A satellite magnetic anomaly map of Greenland

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Summary. A satellite magnetic anomaly map of Greenland has been compiled using data from the POGO 2, 4 and 6 satellites. Data from quiet passes have been extracted and processed into an equivalent source representation in the form of a contour map of the satellite magnetic field at an altitude of 500 km. The satellite magnetic anomaly map contains some very pronounced anomalies: A magnetic maximum of 8nT centred in northern Greenland at approximately 79°30'N, 37°W, a smaller but also significant maximum over southern Greenland at 61°30'N, 44°W, and two minima over the Disko-Nügssuaq area of central West Greenland (70°N, 52°W) and the Scoresby Sund area of central East Greenland (71°N, 24°W), respectively. A qualitative comparison with major geological features shows a good general correlation, although no final conclusions should be drawn from the existing POGO data. The magnetic anomaly map is also compared with the scarce existing geophysical data from this area. Major changes in crustal properties and/or structures are indicated under the Inland Ice across a line connecting the Disko-Nügssuaq area and the Scoresby Sund area.

1 Introduction

In recent years satellite magnetic data have begun to be used for crustal studies. Regan et al. (1975) compiled a global satellite magnetic anomaly map between ±50° latitude. Langel et al. (1982, in preparation) have derived similar maps of the polar regions and Fig. 1 reproduces the map for northern high latitudes. The anomalies that can be observed on these and similar maps are of very long wavelength and probably originate deep in the Earth's crust (Mayhew 1982a). Surface geology and the satellite magnetic anomaly map can be thought of as expressions of major, large scale processes and structures in the Earth's crust. Langel et al. (1980) demonstrated this by comparing a satellite magnetic map with upward continued aeromagnetic data from northern Canada. They found that the aeromagnetic data contained more information than the satellite magnetic data, but that the later data better revealed the
very large-scale features normally obscured in the more detailed aeromagnetic data. Regan & Marsh (1982) in a study of the Bangui magnetic anomaly using corresponding ground geophysical and geological data verified the existence of this large anomaly and determined its source to be in the lower crust.

Very little is known about the properties and structures of the crust underlying Greenland. Most of the geophysical work has been carried out in the narrow strip of ice-free land along the rim of the Inland Ice, and at certain offshore locations.

Geophysical data from below the Inland Ice are extremely scarce. Because of this scarcity of data it is important to explore what information can be gained for Greenland where substantial anomalies occur (Fig. 1) by applying the methods which have been successful for other anomalous regions.

2 The satellite magnetic anomaly map

The POGO satellites (Cain & Langel 1971; Langel 1974, 1980) collected magnetic field magnitude data at altitudes between 400 km and 1500 km. The total magnetic field vector may be considered as the sum of contributions from several sources, many of which must be treated as noise in relation to crustal studies. Especially, local current and magnetospheric ring current effects must be eliminated from the data along with the main magnetic field originating in the Earth’s core. If these reductions can be carried out successfully the remaining magnetic field can be taken as originating in the crust.

For the Greenland data this process of reduction was carried out using the method described by Mayhew (1979), Mayhew et al. (1980) and Langel et al. (1980). A brief summary of the method is given below, with emphasis on the special aspects of the Greenland data.
Because Greenland lies between latitudes 60° and 84° N the effects of the disturbances caused by ionospheric and magnetospheric currents pose a serious problem. Such currents occur very frequently, and the wavelengths of the resulting magnetic fields are of the same order of magnitude as the anomalies originating in the Earth’s crust (Langel 1974). However,

![Magnetic anomaly map of Greenland](https://academic.oup.com/gji/article-abstract/71/3/599/654717)

**Figure 2.** Examples of POGO satellite traces showing magnetic residual data. (a) Two passes with quiet data which could be used in this study. (b) and (c) Two cases of disturbed and moderately disturbed data, which could not be used for crustal studies and had to be omitted from this study.
EXAMPLE OF MODERATELY DISTURBED DATA
FROM THE OGO SATELLITES

Figure 2 – continued

Langel et al. (1980) were able to obtain a map which agreed in large measure with aero-
magnetic data and this procedure has been adapted for the Greenland data.

