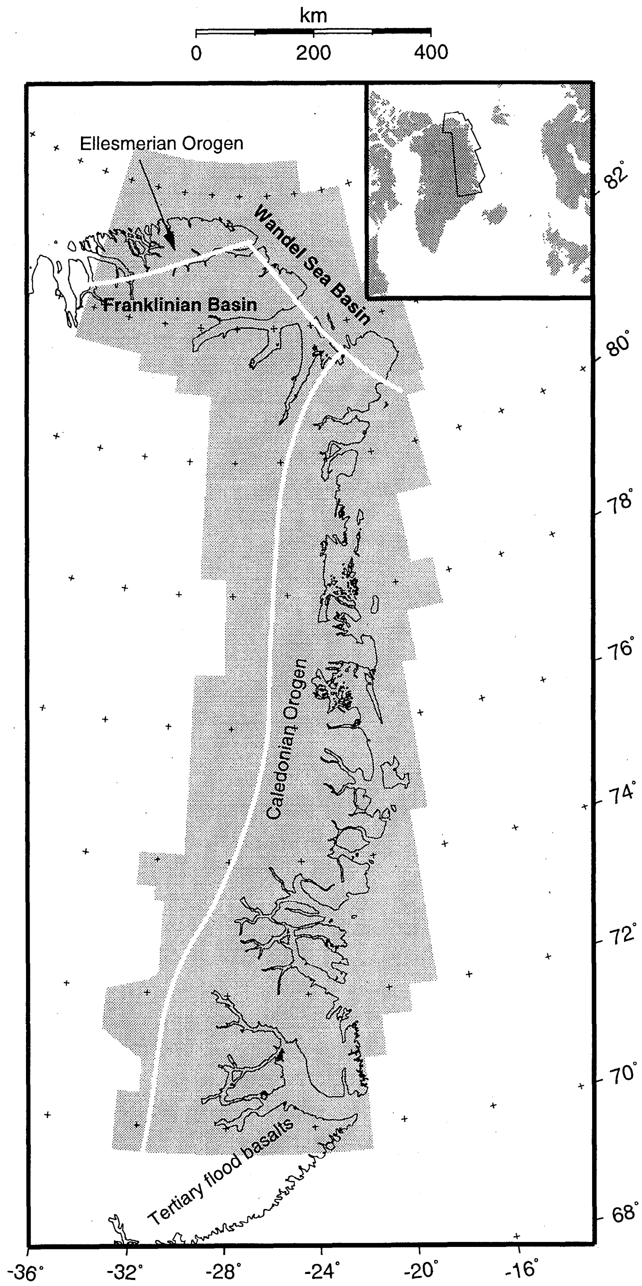

Figure 1. Location of the study area in northeast Greenland. The aeromagnetic data cover the gray shaded area. Main geological provinces are sketched. Scale is valid at 76°N.

The airfields of Constable Pynt (CNP) and Station Nord (NOR) (Figure 2) served as bases of operation for the southern and northern part of the survey area, respectively. The survey was flown at constant barometric altitude. Offshore north Greenland, the flight level was 600 feet (183 m). Onshore, flight levels varied from line to line between 8000 feet (2438 m) and 12,000 feet (3658 m) depending on terrain elevation and weather conditions.

Transient variations of the Earth's magnetic field were recorded at 10-s intervals at the base of operation by a proton precession magnetometer. For AEROMAG96, CNP and NOR were too far away from the survey area. Therefore a second reference magnetometer was deployed at Zackenberg (ZAC) (Figure 2).

The total intensity of the magnetic field was recorded by an optically pumped helium magnetometer mounted on the aircraft. The magnetometer and Global Positioning System (GPS) navigation data were recorded at a sample rate of 10 Hz on board the aircraft. For compilation of the aeromagnetic anomaly maps, data are reduced by filtering to 1-s intervals corresponding to a spatial sampling distance of about 80 m. Aircraft-induced magnetic interference fields are compensated statically by triple compensation coils surrounding the magnetometer and dynamically by recording the sensor's response to flight manoeuvres and reducing the effects by calculation [*Leliak,* 1961].

3. Data Processing and Map Compilation

Magnetic anomalies were obtained by removing the International Geomagnetic Reference Field (IGRF) for the epoch 1990-1995 [*IAGA Division V Working Group 8,* 1991] from the data.

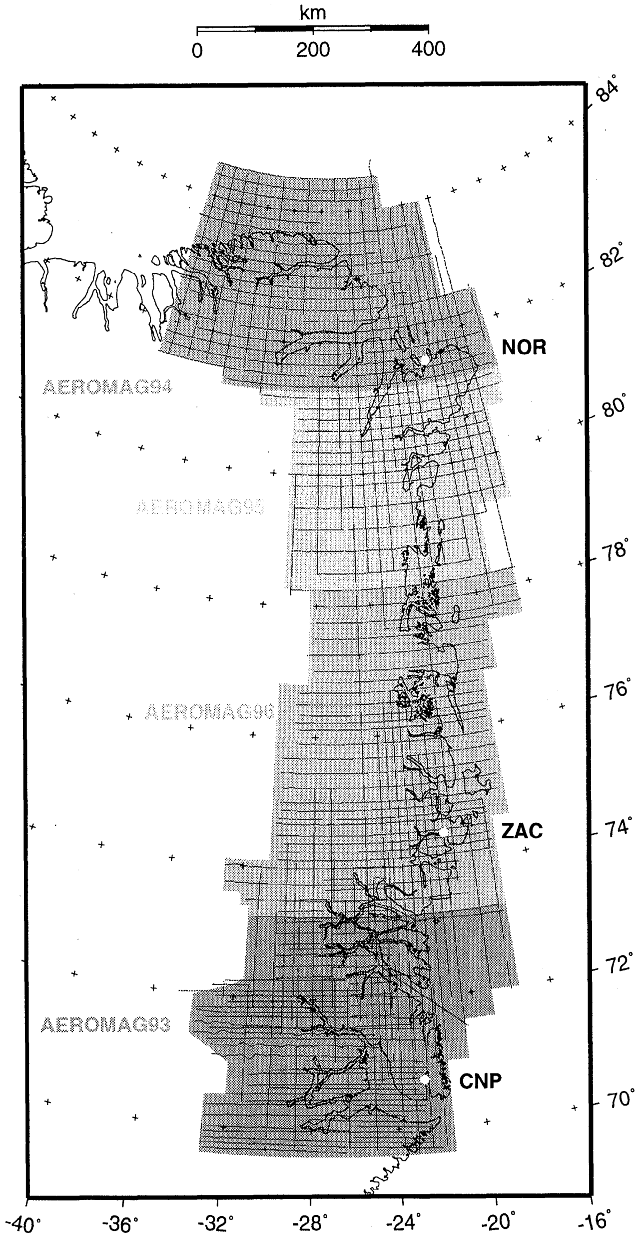

Figure 2. Aeromagnetic data in northeast Greenland. Thin lines mark the profiles flown during the surveys AEROMAG93-96. The gray shaded area shows the extent of the gridded aeromagnetic anomaly map. Reference magnetometers (white dots) were deployed at Constable Pynt (CNP), Zackenberg (ZAC), and Station Nord (NOR). Scale is valid at 76°N.

