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PAPER 68-44

ANALYSIS OF AEROMAGNETIC DATA OVER THE ARCTIC ISLANDS AND CONTINENTAL SHELF OF CANADA

(Report and 6 figures)

B. K. Bhattacharyya

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ABSTRACT

Results of the analysis of aeromagnetic data over the Arctic Islands and Continental Shelf of Canada are presented in this paper. The data cover part of the area from latitude 75° to 81°N and longitude 98° to 129°W. The major magnetic units observed in the area seem to indicate the presence of a basement high, presumably subcrop of the Canadian Shield in southeastern Melville Island, beneath the Parry Islands fold belt and a probable westerly extension of the lower Paleozoic eugeosynclinal belt exposed in northern Ellesmere and Axel Heiberg Islands. Widespread folding and faulting in the area overlain by the Arctic Ocean are suggested because of the evidence of abrupt changes in orientation and marked increase in intensity of the polarization vectors. Several depth determinations have been made and the depths to the tops and bottoms of the causative bodies are presented in contoured form. These contoured maps indicate the probable presence of a deep linear trough trending north-south on the west of Ellef Ringnes Island and another deep sedimentary trough in the Arctic Ocean around latitude 79°45'N and longitude 114°W.

ANALYSIS OF AEROMAGNETIC DATA OVER THE ARCTIC ISLANDS AND CONTINENTAL SHELF OF CANADA

INTRODUCTION[1]

The quantitative interpretation of total-field aeromagnetic data in terms of subsurface geology is greatly assisted today by various semiautomatic methods of treatment and presentation of data. The objective of this interpretation is often to decipher the broad geological structures, to extrapolate the subsurface continuation of the lithological or structural units observed on the surface, and to find new structural features of major and minor proportions. With this objective in mind interpretation of aeromagnetic data over many large areas in Canada is being carried out in the Geological Survey of Canada.

One such study has been concerned with the magnetic data over the Arctic Islands and Continental Shelf of Canada. With the help of these data residual values were calculated and the resulting anomaly map was studied to delineate the major geological features. Because of the large depth of the crystalline basement in the area, the magnetic anomalies have very broad, flat characteristics and low gradients. In order to make the anomalies more pronounced, the residual values were continued downward to a depth of one mile. A large number of anomalies were then chosen from the residual and continuation maps for determining depths, polarization vectors and vertical extents of the causative bodies. This paper presents the preliminary results of analysis of aeromagnetic data mentioned in this paragraph.

DETAILS ABOUT THE DATA AND DIGITIZING

The aeromagnetic data cover part of the area from 75°N to 81°N in latitude and 98°W to 129°W in longitude. The flight altitude was 304.8 m (1,000 feet). The major part of this area was flown with a fluxgate type of magnetometer and the rest with an absolute proton-precision magnetometer. Because of this, the area was suitably divided into two parts and for each

[1]This paper was first presented at the seventh World Petroleum Congress, Mexico City, Mexico in 1967. But because of delay in the submission of the paper to the editor, it was unfortunately not published in the Proceedings of the Congress.

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Author's address: Geological Survey of Canada,
601 Booth Street,
Ottawa 4, Ontario.

part the regional magnetic variation was calculated by fitting a least squares quadratic surface to the data. The residual field values were then obtained by subtracting the regional variation from the total field data.

A uniformly-spaced grid was chosen for digitizing the total magnetic field values. The spacings along latitude and longitude lines were taken to be 0.5 minute and 2.5 minutes respectively. Over the Arctic Islands these spacings are on the average a little over 0.8 km (0.5 mile).

Digitizing of the total field values from published aeromagnetic maps according to the chosen spacing, was done carefully along two orthogonal directions with the aid of the EAI (Electronic Associates, Inc.) 1.092 Electronic Coordinatograph and Recording System. This process of digitizing was then thoroughly checked with the symbolic and numerical maps prepared by the IBM 360, Model 50 computer (Morley and Bhattacharyya, 1966). Careful attention was paid to reduce, as much as possible, two sources of error inherent in the process of digitizing, (i) the random error in interpolation between flight lines caused by the original contouring of the data at the time of preparation of the total field map and (ii) unavoidable error in interpolation while digitizing the information on the map.