All available POGO passes over Greenland have been inspected in the form of computer
plots of the type reproduced in Fig. 2. These show the residual magnetic field obtained by
subtracting a model of the core field from the magnetic field measured by the satellite. A
spherical harmonic model of degree and order thirteen, POGO (2/72), Langel et al. (1980),
was used. Before selection, the residual field of individual passes (see examples in Fig. 2) in
general results from two major sources and probably several minor ones in various propor-
tions. The major ones are the fields of external origin and the field originating in the crust.
Minor ones can be instrument noise and errors in the main field model subtracted. Some-
times the external fields are totally dominating, and the magnetic data must then be discarded
from further use. Therefore, traces showing values of the residual magnetic field in excess of
20 nT at any place north of 50° N were immediately eliminated from the analysis, as these
data were almost certainly dominated by mainly external fields. All remaining (319) traces
were visually inspected and all passes appearing to contain significant contributions from any
time varying field were further omitted. Passes with very small amounts of data were also
removed. This process left 134 passes, see Fig. 3, which were accepted as containing mainly
crustal anomalies and which could be used for the production of the satellite magnetic ano-
maly map. When comparing these remaining passes it was found that significant differences
between traces were still present in the form of fields with wavelengths of the order of a few
thousand kilometres. As in the cited references, a linear function was fitted to each individu-
al pass and subsequently subtracted from the residual field of that pass. The process signi-
ficantly improved the already substantial internal agreement between nearly coincident
passes.
To obtain data relative to a common altitude, the gridded magnetic field was modelled by an equivalent source procedure (Mayhew 1979; Mayhew et al. 1980). A grid of dipoles was placed at the surface of the Earth aligned in the direction of the present magnetic field. The dipoles were spaced in equal area with the distance between dipoles equivalent to 3° at the pole. Magnetic moments which would reproduce (in a least-squares sense) the measured magnetic field anomaly at the original observation altitude were calculated. From the dipole moments the corresponding magnetic field at an altitude of 500 km was calculated. Fig. 4 shows a contour map of this field, herewith presented as a good and consistent representation of the crustal contribution to the POGO data over Greenland.

The equivalent source representation used to derive Fig. 4 may also be utilized to infer the relative average bulk magnetization of the magnetized crustal layer, provided the thickness of that layer is known. In the absence of definitive crustal thickness data we have calculated an equivalent magnetization assuming that the crust is 40 km thick, as a first approximation, see the discussion later. This is shown in Fig. 5. In this model the relationship between relative magnetization and thickness of the magnetic crust is linear so that the variations reflect a combination of changing crustal thickness and magnetization.

3 Major geological features of Greenland

Some 80 per cent of the area of Greenland is covered by the Inland Ice, and practically nothing is known about the geology of the bedrock under the ice. Some general features can perhaps be inferred from the coastal areas by extrapolation. By contrast the mostly ice-free mountainous areas around the rim of the Inland Ice expose the geology of these areas very
Figure 4. The satellite magnetic anomaly map of Greenland. This is the best and most consistent representation of all existing POGO data over Greenland. The map has been produced by an equivalent source calculation to 500 km. (The kinks in the contours are due to the contouring method.)

Figure 5. Contour map of equivalent magnetization calculated from the equivalent source representation forming the basis for the map of Fig. 4 assuming a 40 km thick magnetic crust. Contour interval is $1 \times 10^{-3}$ A m$^{-1}$. 
well, and this is where the geology of Greenland has been studied in detail. A recent comprehensive review of the Greenland geology is given in Escher & Watt (1976), from which the simplified picture of Greenland geology of Fig. 6 is taken as is the ensuing discussion. Only references adding to or significantly changing the information given in Escher & Watt (1976) are given in the following. The main geological features will be described very briefly. While it is probably true that clues to the understanding of satellite magnetic data can be found in quite detailed work, the magnetic map of Fig. 4 is best understood in terms of structures of the same order of magnitude as those described below.

The Precambrian shield makes up the major part of the ice-free regions. It is divided into four major structural units. The Archaean gneiss complex is found on the west and east coasts of southern Greenland, and probably also under the corresponding southern part of the Inland Ice. Some of the oldest rocks in the world are found in this area, which is best described as a very stable shield area consisting of various units ranging in age from 3750 (or older) to 2500 Myr, and to a large extent unaffected by any geological events in the last 2500 Myr. Isolated remnants of Archaean rocks with similar ages have been identified in North and East Greenland.