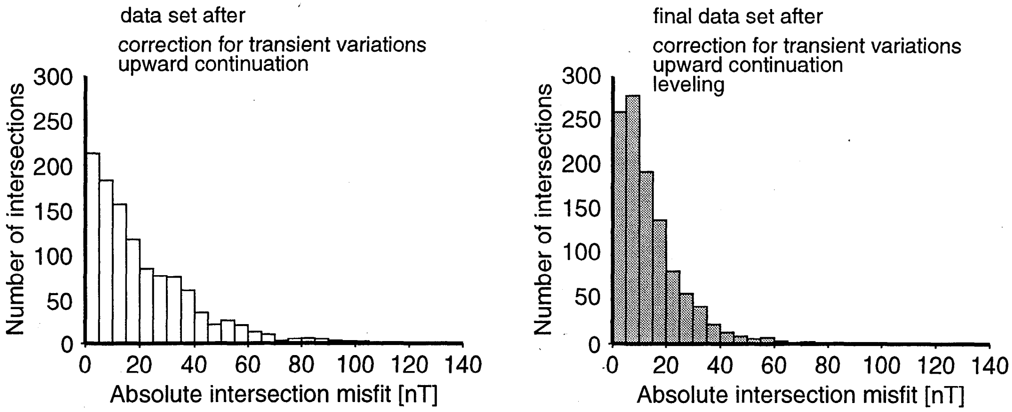

Figure 3. Statistics of absolute misfits at line intersections. The entire data set with 280 lines intersecting at 1126 points is represented. The effect of leveling is shown. The resulting statistics gives an impression of the accuracy of the data set.

Correcting transient variations of the Earth's external magnetic field in polar regions is a critical step in the data processing. It was assumed that long-period disturbances have a more regional extent, while short-period variations occur locally. With distances of up to 500 km between the survey profiles and the base station it was not attempted to correct for these short-period variations. Transient variations were calculated from the total field recordings of each base station by subtracting the mean total field of a quiet day within the survey period, respectively. After several tests, the long-period component (> 30 min) of the variations was extracted by low-pass filtering and subtracted from the survey data. For AEROMAG93, CNP was used as reference, ZAC for the main part of AEROMAG96 and NOR for the remaining data set. The result of the correction was carefully assessed by comparing parallel lines and analyzing misfits at line intersections. Heavily disturbed data were removed.

The line data were then upward continued in the Fourier domain to a common level of 3700 m altitude. Subsequently, the misfits at all line intersections were analyses (Figure 3). After correction for transient variations and upward continuation, the average intersection misfit is 21 nT. Finally, the data set was leveled by shifting lines by individual constants. This reduced the average intersection misfit to 14 nT, while 90% of the line intersections fit better than 30 nT (Figure 3).

These values provide an estimate of the accuracy of the magnetic anomaly map. They have to be considered in relation to the size of the observed magnetic anomalies with maximum amplitudes of 1450 nT. Imperfect removal of transient variations is the main source of error.

For map display (Plate 1), the aeromagnetic data, including profile and tie lines, were interpolated onto a regular grid using the continuous curvature algorithm by *Smith and Wessel* [1990]. A grid cell size of 0.05° longitude and 0.042° latitude, or 1.5 km x 4.7 km at 75°N latitude, was chosen. Prior to gridding, the data were averaged if more than a single value came to lie within one grid cell. As gridding averages densely spaced data along the flight tracks and interpolates between the flight lines, it is advantageous to also display the data along flight lines in so-called "wiggle plots" (Figures 4-6; for clarity, only E-W lines are shown). Details of the anomalies are not lost by averaging and the data coverage is clearly shown. Both types of display were used for the geological interpretation of the aeromagnetic data.

4. Correlation of Magnetic Anomalies and Geological Provinces

On the basis of the aeromagnetic data, northeast Greenland was divided into areas with distinct magnetic anomalies. These anomalies are marked in Plate 1 and analyzed below in context with surface geology in order to define possible sources for the magnetic anomaly pattern. The understanding of the links between aeromagnetic measurements and magnetic properties of crustal rocks is greatly enhanced by susceptibility measurements of exposed rocks in central east Greenland undertaken in summer 1997 by *Schlindwein* [1998a]. Emphasis is placed in the following on the interpretation and discussion of the magnetic anomalies of the Caledonian fold belt.

4.1. Anomaly 1, Morris Jesup Plateau (Plate 1)

Offshore north Greenland lies a broad marginal plateau that extends toward the northeast [*Dawes,* 1990]. It is characterized by large positive magnetic anomalies which have been investigated, for example, by *Riddihough et al.* [1973] and attributed to the predominantly oceanic nature of the Morris Jesup Plateau. However, the detailed structure of the Morris Jesup Plateau and the sources for the complex magnetic pattern are subject to speculation (see *Dawes* [1990] for a review).

4.2. Anomaly 2, Kap Washington Group Volcanics (Figure 4)

An isolated positive magnetic anomaly is situated on the north coast of Peary Land. It coincides with exposures of the Late Cretaceous Kap Washington Group consisting of sedimentary units and per-alkaline volcanics [*Surlyk,* 1991], which probably cause the magnetic anomaly.

4.3. Anomaly 3, Independence Fjord Group, Anomaly 4, Franklinian shelf, and Anomaly 5, Franklinian Trough (Figure 4)

North Greenland is characterized by a sequence of three distinct magnetic anomalies. It consists to the south of positive anomalies with a distinct short-wavelength pattern (anomaly 3). To the north, these positive anomalies change into flat long-wavelength anomalies 4. This pattern ends abruptly and is replaced to the north by a trough of negative anomalies 5.