These two forms of error could be eliminated if digitizing were done only along flight lines. In such a case, spacing is nonuniform and total field values have to be read along curved flight lines. However, at the time the present work was carried out, no reliable method was available for treating nonuniformly spaced data without introducing large computational errors. It was, for this reason, decided to digitize map data at uniform spacings and reduce the human errors in interpolation as much as possible.

The process of digitizing aeromagnetic data at uniformly-spaced points is mathematically equivalent to filtering. The greatest danger in this process is that it may selectively emphasize and sometimes eliminate anomalies caused by subsurface bodies. In order to avoid this danger, the spacing is normally chosen to be much smaller than the smallest size of the anomalies of interest in an area. In this way the digitizing process acts as a filter that suppresses unwanted small-wavelength anomalies without at all affecting the anomalies of interest.

In the Arctic Islands the magnetized rock masses are overlain by several thousand feet of sediments deposited at various geological times. Consequently the horizontal dimensions of the smallest anomaly in this area are normally many times greater than the spacing of 0.8 km. This ensures that the digitizing process will not in any way affect the results of interpretation.

RESIDUAL MAP AND MAJOR GEOLOGICAL FEATURES

A quadratic surface in both x and y were fitted to the data by the principle of least squares in order to determine the 'regional'. The regional gradient along either north-south or east-west direction has been found to be very small. The regional values were then subtracted from the original total field to obtain the 'residual'. The residual map is shown in Figure 1. The major features of this map will now be briefly discussed in terms of known geology of this area. For this purpose the tectonic map of northwestern Canadian Arctic Archipelago is presented in Figure 2. This map compiled from Figure 2 of the paper published by Thorsteinsson and Tozer (1960) shows the structural geology in and around the area under study.

There is a prominent magnetic high over the part of Melville Island covered by the present aeromagnetic data. This area lies within the Parry Islands fold belt. The northern boundary of this magnetic high probably indicates the northern limit of the area where basement, presumably subcrop of the Canadian Shield, is relatively close to the surface. The striking character of this high is the lack of any major local variation of the field with consequent absence of anomalies. This seems to indicate that the basement surface lacks relief and forms a plane surface. It is to be noted that the residual magnetic field values are not high in absolute magnitude, indicating considerable depth of the basement surface. They are however, high relative to values in the surrounding region.

To the north of this area lies the Sverdrup Basin, the southern boundary of which is adjacent to the northern limit of the magnetic high. The geological history of this basin has been discussed by Thorsteinsson and Tozer (1960), Douglas et al. (1963) and Tozer and Thorsteinsson (1964). The northern outcrop limit of strata deposited within the basin crosses the western side of the area at the latitude 77.5° N and the eastern side at 79° N. This basin was a site of heavy sedimentation from the Carboniferous to the early Tertiary. Widespread folding and thrust faulting occurred in the Tertiary but in the area studied, the deformations were generally not severe. Evaporites of Carboniferous age form a number of piercement structures along the axial part of the basin. The local anomalies in this area may be attributed to tabular magnetic bodies and to horizontal sills and volcanic rocks locally folded, faulted and intruded by gypsum in piercement structures (Gregory et al., 1961).

Prominent magnetic lineaments trending north-northeast are evident in the area adjoining the northeastern part of the Sverdrup Basin covered by this study. These lineaments are located in Prince Gustaf Adolf Sea. They cut across a group of magnetic lows with north-south trend. It is suggested here that these lineaments are caused by diabase dykes belonging to the group observed in the Deer Bay Formation of nearby Ellef Ringnes Island (Heywood, 1957). The magnetic lows in this area are probably due to deep linear structural troughs coincident with Tertiary fold axis.