The Nagssugtoqidian mobile belt lies north of the Archaean rocks, on both the west and the east coasts. These rocks were later reworked with the deformation taking place in several episodes between 1700 and 2700 Myr ago. The deformation is related to strong horizontal movements in shear belts (Korstgård 1979), and rocks of similar age and tectonics can be seen in Scotland (Meyers 1980). The Rinkian mobile belt is of approximately the same age, 1870 to 1650 Myr, but is considered to be a separate structural unit mainly because of its different tectonic style. South of the Archaean block is the Ketilidian mobile belt, with sediments and volcanic rocks overlying the Archaean gneisses and with ages ranging from 1850 to 1740 Myr. The region is characterized by many intrusive granite plutons. Approximately 1200 Myr ago the area was affected by extensive basaltic volcanism, forming the Gardar volcanic province, accompanied by faulting and dyke intrusion and with the emplacement of a major suite of alkaline igneous rocks.

In North and East Greenland sedimentation took place in the Proterozoic with sediments of various types overlying the Precambrian shield rocks, see Fig. 6. In some areas sedimentation continued up into the Palaeozoic, sometimes accompanied by implanation of dykes and sills. Significant events took place in the Palaeozoic: i.e. major parts of East Greenland, north of Scoresby Sund and up to the NE corner of Greenland were affected by the Caledonian orogeny c. 400 Myr ago. North Greenland was affected by the eastward extension of the Innuitian orogeny of NE Canada.

Sedimentation of both continental and marine character continued in the Mesozoic in both central West Greenland and central East Greenland. In the latter area major tectonic activity in connection with the opening of the North Atlantic resulted in rifting along N–S and NW–SE fractures and faults. In the Tertiary some 55 Myr ago major volcanism was related to the opening of the Greenland–Norwegian Sea producing vast amounts of tholeiitic lavas south of Scoresby Sund in East Greenland. In the sedimentary basin of the Disko-Nugssuaq area of West Greenland, where sedimentation had occurred since the lower Cretaceous, there was also volcanism at approximately the same time, creating similar lava fields which are also identifiable offshore.

During the Quaternary of Greenland the vast Inland Ice was created starting probably about 3 Myr ago. At times it had a greater extension than at present. The greatest thicknesses are at present about 3 km, and the total mass of the ice makes up a very considerable load on the crust under Greenland, resulting in subsidence of central Greenland and some relative uplift of the rim areas.
Figure 6. Major geological structures of Greenland. Adapted from Escher & Watt (1976) with permission, and with changes according to Jepsen & Kalsbeek (1981).
In view of this long and varied evolution of Greenland there is an obvious interest in improving the understanding of the underlying crust. In the following discussion the satellite magnetic anomaly map will be related to the geological features of Greenland.

4 Discussion

Interpretation of the satellite magnetic anomaly map is limited by its accuracy and resolution. These are difficult to define unambiguously, but some indications can be given. Fig. 7 shows the 95 per cent confidence interval for the map of Fig. 1, calculated as the standard error of the mean for each average. Modelling these anomalies with equivalent sources results in additional smoothing and, presumably, comparable or better accuracy, always keeping in mind that the zero level is arbitrary. For Greenland and vicinity relative amplitude differences of 1–2 nT are near the limit of accuracy.

By anomaly map resolution we mean the ability to distinguish separate sources. This obviously depends upon the relative amplitude of the anomalous fields from those sources. Model studies indicate that dipole sources of equal amplitude can be distinguished at an altitude equal to their separation if their amplitude is greater than about 3 nT and if the relative measurement accuracy is at least 2 nT. Mayhew (1982a) states that the model resolution approaches half the mean data elevation. This seems to us to be somewhat over-optimistic. For the Greenland data presented here, the mean altitude was at or less than 500 km so the resolution is in the 250–500 km range. For the equivalent source model the resolution is clearly limited by the dipole spacing which is about 330 km.

The satellite magnetic anomaly map of Fig. 4 and the derived magnetization map of Fig. 5 are dominated by a high centred over the northern half of the Inland Ice (79° 30'N, 37° W). It is of considerable areal extent, and on the map of Fig. 1 it can be seen to be one of the major anomalies of the northern polar region. This North Greenland magnetic anomaly...
anomaly is clearly separated from a smaller, but in relation to the surrounding field still significant, South Greenland magnetic maximum (61° 30′N, 44°W) by two minima centred over the central parts of the east and west coasts of Greenland. A southward extension of the North Greenland high into the centre of Greenland is evident at about 40°W longitude. The data resolution is insufficient to determine if this is a separate feature or an extension of the main anomaly.