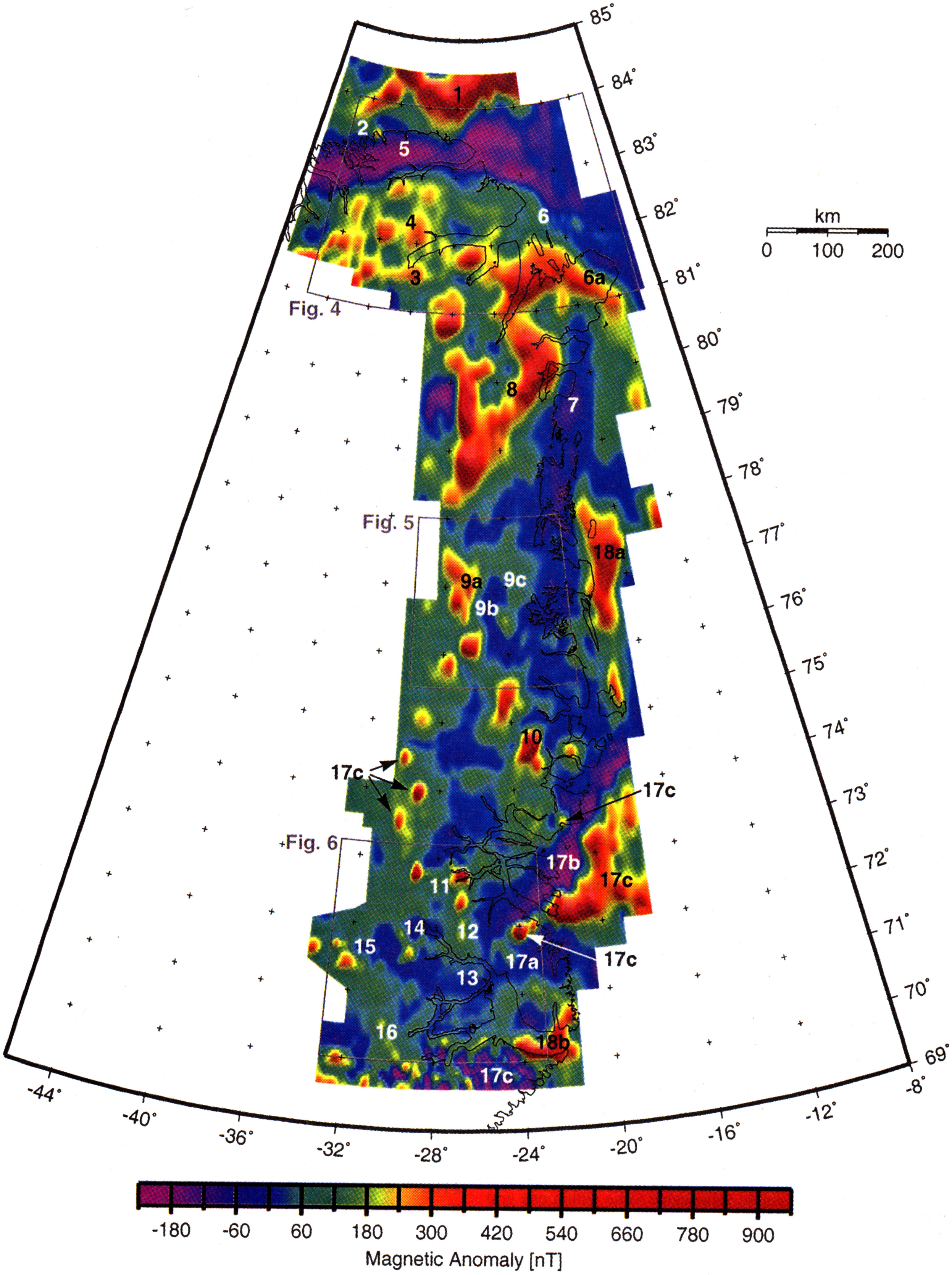

Plate 1. Aeromagnetic anomalies over northeast Greenland at 3700 m altitude. Numbers mark magnetic anomalies described in the text. Gray boxes mark the areas displayed in Figures 4-6.