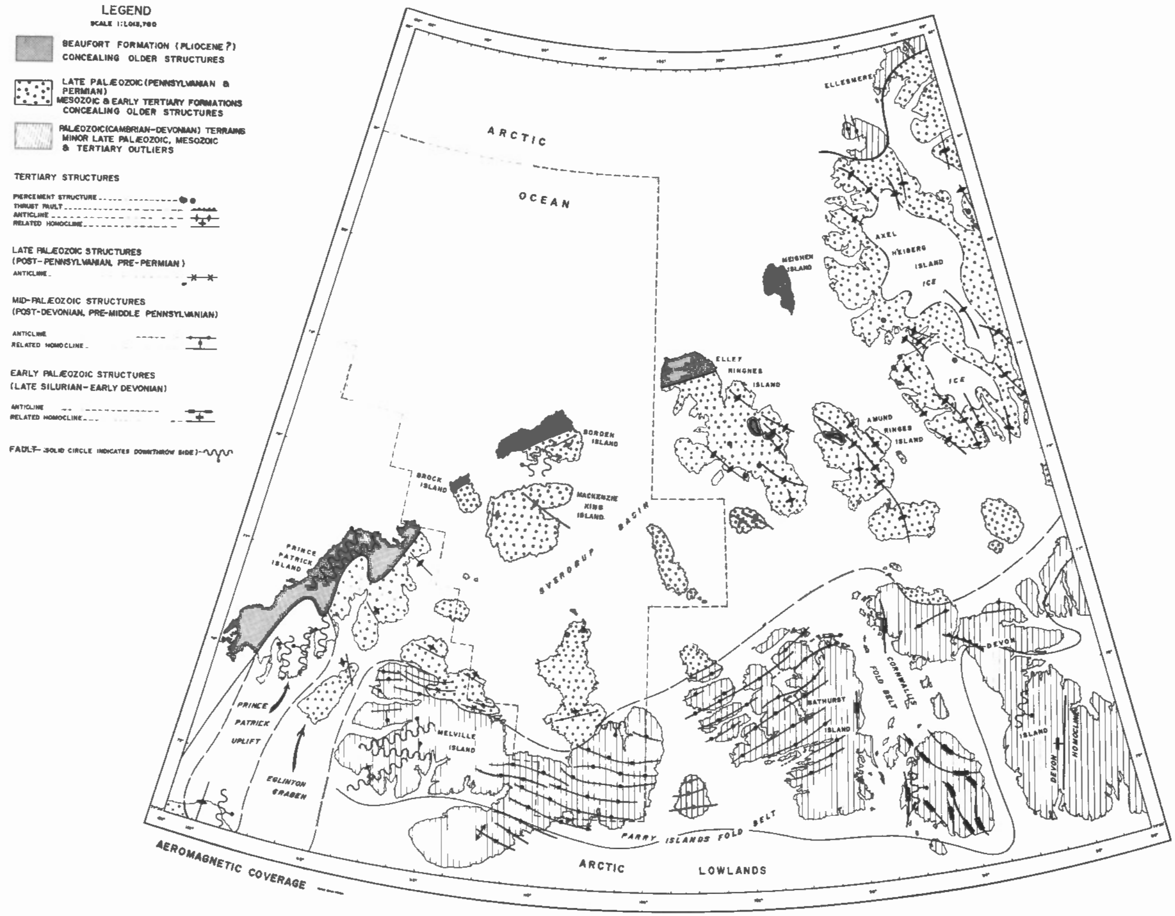

Figure 2. Tectonic map of northwestern Canadian Arctic Archipelago in and around the area under study (from Fig. 2, Thorsteinsson and Tozer, 1960). Work done since 1960 has resulted in more precise determination of the age of some structures (see Douglas et al., 1963, Fig. 2).

Immediately to the north close to the edge of the Continental Shelf and at an angle with lineaments, runs a band of magnetic highs with a predominant northeast-southwest trend. The central axis of the band crosses the eastern side of the project area at latitude 80°N and the western side at latitude 78° 30'N. This is probably associated with a rise in the basement underlying the Continental Shelf. This structure may be a southwesterly extension of the highly metamorphosed and consolidated Franklinian eugeosynclinal belt that is exposed only in northern Ellesmere and Axel Heiberg Islands (Christie, 1957; Trettin, 1967).