The Disko-Nuugssuaq magnetic minimum (70°N, 52°W) is elongated in a NW–SE direction from well out in Baffin Bay into the Inland Ice. The Scoresby Sund magnetic minimum (71°N, 24°W) is more circular in form, and a trough of generally negative values surround the two magnetic lows along a line across the Inland Ice. To the NW of Greenland a trough separates the North Greenland magnetic high from an anomaly of similar character over the Alpha ridge of the Arctic Ocean (see Fig. 1).

The sources of the long wavelength anomalies in Figs. 4 and 5 lie in the upper layers of the Earth. The Curie isotherm defines a lower boundary below which no material is magnetic, and Wasilewski et al. (1979) have shown that the mantle just below the Moho is dominantly of non-magnetic mineralogy, even if the Curie isotherm is deeper than the Moho. Thus the lower boundary of the magnetic crust is defined by the Moho, and by the Curie isotherm where this rises above the Moho. The magnetic anomaly field is therefore a result of variations in the thickness of the magnetic crust, combined with the effect of lateral variations in average crustal magnetization, arising from petrological and structural differences.

Wasilewski et al. (1979) argue along theoretical lines that in general the most likely source area can be limited to the lower crust. Few anomalies have been modelled so far, but two (Regan & Marsh 1982; Mayhew et al. 1982) have been associated with distinct regions of intrusion of mafic material fractionated from the mantle. On the other hand Mayhew (1982b) has noted for anomalies in the Western USA an anti-correlation with heat flow, i.e. variation in the Curie isotherm. Thus on the basis of information now available it seems that in general the satellite magnetic anomalies of regional scale reflect the structure and petrology of the lower crust or variations in the depth to the Curie isotherm.

The source area of the North Greenland anomaly is almost totally covered by the Inland Ice, which here has a thickness of up to approximately 2.5 km. Bedrock exposures along the rim of the Inland Ice show rocks of Precambrian age on three sides of the area, and presumably the rocks below the ice in this area are of similar age. Otherwise very little additional information is available. Oliver et al. (1955) used propagation paths of the Lg surface-wave phase to show that the crust under Greenland is of continental type. Pawlowicz (1969) used gravity data (average Bouguer anomalies) from the British North Greenland Expedition, BNGE, and from Expédition Glaciologique Internationale au Groenland, EGIG, combined with radar measurements of the ice thickness in an isostatic study of the crust along two profiles over the Inland Ice. In northern Greenland (BNGE) depths to the Moho from 36 km near Thule to 42 km in the central part of the northern Inland Ice were obtained. In central parts of the Inland Ice (EGIG) depths from 35 to 39 km increasing linearly from west to east were calculated. Ostenso (1968) found that gravity data from the northern East Greenland shelf were best explained by a relatively abrupt increase in thickness of the crust from 18 to 36 km. Thus, indirect evidence points toward a crustal thickness of approximately 36 km under the shelf areas increasing to approximately 42 km under central parts of the northern part of Greenland. This is confirmed by Gregersen's (1970) analysis of the group and phase velocity dispersion of Rayleigh and Love waves crossing the interior of Greenland. His preferred model has three layers: ice down to 2.5 km, below which is a 'Granitic' layer to 19.0 km, underlain by a 'Basaltic' layer to 42.7 km. The seismic paths crossed mainly the part of Greenland where the North Greenland magnetic high is located. A thickened crust is con-
sistent with the magnetic anomaly data in that a thickened crust with either a constant or increasing average bulk magnetization would result in a magnetic high.

The trends and positions of the elongated magnetic lows North and East of the North Greenland magnetic high correlate well with the fold belts of the Innuitian tectonic province and Caledonian fold belt. Langel & Thorning (1982) in a discussion of the Nares Strait region conclude that the magnetic contrast in this region is probably caused by a change in the thickness of the Precambrian crust and/or a petrological change brought about during the formation of the fold belt and resulting in lower magnetization in that region. A similar explanation may be evoked for the Caledonian belt, but here the expression in the magnetic anomaly field is less clear because of the complications brought about by the later creation of the Greenland—Norwegian Sea.

No additional geophysical information is available for the area between Scoresby Sund and Disko Bugt. If the same effect observed over the two major mobile belts mentioned above is at work here this would indicate the possible existence of a similar geology under the Inland Ice, i.e. a fold belt or otherwise modified Precambrian rocks. As long as no supporting geophysical evidence is available this remains a speculation.