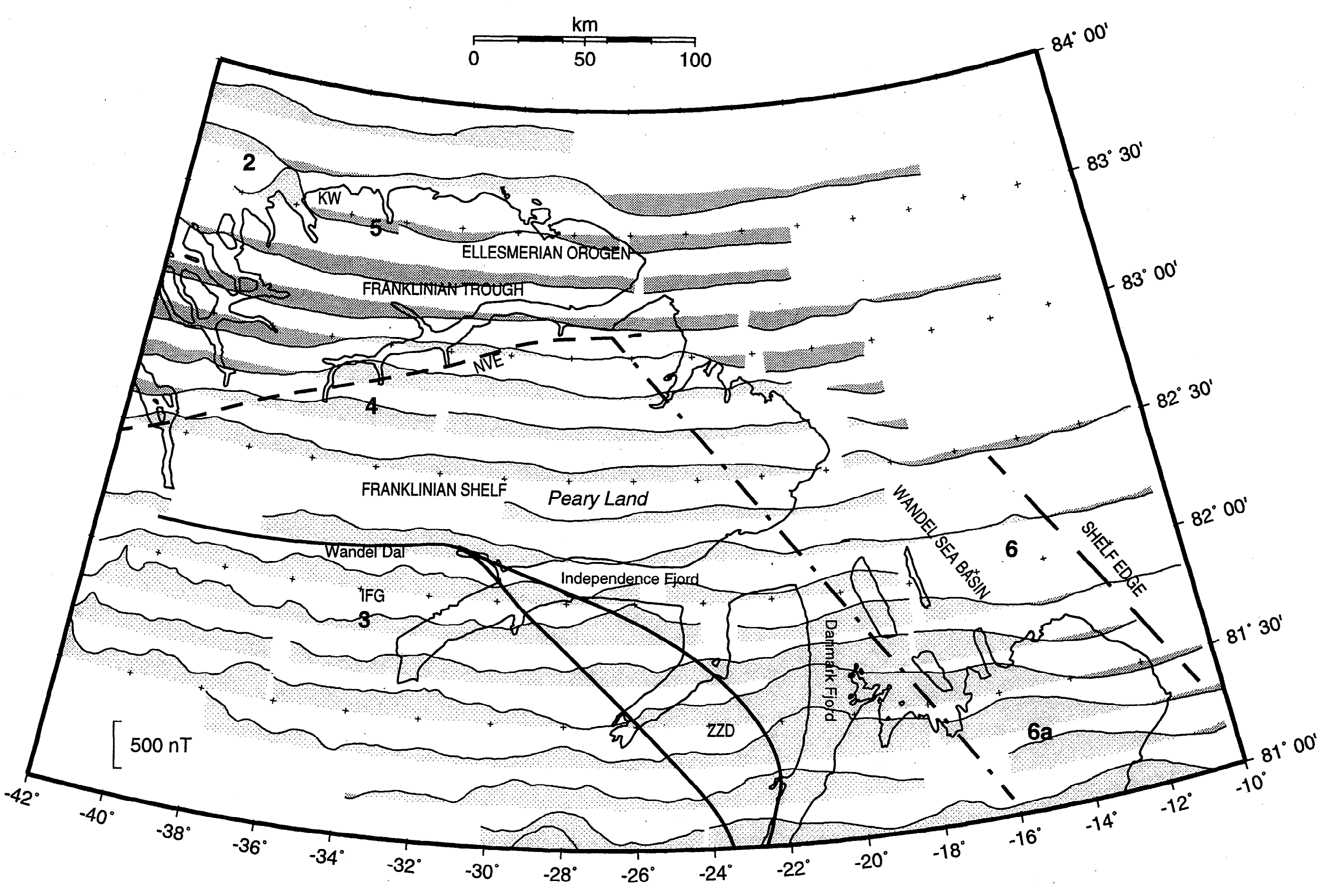

Figure 4. Aeromagnetic anomalies along flight lines over north Greenland. Positive anomalies are shaded in light gray; negative anomalies are shaded in dark gray. Numbered anomalies are discussed in the text. Relevant geological structures are roughly sketched and labelled in capitals. The buried Navarana Fjord escarpment (NVE) forms a boundary between Franklinian shelf and trough [*Surlyk,* 1991]. KW, Kap Washington; IFG, Independence Fjord Group; ZZD, Zig-Zag Dal basalts. Scale is valid at 82°N.

4.3.1. Anomaly 3. The magnetic anomalies 3 are encountered where rocks of the Independence Fjord Group (IFG) are exposed [*Escher and Pulvertaft,* 1995]. The short-wavelength character of the anomalies correlates to some extent with the topographic relief suggesting a shallow or outcropping magnetic source.

The IFG consists mainly of sandstones deposited in Middle Proterozoic times on Archean basement [*Surlyk,* 1991]. Both basement and the IFG sandstones were heavily intruded during a volcanic event at about 1230 Ma, producing large volumes of basic magmas [*Kalsbeek and Jepsen,* 1983]. The resulting Midsommersø Dolerite Formation frequently forms extensive, flat-lying sheets of dolerites reaching a thickness of up to several hundreds of meters [*Sønderholm and Jepsen,* 1991]. We suggest that these dolerites cause the magnetic anomaly 3.

The magnetic anomaly pattern 3 extends to the east across the area between Independence Fjord and Danmark Fjord where the Zig-Zag Dal Basalt Formation (ZZD) overlies IFG rocks and Midsommersø Dolerites. The basalts are regarded to be the extrusive equivalent of the Midsommersø Dolerites [*Kalsbeek and Jepsen,* 1983]. They could contribute to the magnetic anomalies.

4.3.2. Anomaly 4. North of Wandel Dal, the positive anomalies remain at the same amplitude level but show longer wavelengths in anomaly 4. Topography no longer influences the shape of the anomalies. Thus the magnetic sources lie beneath the surface.

At Wandel Dal the southern boundary of the Lower Paleozoic Franklinian Basin is exposed [*Escher and Pulvertaft,* 1995]. It consists of a wide shelf area to the south with mainly carbonate and siliciclastic deposits increasing in thickness toward the north. The shelf area is bordered to the north by a deep trough filled with siliciclastic sediments [*Surlyk,* 1991]. The magnetic anomaly pattern 4 coincides with the shelf region of the Franklinian Basin. As the sedimentary infill is unlikely to have significant magnetic susceptibilities, the magnetic sources must be sought below the basin. Outcrops of IFG including dolerites northeast of the Franklinian shelf [*Escher and Pulvertaft,* 1995] indicate a large spatial extent of the volcanic event. We therefore assume that the basement beneath the shelf part of the Franklinian Basin is also intruded by dolerites which cause the magnetic anomalies 4. The change in magnetic anomalies from 3 to 4 is then due to a magnetic layer dipping northward beneath a thickening nonmagnetic cover.

4.3.3. Anomaly 5. The transition from anomaly pattern 4 to the smooth negative anomaly 5 correlates with the boundary between the shallow and deep part of the Franklinian Basin. *Riddihough et al.* [1973] and *Coles et al.* [1976] interpret this transition as the northern boundary of the stable Precambrian craton of north Greenland. This interpretation can be expanded by our data. As the

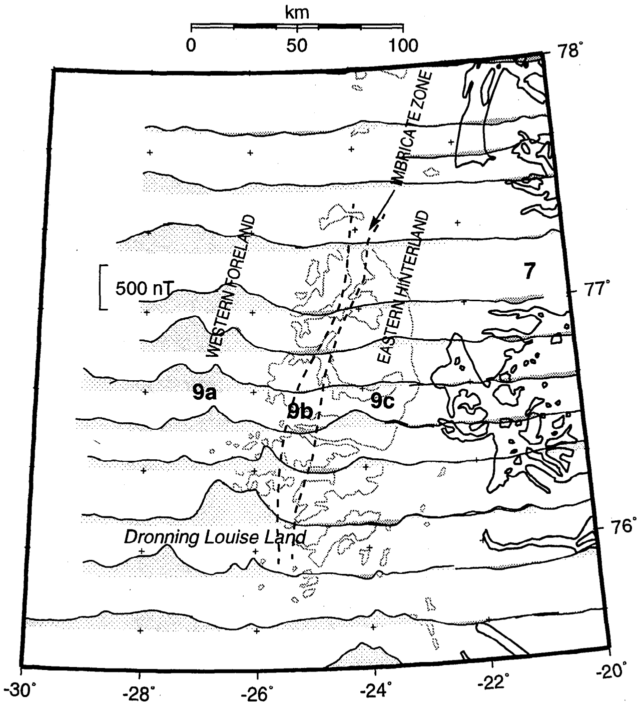

Figure 5. Aeromagnetic anomalies along flight lines over Dronning Louise Land. See Figure 4 for map explanation. Nunataks are outlined by dark gray lines. Scale is valid at 77°N.

sedimentary rocks exposed in the shelf and trough region of the basin are assumed to be nonmagnetic, the source for the change in magnetic pattern must be sought at depth. During the rifting process, which formed the Franklinian Basin, the Precambrian basement north of this boundary was downfaulted and thinned, eventually even cut off and replaced by a narrow ocean [*Surlyk,* 1991]. Thus the negative magnetic anomaly 5 can be attributed to an edge effect over the boundary between unaffected Precambrian basement to the south beneath the shallow Franklinian shelf, characterized by magnetic anomaly 4, and rifted basement beneath the deep Franklinian trough to the north. The Ellesmerian orogeny affected the Franklinian trough and may have contributed to the nonmagnetic character of the area by destruction of any still existing ferrimagnetic material.