Just to the north of this band and running parallel to it, is a string of magnetic lows. The Polar Continental Shelf appears to terminate at the southern edge of this feature. The rather sharp gradients of the residual field at the boundaries of this feature indicate steep sides of a deep linear trough which may be a graben or an oceanic trench.

Farther north of this feature the whole northwestern section of the project area lies under the Arctic Ocean. This part exhibits a highly intense magnetic activity. A north-northwest and south-southeast trend appears to be superimposed on the northeast-southwest trend which is noticeable in practically all the magnetic features of the area studied in this paper. In the middle of this part of the Arctic Ocean a group of magnetic lows with a north-northwest-south-southeast trend lies surrounded by magnetic highs. These lows may be due to the presence of a deep sedimentary basin in this part. The irregular contours and many linear features of the magnetic highs in this area suggest widespread folding and faulting.

QUANTITATIVE TREATMENT OF RESIDUAL DATA

Various schemes are available today for quantitative treatment of equispaced residual data. One of these is the reduction of the residual to the pole (Bhattacharyya, 1965). The method of reduction to the pole is essentially based on a mathematical transformation of the residual field values into a new set of values which would be obtained if the causative bodies were physically moved from their original location to the north pole. The resulting anomaly map is free from the distorting effects of the dip of the magnetic field. The method of reduction to the pole works favourably at low geomagnetic latitudes and it is worth attempting only when the geomagnetic latitude of the central point of the project area is less than 70°. For this reason it was not felt necessary to apply this method to the present data.

Another scheme which is often used for quantitative treatment of aeromagnetic data is the second vertical derivative map of the residual field. This map normally tends to delineate the horizontal boundaries of magnetized geological formations. Moreover, the second vertical derivative, being the negative of the sum of the second horizontal derivatives along two normal directions, shows clearly the nonlinear part of the residual field and hence it is more likely to resolve more clearly the different magnetic units associated with geological structures in the area.

In order to calculate the second vertical derivative the residual values were represented analytically by a double Fourier series expression. The method used in the computation of second derivative has been described in detail by Bhattacharyya (1965). The anomalies in the residual map are conspicuous by their low gradients and broad, flat characteristics, indicating great depths to the basement. Because of the lack of nonlinear regions the second vertical derivative has significant values only over insignificantly small areas scattered throughout the map.

In order to remedy this unusual situation and to make the anomalies in the residual map more prominent, it was decided to continue the residual field downward to depths of half a mile and one mile respectively. In the process of downward continuation erroneous results were first encountered due to strong influence of short wavelength components produced by very tight spacing chosen initially for digitizing the data. Hence it was decided to filter out all wavelengths shorter than 3.2 km (two miles). This process of filtering removed unwanted oscillations and provided reliable and accurate values for the anomaly field continued downward up to 1.6 km (one mile) from the flight elevation. Figure 3 shows this downward continuation map.

In contrast to the residual map, the trend and orientation of the anomaly bands in the continuation map are much better defined and are more apparent. The anomalies are much more accentuated. The magnetic lineaments that appear in the north of the northeastern section of the Sverdrup Basin are now very prominent and seem to have intruded the Mesozoic sediments of the basin.

As noted before in connection with the residual map, the part of the Sverdrup Basin which is covered by the present aeromagnetic data contains a few local anomalies caused by near-surface features. Gregory et al. (1961) made a justifiable observation that these local anomalies stand in the way of studying any possible large-wavelength anomalies for accurate estimation of the depth of the basin. Some of the local anomalies in the residual map have broken up into oscillations in Figure 2 because the residual field has been continued downward to a depth greater than the depths of the causative bodies.