Examination of Fig. 4 and, particularly, Fig. 5 makes it clear that a major structural or petrological change has taken place between the North Greenland magnetic high, at latitudes of 76°–83°, and the Precambrian mobile belts to the south. As already noted, it is not clear how the southward extension of the magnetic high relates to this change. It could reflect an actual southward extension of the source of the magnetic high or a totally separate structural or petrological region. Sobczak (1978), on the basis of ground and satellite gravity data, also reached the conclusion that there is a change either in crustal thickness or in lithologies and densities between northern and central Greenland. The two very pronounced closed magnetic lows over Disko Bugt and Jameson Land are situated over regions of recent geological activity, involving rapid subsidence, sedimentation and vulcanism. These very complex regions contain thick sedimentary sequences partly overlain by reversely magnetized basaltic rocks. Both regions have been subsiding since about the end of the Cretaceous. The magnetic minima are then due to some complex combination of causes, presumably including the reversely magnetized rocks, thick sedimentary sequences, and possibly a thinning of the magnetic crust.

The relative high in south Greenland (Figs 4 and 5), which presumably also reflects another structural or petrological change, is centred over the boundary between the Archaean and Kettillidian rocks, and may be caused by the Precambrian shield, which in this area has experienced both vulcanism and plutonism, also to a large extent affecting the lower crust.

The contours of Fig. 4 hint at a possible relation between the two maxima centred over Iceland and South Greenland, areas of recent and Precambrian igneous activity, respectively. Note that the separation between the maxima of the Icelandic and South Greenland highs is over 500 km, which is within the resolution of the data. The amplitudes are small but the relative low between the two highs is still significant at the 95 per cent level, see Fig. 7. The region between these anomalies has a complex history (Vogt et al. 1981), including episodes of complex spreading (Larsen & Jacobsen, in preparation). The whole area has occasionally been above or at sea level. The coastal region of Greenland south of Scoresby Sund has experienced major upward movement (doming) in the Tertiary with later major subsidence of offshore areas (Brooks 1973). This is also an area with many deep intrusions and major dyke swarms. The relative minimum between the Icelandic magnetic high and the South Greenland high may thus be an expression of crustal extension and thinning, perhaps in connection with the attempted and partially successful seafloor spreading in that area (Larsen & Jacobsen, in preparation).
It has been noted by Frey & Langel (in preparation) that many long wavelength satellite magnetic anomalies are nearly continuous over reconstructed boundaries of Pangaea. Fig. 8, reproduced from their paper, shows that if the Greenland–Norwegian Sea is closed to a Mesozoic pre-drift position the North Greenland magnetic high would be just adjacent to a high over Western Scandinavia, separated from this by an elongated relative trough following the reconstructed Caledonian mobile belt, i.e. a situation quite similar to what can now be observed over the Nares Strait region. The negative anomalies over central parts of Greenland line up with a major minimum centred over an area of the Baltic shield. If these correlations are meaningful indications of once continuous structures of the lower crust it would imply that the anomaly sources were in existence prior to the separation of Greenland and Scandinavia, and that consequently the structures below the Inland Ice discussed above probably are of Precambrian age. Later developments in the Palaeozoic (?)–Mesozoic basins then gave rise to the accentuated minima over these regions.

5 Conclusions

Results of these studies can briefly be summarized as follows:

(1) It has been possible to compile a satellite magnetic anomaly map from POGO data over Greenland which is relatively free of the effects of external fields.

(2) A qualitative correlation of magnetic anomalies and major geological features has been demonstrated, further confirming the usefulness of satellite magnetic data for regional studies of lower crustal structure.

(3) Significant changes in crustal structure and/or petrology are indicated under the central part of Greenland. This may have a bearing for future plate-tectonics studies, and should be considered in the planning of further geophysical work over the Inland Ice.

The results obtained with the POGO data have encouraged the planning of further work using the MAGSAT data. The better resolution of the new data may reveal more detail of
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geologically interesting trends hinted at in the POGO data. It is hoped that results emerging from the rapidly progressing interpretation of new aeromagnetic data from the East Greenland shelf, e.g. Larsen & Thorning (1980), Andersen et al. (1981), will provide additional information of use in the geological interpretation of MAGSAT data.

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