4.4. Anomaly 6, Wandel Sea Basin (Plate 1 and Figure 4)

A prominent NW-SE trending gradient in the magnetic field is marked by anomaly 6 in Plate 1 and Figure 4. It is situated between the western boundary of the Wandel Sea sedimentary sequences, deposited from Upper Carboniferous times throughout the Mesozoic, and the shelf break [*Escher and Pulvertaft,* 1995]. The gradient trends parallel to the NW-SE oriented oblique-slip belt with fault-controlled basins [*Surlyk,* 1991] formed by Mesozoic E-W extension. The continental shelf break follows the strike direction of the mobile belt and is probably controlled by faults related to the mobile belt [*Dawes,* 1990].

The sedimentary sequences contain no likely source rocks for the magnetic anomalies. Instead, the eastward extent of magnetic anomaly 4 suggests that the dolerite-intruded basement may underlay the Wandel Sea strata. Downfaulting in the oblique-slip belt, perhaps accompanying the formation of the shelf break, may have displaced the magnetic basement to the northeast considerably downward. A smooth magnetic gradient over the edge of the magnetic basement would be the result.

The large positive anomaly 6a cuts off the magnetic anomaly 7 of the Caledonian fold belt (Plate 1). The northward extent of the Caledonides is unknown, as it is obscured by the younger structures of the Wandel Sea mobile belt. The northeasternmost outcrops of Caledonian crystalline basement are seen at about 81°N [*Escher and Pulvertaft,* 1995]. If the Caledonian crystalline complex extended farther north and was essentially nonmagnetic as to the south (anomaly 7), the formation of the NW-SE trending anomaly 6a must postdate Caledonian orogeny. This implies the introduction of magnetic material to the predominantly nonmagnetic crust, preferably during the tectonic regime of the Mesozoic oblique-slip belt. On the other hand, the positive anomaly might be caused by older geological units and cut off to the east by faulting related to the mobile belt and shelf break. In that case, the positive anomaly must have remained unaffected by the Caledonian orogeny and represents a northern boundary of thick-skinned Caledonian tectonism, comparable to the scenario reflected by the contrasting anomalies 7 and 8 (see section 4.5). Owing to the lack of additional geophysical and geological information on the crustal structure of this area, this key question for the understanding of the northern extremity of the Caledonides has to remain unsolved for the time being.

4.5. Anomaly 7, Caledonian Crystalline Complex of Northern East Greenland, and Anomaly 8, Caledonian Foreland (Plate 1)

A weakly magnetic area (anomaly 7) extends in a N-S direction from about 75°N to 81°N. It coincides with the Caledonian crystalline complex of northern east Greenland consisting mainly of amphibolite facies gneisses [*Higgins,* 1986]. Caledonian eclogites in the gneiss complex point to pervasive high-grade metamorphism during Caledonian orogeny [*Gilotti,* 1993; *Brueckner et al.,* 1998]. To the west, this nonmagnetic region is bordered by the positive anomalies 8 and 9. Geologically, this area is dominated by Caledonian nappes, which were thrust westward during the Caledonian orogeny, and the Caledonian foreland comprising IFG rocks [*Escher and Pulvertaft,* 1995]. Deformation and thrusting decrease toward the west [*Hurst et al.,* 1985] and has affected only higher crustal levels [*Henriksen,* 1994].

The magnetic anomaly pattern 8 consists of large long-wavelength anomalies locally superimposed by short-wavelength anomalies. Whereas the latter was correlated with exposures of IFG and related rocks (see *Schlindwein* [1998b] for details), the long-wavelength anomalies could not be explained in terms of surface geology and must have a deep-seated source.

We suggest the following hypothesis to explain the marked contrast between the positive magnetic anomalies 8 and the practically nonmagnetic Caledonian crystalline complex anomaly 7:

The positive anomalies could be of pre-Caledonian origin and a property of the basement beneath the Caledonian nappes. Magnetic sources may, for example, have formed during the large volcanic event in the Middle Proterozoic. The magnetic boundary between anomalies 7 and 8 may then have developed in Caledonian times and represent the boundary between thin-skinned and thick-skinned Caledonian tectonism. This means that the crust was largely unaffected by the Caledonian orogeny in the western part and could retain its earlier acquired magnetic properties. To the east, where the crystalline complex of the Caledonian fold belt is exposed, Caledonian reworking pervasively affected large parts of the crust and destroyed previously existing ferrimagnetic material by metamorphism.

Magnetite is considered the dominant ferrimagnetic phase for magnetic studies of crustal rocks [*Blakely and Connard,* 1989]. Its