The same type of oscillatory behaviour of the downward continued values is observed for a few small-wavelength anomalies around longitude 114°W and latitude 78°W. This behaviour indicates that the depths of the bodies causing the above anomalies are less than 4,280 feet from the ground surface.

The anomalies over the Arctic Ocean are very well-defined in Figure 3. There is a string of positive anomalies crossing the big magnetic low north of latitude 80°N. The southern edge of this string is marked by a

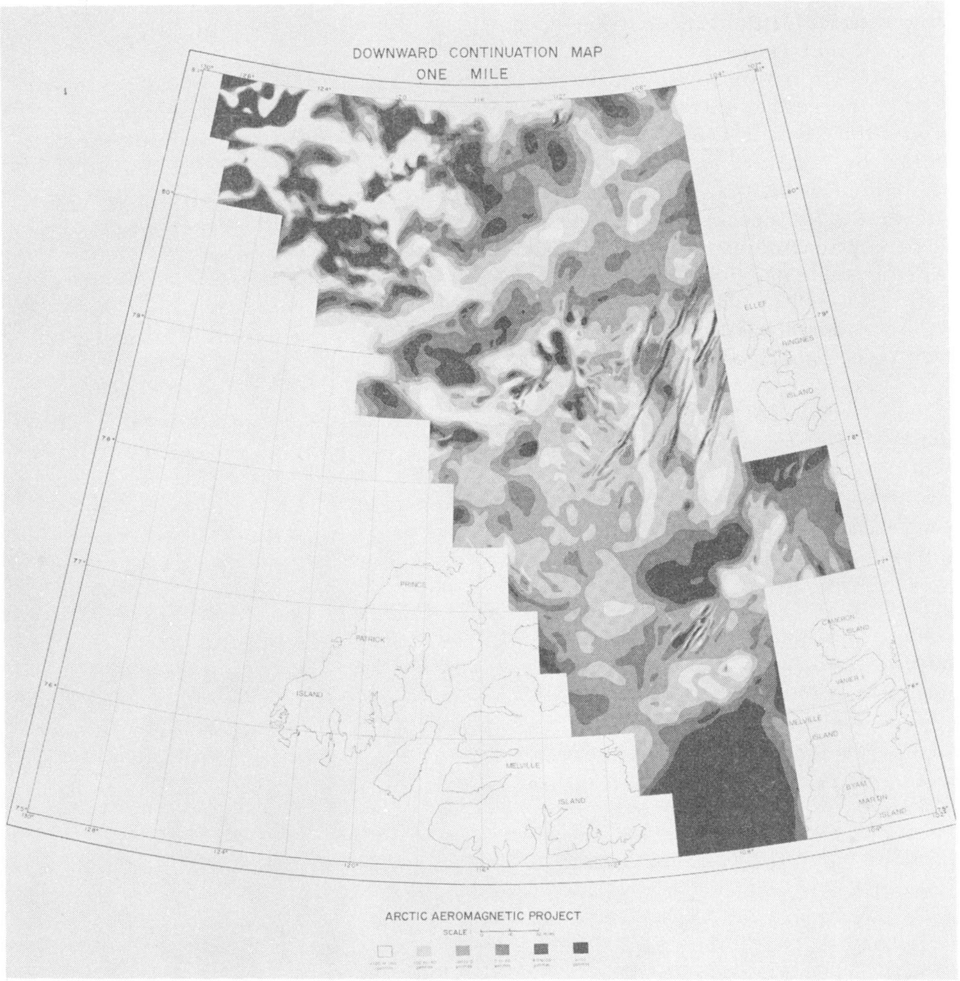

Figure 3. Residual map continued downward to a level of 1.6 km from flight elevation.

straight linear feature with very abrupt change in magnetic gradient. This characteristic of the feature is also noticeable in Figure 1 indicating faulting in that region.

RESULTS AND DISCUSSION OF THE ANALYSIS OF INDIVIDUAL ANOMALIES

The maps of the residual and continuation fields are important and necessary for choosing the anomalies to be analyzed, for estimating the approximate locations of the centres and the horizontal dimensions of the causative bodies, and, above all, for giving a rapid and reliable view of the distribution and orientation of the bodies in an area. However, they themselves do not provide any information about the depth, vertical dimension and state of polarization of the rock mass.

A great majority of the methods available to calculate the depth to the top of a magnetized body (Peters, 1949; Vacquier et al., 1951) utilizes for this purpose the horizontal gradient length or horizontal distance between maximum and half-maximum points on an anomaly. These methods are very much oriented toward the analysis of profiles and hence the estimation of depth becomes subject to gross errors due to many simplifying assumptions (Agocs, 1958).

There have not been many serious attempts to determine the direction and magnitude of the magnetization vector associated with magnetized bodies. Consequently most of the methods available for determination of depth have made the assumption that the rock mass has been magnetized by induction of the present geomagnetic field. Contrary to these assumptions, presence of permanent magnetization is often the rule, rather than exception in the rocks of the earth's crust.

In this paper the method suggested by Bhattacharyya (1966) has been used for the calculation of the total polarization vector, depth, and the horizontal and vertical dimensions on the assumption of rectangular prismatic models for the causative bodies. The reason for using this model in preference to point or line sources is that the magnetic effects of a number of closely-spaced sources will blend together to such an extent, when viewed from a large distance, that they will appear as a single anomaly pattern. The rectangular block model serves to outline the volumes of rock within which the magnetic minerals are found in greatest concentration.

Both the continuation map (Fig. 3) and the residual map (Fig. 1) were used for choosing suitable anomalies for estimating the depths and polarizations of causative bodies. Since the process of reduction to the pole was abandoned because of high geomagnetic latitude of the area, it was assumed that the maximum value of the anomaly field occurs at a point which is practically at the top of the centre of the body. Then a contour of a suitable value was drawn close to this point and the axes of the contour were taken as the axes of the body.

The anomaly field values were then represented exactly by a two-dimensional Fourier series expression. This expression was utilized to construct the two profiles along the two axes of the body. The values along each of the profiles were then analyzed to evaluate the second derivative of the odd component of the anomaly field for determining the horizontal dimensions of the body.

Once the estimates of the center, axes and the horizontal dimensions of the body were known, the parameters of the prismatic model namely the depths to the top and bottom of the body and the polarization, could be calculated with the aid of a digital computer (Bhattacharyya, 1966).

The contoured map of the depth to the top of the magnetized bodies is presented in Figure 4. The main characteristics of this map will now be summarized here.

Unfortunately very few well-defined large-wavelength anomalies attributable to the crystalline basement rocks have been noticed inthe parts of the Sverdrup Basin and Melville Island that lie within the project area. Further attempts with different methods are being made to evaluate the depth to the magnetic basement in this region. Some shallow anomalies associated with piercement structures have been detected in this area. The depths in kilometres to the tops of the magnetized bodies have been shown within brackets. The dashed contours in this area are probably indicative of the depths of the shallow structures. According to the residual and downward continuation maps (Figures 1 and 3) the basement seems to dip in the

On the eastern side of the central part of the area a deep linear trough stands out noticeably with a maximum depth of 7 to 8 km. This trough is associated with magnetic lows evident in the residual map.

In the north the depth of the magnetic basement running in the northeast-southwest direction increases rather sharply from 7 km to 12 km and this area of sloping basement coincides with the northeast-southwest band of magnetic highs over the Continental Shelf. Immediately north of this area, the depth begins to increase reaching a maximum value of 19 km at two places. This part of the area, as mentioned before, contains a group of magnetic lows indicating a deep linear, sedimentary trough. Starting from the west, the depth contours trend towards the northeast before veering to the north on the eastern side of this area. At this point the northeast trend appears to be lost. However, it is to be noted that due to the lack of suitable anomalies in the eastern section it is not possible to conclude that the northeast trend definitely terminates here.

The central part of the northwestern section of the project area is marked by a deep basin type of structure with a maximum depth of 12 km. Towards the east of this basin, a rise in the magnetic basement up to a depth of 5 km is noticeable.