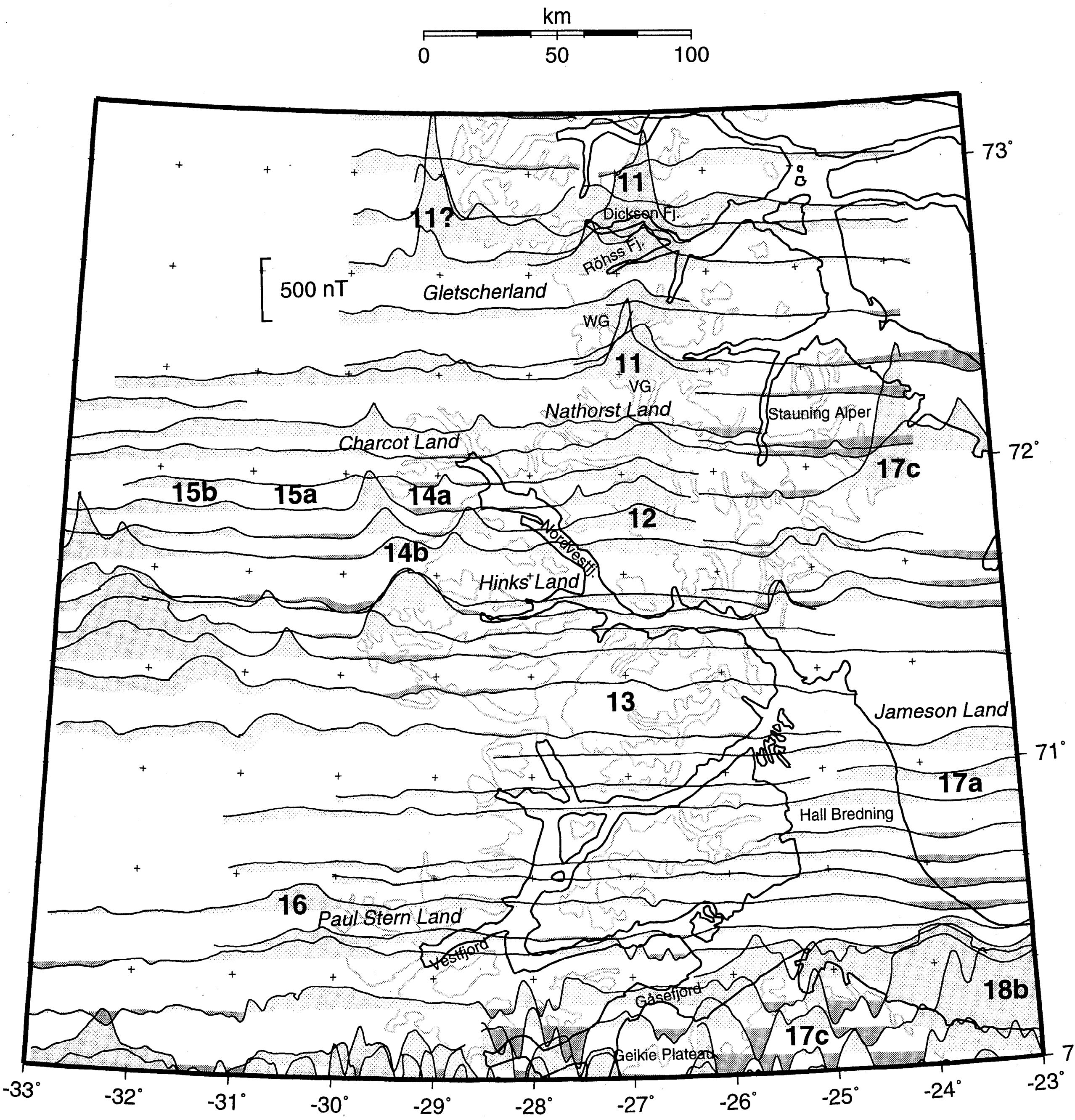

Figure 6. Aeromagnetic anomalies along flight lines over central east Greenland. See Figure 4 for map explanation. Light gray lines delineate borders of glaciers and ice caps. WG, Wahlenberg Gletscher; VG, Violingletscher. Scale is valid at 72°N.

behavior during metamorphism is complex, and no general rules apply [*Schlinger,* 1985]. However, nonmagnetic amphibolite facies rocks have been reported from several areas including east Greenland [*Larsen,* 1981] (see section 4.7), the Lofoten [*Schlinger,* 1985], and central Norway [*Skilbrei et al.,* 1991] and support the hypothesis of demagnetization of the crust by pervasive Caledonian metamorphism.

4.6. Anomaly 9, Dronning Louise Land (Plate 1 and Figure 5)

The magnetic anomalies over Dronning Louise Land consist of high-amplitude and short-wavelength anomalies to the west (anomaly 9a), a narrow nonmagnetic trough (anomaly 9b), and a moderately magnetic area in eastern Dronning Louise Land (anomaly 9c), grossly matching the three geological units of *Friderichsen et al.* [1990] (Figure 5):

1. The Western Foreland is largely unaffected by Caledonian events. It consists of Late Archean to Early Proterozoic gneissic basement [*Strachan et al.,* 1994] overlain by a sedimentary series, which was correlated with the IFG to the north. Both are intruded by numerous dolerites comparable to the Midsommersø dolerites. The short-wavelength anomalies 9a point to a shallow or outcropping magnetic source. The dolerites are the only likely magnetic source rocks in this area (see *Schlindwein* [1998b] for details). In addition, the geological and magnetic similarity of the areas defined by anomalies 9a and 3 supports this hypothesis.

2. In the Imbricate Zone (anomaly 9b) adjacent to the east the

foreland basement and sedimentary cover sequences suffered Caledonian deformation and amphibolite facies metamorphism [*Friderichsen et al.,* 1990], probably destroying the magnetization of the dolerites. The correlation of the magnetic low with the Imbricate Zone is best observed at the aeromagnetic profile along 76°30'N. However, there is a discrepancy between the situation of the Imbricate Zone as defined by *Friderichsen et al.* [1990] and the magnetic trough (anomaly 9b): The nonmagnetic trough 9b extends into the Western Foreland in northwestern Dronning Louise Land (about 77°N). Low- to medium-grade Caledonian overprinting was observed in this area [*Henriksen and Higgins,* 1976]. In contrast, in the southwestern part of Dronning Louise Land, just north of 76°N, positive magnetic anomalies 9a extend into the Imbricate Zone. Frequent dolerites occur in this area which are only low metamorphic and almost undeformed (J. D. Friderichsen, personal communication, 1997). This seems to underline the sensitivity of the magnetic properties of, in this case, dolerites to Caledonian metamorphic overprint and yields additional support for the above interpretation of anomalies 7 and 8.

3. The Eastern Hinterland consists of a high-grade migmatitic basement complex and a medium-grade metasedimentary cover sequence. Despite the metamorphic overprinting, the area is moderately magnetic, demonstrating that the relationship between magnetic properties and metamorphic grade is intricate. Locally, the occurrence of a cover sequence, including magnetite sandstones [*Friderichsen et al.,* 1990], coincides with positive magnetic anomalies. However, magnetite-bearing sandstones are also reported from the Imbricate Zone, where they do not produce anomalies. No information on the volumes and susceptibilities of these rock units exists which could solve this discrepancy.

4.7. Anomaly 10, Payer Land (Plate 1)

Northwest Payer Land (74.5°N, 24°W) shows a local positive magnetic anomaly attaining more than 750 nT in amplitude. The anomaly has been subject to a detailed aeromagnetic and ground investigation by *Larsen* [1981]. He showed that a high-pressure, granulite facies gneiss complex has higher susceptibilities than its amphibolite facies surroundings. *Larsen* [1981] considers the metamorphic development of this area to be pre-Caledonian.