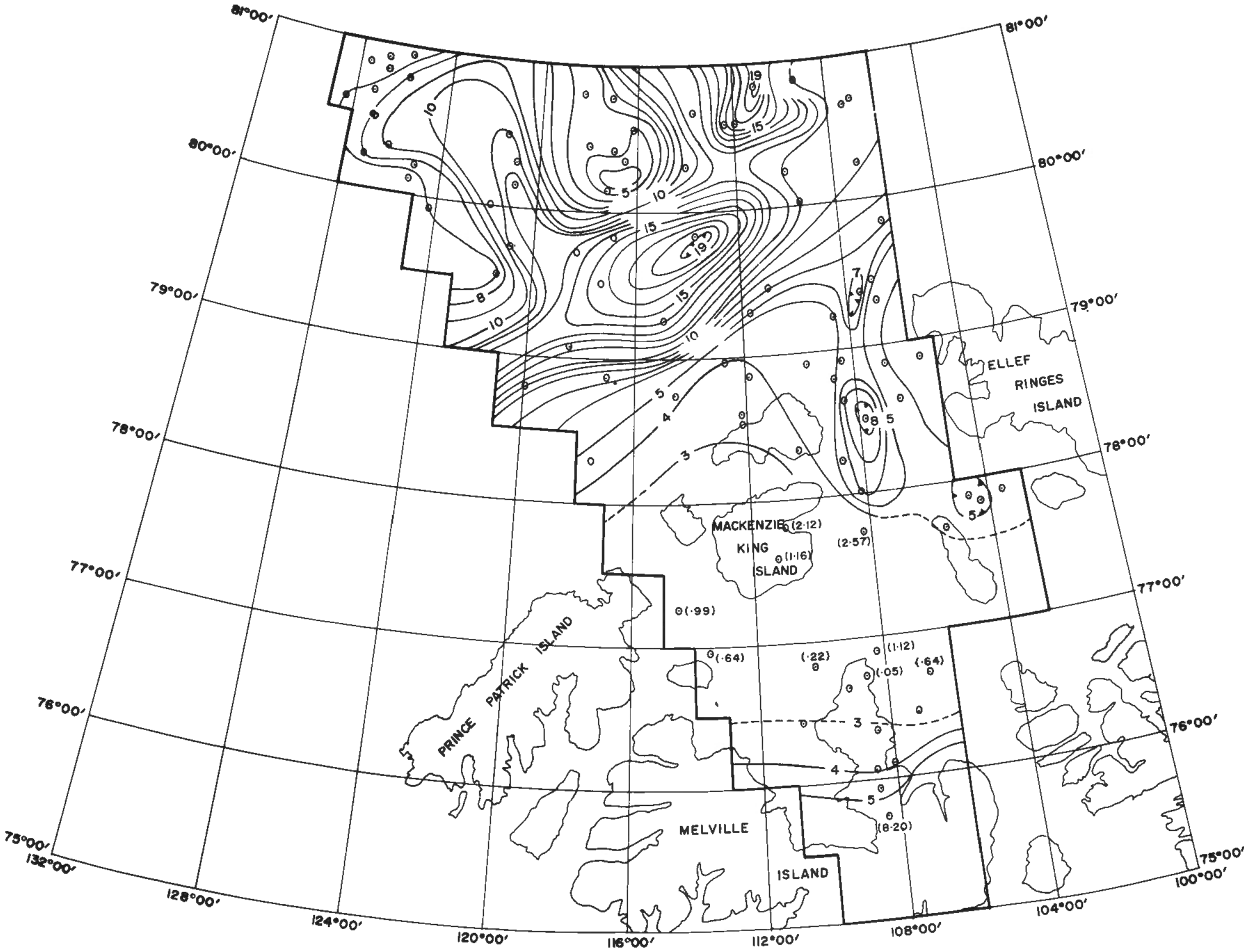

Figure 4. Contoured map (in km) of the depths to the top of magnetized bodies.