4.8. Anomaly 11, Gletscherland Complex (Figure 6)

Pronounced positive magnetic anomalies 11 with maximum amplitudes of more than 850 nT occur between Dickson Fjord and the northern part of Violingletscher. In situ susceptibility measurements were carried out on surface rocks in the area of the largest anomalies at three localities at the north side of Röhss Fjord and south of Violingletscher [*Schlindwein,* 1998a]. A magnetite-bearing granitic gneiss of homogeneously high susceptibility (42 x 10^{-3} SI units) was found at all three localities. *Rex and Gledhill* [1981] report a similar rock from the south side of Dickson Fjord. The dimensions of the outcrops are of the order of several hundred meters to 1 km and estimated to be sufficient to produce the observed anomalies. The occurrence of these magnetite-bearing granitic gneisses causing high-amplitude magnetic anomalies seems to be confined to the Gletscherland infracrustal complex. This has implications for the evolution of the Gletscherland complex.

The degree of Caledonian overprinting of the Gletscherland complex is debated. *Haller* [1971] attributed the majority of the structures to Caledonian tectonics, whereas *Henriksen and Higgins* [1976] and *Higgins et al.* [1981] favor a pre-Caledonian origin. They consider the Late Archean to Early Proterozoic complex as being largely intact and having experienced only minor Caledonian overprinting.

Whereas the Caledonian orogen as a whole appears to be largely devoid of increased concentrations of magnetic minerals (compare anomaly 7), magnetite is present in large quantities in the granitic gneisses of the Gletscherland complex. The uniform distribution of magnetite in these rocks at all studied localities suggests that magnetite is primary rather than produced locally, for example, during Caledonian metamorphism at favorable P-T and compositional conditions. The rock crosscuts older structures but is itself foliated.

It is unknown if this foliation is Caledonian or Pre-Caledonian. In any case, magnetite survived at least the Caledonian orogenic event. This can have two reasons: (1) Either the special lithology of this rock was able to preserve magnetite during metamorphism. Then, the magnetic anomaly 11 can be used to distinguish the Gletscherland complex from the otherwise hardly distinguishable surrounding gneiss complexes [*Elvevold and Gilotti,* 1998; *Haller,* 1971]. (2) Alternatively, metamorphic conditions in Gletscherland must have been such that magnetite was not consumed (e.g., low-grade), supporting the hypothesis of *Henriksen and Higgins* [1976] (see above). A combination of both factors is also possible. Detailed studies of the metamorphic history of the Gletscherland complex are currently under way [*Elvevold and Gilotti,* 1998].

4.9. Anomaly 12, Grænsedal-Jomfrudal Metasedimentary Sequences (Figure 6)

Flat and wide magnetic anomalies 12 less than 250 nT in amplitude are centered around 26°30'W in Nathorst Land. It is uncertain whether this region is part of the Gletscherland infracrustal complex whose southern boundary is drawn at different locations between Wahlenberg Gletscher and Nordvestfjord by different authors [*Henriksen and Higgins,* 1976; *Higgins et al.*, 1981; *Escher and Pulvertaft,* 1995]. However, magnetically the region can be distinguished from the area immediately to the north by the lack of high-amplitude anomalies 11 and from the area to the south by the presence of moderate long-wavelength anomalies.

Probable sources are the metasedimentary sequences encountered frequently in this area as prominent flat-lying bands of up to 100 m thickness. An average susceptibility of about 18 x 10^{-3} SI units was calculated based on measurements on an extensive 100-m-thick band of metasedimentary rocks [*Schlindwein,* 1998a]. Primitive modeling showed that this susceptibility and dimensions are sufficient to account for the observed anomalies. The magnetically susceptible rocks from this area show in places a retrograde alteration. The distribution of ferrimagnetic minerals is very heterogeneous, suggesting that they may have been produced locally at favorable conditions during retrogression (M. Sergeyev, personal communication, 1996). Again, this process can be attributed to the combination of favorable lithology and special metamorphic conditions characterizing the region.

4.10. Anomaly 13, Gåsefjord-Stauning Alper Migmatite and Vestfjord-Hinks Land Gneiss Zones (Figure 6)

A large nonmagnetic area adjoins the anomalies 12 to the east and south and extends as far south as 70°20'N. Geologically, the area is dominated by the Gåsefjord-Stauning Alper migmatite and granite zone and the Vestfjord-Hinks Land gneiss and schist zone [*Henriksen and Higgins,* 1976]. The degree of Caledonian overprint and deformation of these complexes is difficult to assess due to the polyphase reworking of the rocks.

4.11. Anomaly 14, Charcot Land window (Figure 6)

The Charcot Land window shows a central nonmagnetic area 14a surrounded by moderately positive anomalies 14b. Detailed susceptibility measurements were undertaken in this area [*Schlind-*

wein, 1998a] and show a close link between surface geology and aeromagnetic anomalies. The central nonmagnetic area 14a results from the generally low susceptibilities of the Charcot Land basement and supracrustal sequences. The positive anomalies 14b coincide with outcrops of weakly metamorphosed basic extrusives and intrusives belonging to the Charcot Land supracrustal sequence [*Higgins,* 1982]. High susceptibilities were measured for weakly overprinted rocks, whereas amphibolite facies varieties of these rocks were observed to have lost their ferrimagnetic minerals.

4.12. Anomaly 15, Caledonian Foreland (Figure 6)

West of the Charcot Land window lies a magnetically quiet area 15a. From outcrops on nunataks this largely ice-covered region is inferred to belong to the Vestfjord-Hinks Land gneiss complex (compare anomaly 13) thrust westward over the Charcot Land tectonic window [*Henriksen and Higgins,* 1976]. Between about 72°N and 71°30'N, a distinct magnetic boundary delineates the western margin of this zone. Short-wavelength positive anomalies 15b dominate the magnetic field of the area to the west. We suggest that this change in magnetic pattern may mark the border to the Caledonian foreland and hence define the otherwise unknown westward extent of the Caledonian fold belt in this area. Similar magnetic relationships between the Caledonian orogen and the undisturbed foreland have been observed farther north (anomalies 8 and 9). In addition, the occurrence of tectonic windows (e.g., Charcot Land window), exposing foreland beneath Caledonian thrusts [*Henriksen and Higgins,* 1976], could point to shallow Caledonian structures which fade out toward the west.

4.13. Anomaly 16, Paul Stern Land (Figure 6)

Another tectonic window, the Gåseland window, exposes Caledonian foreland in Paul Stern Land. The window shows basement rocks in amphibolite facies and a supracrustal metasedimentary sequence [*Henriksen and Higgins,* 1976]. As this lithology in terms of magnetic properties is similar to the adjacent Vestfjord-Hinks Land gneiss and schist zone, no pronounced magnetic contrast can be expected. However, a slight increase in the magnetic field 16 is observed in this area which could be attributed to rocks in the foreland window.

4.14. Anomaly 17, Tertiary Volcanics (Plate 1 and Figure 7)

Tertiary magmatism related to the breakup of the North Atlantic affected the survey area south of about 75°N. A number of magnetic anomalies marked 17c can be directly correlated with outcrops of Tertiary volcanic and intrusive rocks. For example, the southernmost anomaly pattern 17c is produced by the flood basalts of Geikie Plateau, which extruded during a reversed polarity epoch, probably magnetic chron 24-26R (see, e.g., *Saunders et al.* [1997] for a review). A detailed discussion of these anomalies is presented by *Schlindwein* [1998b] and for the coastal and offshore region by *Larsen* [1990]. Of further interest in terms of crustal structure are the contrasting magnetic signatures 17a and 17b.

4.15. Anomaly 17a, Jameson Land Basin (Plate 1 and Figure 6)

Jameson Land and the adjacent Hall Bredning are marked by broad smooth magnetic anomalies of both weakly positive and negative amplitudes. The area hosts a deep Mesozoic sedimentary basin which is heavily intruded by Tertiary dikes and sills [*Escher and Pulvertaft,* 1995]. The dikes are generally of meter size, whereas sills attain thicknesses of several tens of meters. Seismic reflection data show evidence for sills also deeper in the sedimentary basin [*Larsen and Marcussen,* 1992]. The intrusives were emplaced during the same volcanic event which produced the flood basalts of Geikie plateau and probably carry a remanent magnetization of reversed polarity. However, this remanence is largely balanced by an induced magnetization [*Larsen and Marcussen,* 1992], such that the net effect in many cases may be close to zero. Both the magnetic properties and the limited volume of the intrusives may be responsible for the low amplitude of the magnetic anomalies over Jameson Land and Hall Bredning.

4.16. Anomaly 17b, Northern Flood Basalt Province (Plate 1)

A pronounced negative magnetic anomaly extends from about 72°N across two islands north-northeastward to about 75°N. Mesozoic sedimentary basins are exposed along the coast in the area of anomaly 17b. In addition, north of 73°N, the sedimentary units are partly covered by scattered outcrops of tholeiitic basalts, which attain a maximum thickness of about 800 m [*Upton et al.,* 1995]. The magnetic properties of the northern flood basalts were studied by *Abrahamsen and Nordgerd* [1994]. All their samples carry a reversed polarity remanence which is a factor 2.8 larger than the induced magnetization. *Upton et al.* [1995] argue that the source of the northern basalts must have lain farther east and that the outcrops along the coast represent the westernmost manifestation of this volcanic event. The presence of reversely magnetized basalts along the coast and presumably also offshore could therefore explain the magnetic anomaly. However, in the area of the islands between 72°N and 73°N no exposures of basalts exist to account for the southern part of the negative magnetic anomaly. The Mesozoic sedimentary basins in this area are intruded by dikes and sills carrying both normal and reversed polarity magnetizations [*Hald,* 1996]. In addition, the intrusives are related to those of the Jameson Land Basin which, in spite of much larger volumes, do not produce a magnetic anomaly. We therefore suggest that the intrusives are not responsible for the pronounced negative anomaly over the islands between 72°N and 73°N and conclude, that the negative magnetic anomaly 17b as a whole must have an additional source which is not exposed.

Seismic refraction studies carried out in this area revealed the existence of a seismic high-velocity layer in the lower crust between about 16 km and 22 km depth (Schlindwein and Jokat, submitted manuscript, 1998). The occurrence of this high-velocity layer correlates with the negative magnetic anomaly. We propose a magmatic origin for the high-velocity layer and suggest that it formed at the same time as the Geikie Plateau flood basalts and hence acquired a strong reversed polarity remanent magnetization.

4.17. Anomaly 18, Unexplained Anomalies (Plate 1)

Two major anomalies could not be explained in terms of surface geology or crustal structure. Anomaly 18a trends roughly N-S along the coast between 75°N and 78°N. *Larsen* [1990] interpreted the magnetic anomaly as a basement high in a series of horst and graben structures which probably evolved contemporaneously with the Paleozoic to Mesozoic sedimentary basins farther south. However, the geology onshore is dominated by Caledonian crystalline rocks including eclogites which testify to pervasive Caledonian reworking. Therefore we would expect the crust in this area to be demagnetized during Caledonian metamorphism. Horst-graben structures in a nonmagnetic basement cannot produce a pronounced magnetic anomaly such as anomaly 18a. Hence the interpretation requires the introduction of magnetic minerals to the crust at a later stage, preferably during the tectonic regime, which formed the horst-graben structures. However, none of the Mesozoic basins farther south shows a comparable magnetic signature. No explanation in terms of surface geology can be brought forward for anomaly 18b. A Tertiary magmatic origin is likely.

5. Conclusions

This study offers new insights into the structure and evolution of the continental crust of northeast Greenland on the basis of its magnetic properties. The stable Precambrian craton of north Greenland is characterized by positive magnetic anomalies produced by volcanic rocks emplaced during a major volcanic event in Middle Proterozoic times. The aeromagnetic data outline the margins of the craton where rifting episodes affected the magnetic basement and downfaulted or thinned it.

The magnetic data suggest a subdivision of the Caledonian fold belt into a northern and southern part having experienced different geological evolution: Pervasive Caledonian reworking of the crystalline complexes north of about 76°N led to a homogeneous demagnetization of the crust. Areas in the western part of the fold belt experienced only shallow Caledonian tectonism and retained their earlier acquired magnetic properties. As a result, the northern part of the Caledonian fold belt shows a characteristic nonmagnetic area bordered to the west by pronounced positive anomalies. The occurrence of isolated strongly positive magnetic anomalies characterizes the southern part of the east Greenland Caledonides. Magnetite survived the Caledonian orogeny in these crystalline complexes probably due to special metamorphic or petrological conditions.

By jointly analyzing magnetic anomaly pattern and geological structures we observed that magnetite is sensitive to metamorphic overprint at several places in the Caledonian fold belt of east Greenland. This is particularly evident in the northern part of the Caledonides. In situ susceptibility measurements on mafic rocks in the Charcot Land window present an additional example for magnetite being destroyed by amphibolite facies metamorphism. The sensitivity of magnetite to metamorphism could be used to trace the west extent of Caledonian overprinting in the ice-covered regions west of Dronning Louise Land and Charcot Land.

In the southern Caledonides the aeromagnetic data and the supplementing ground studies of the magnetic properties of exposed rocks can presently be used to distinguish Caledonian crystalline complexes with different petrophysical evolution. Combined with petrological studies the magnetic data may in future help to shed light on the much debated problem of the degree of Caledonian reworking in the southern Caledonides of east Greenland.

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