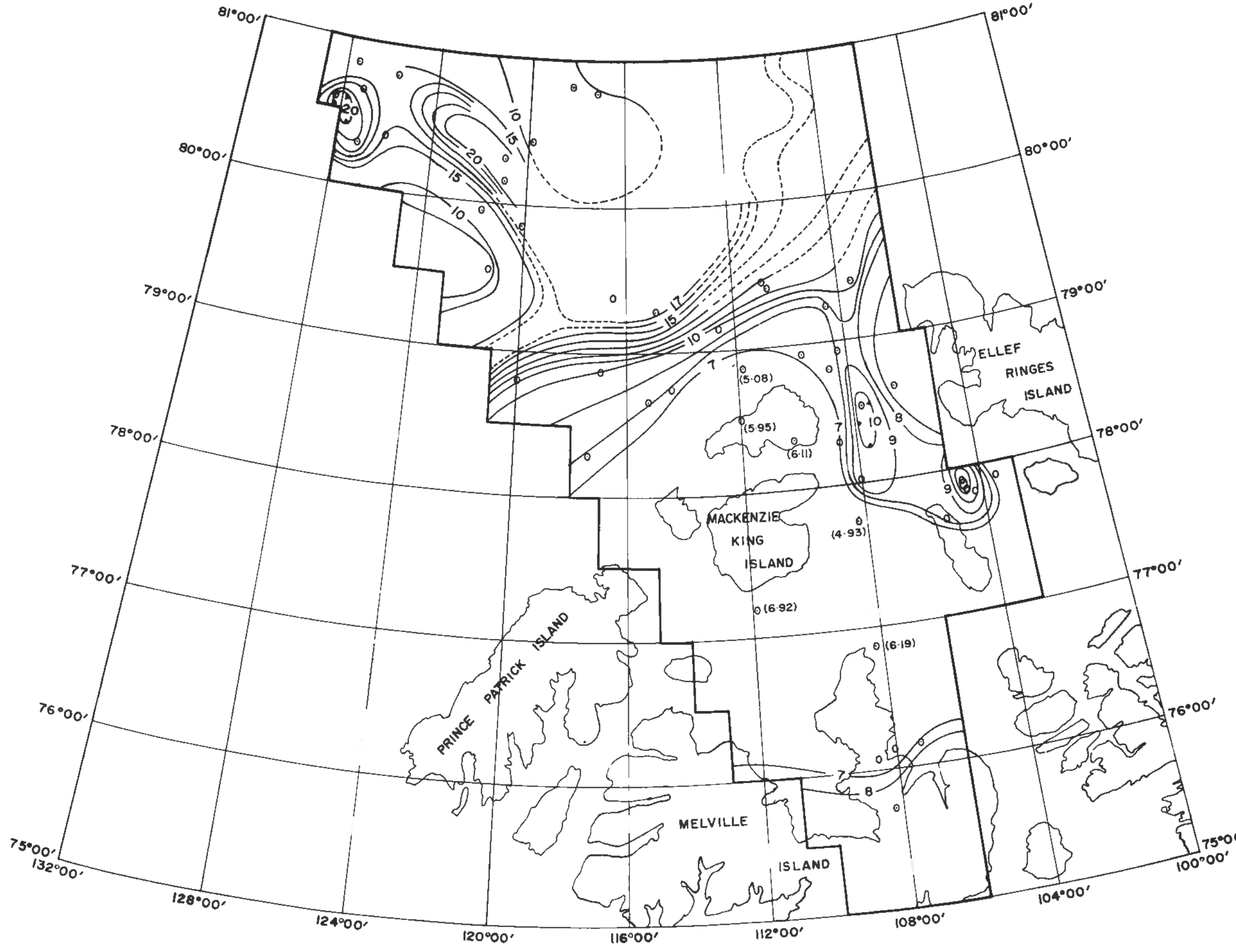

Figure 5. Contoured map (in km) of the depths to the bottom of magnetized bodies.

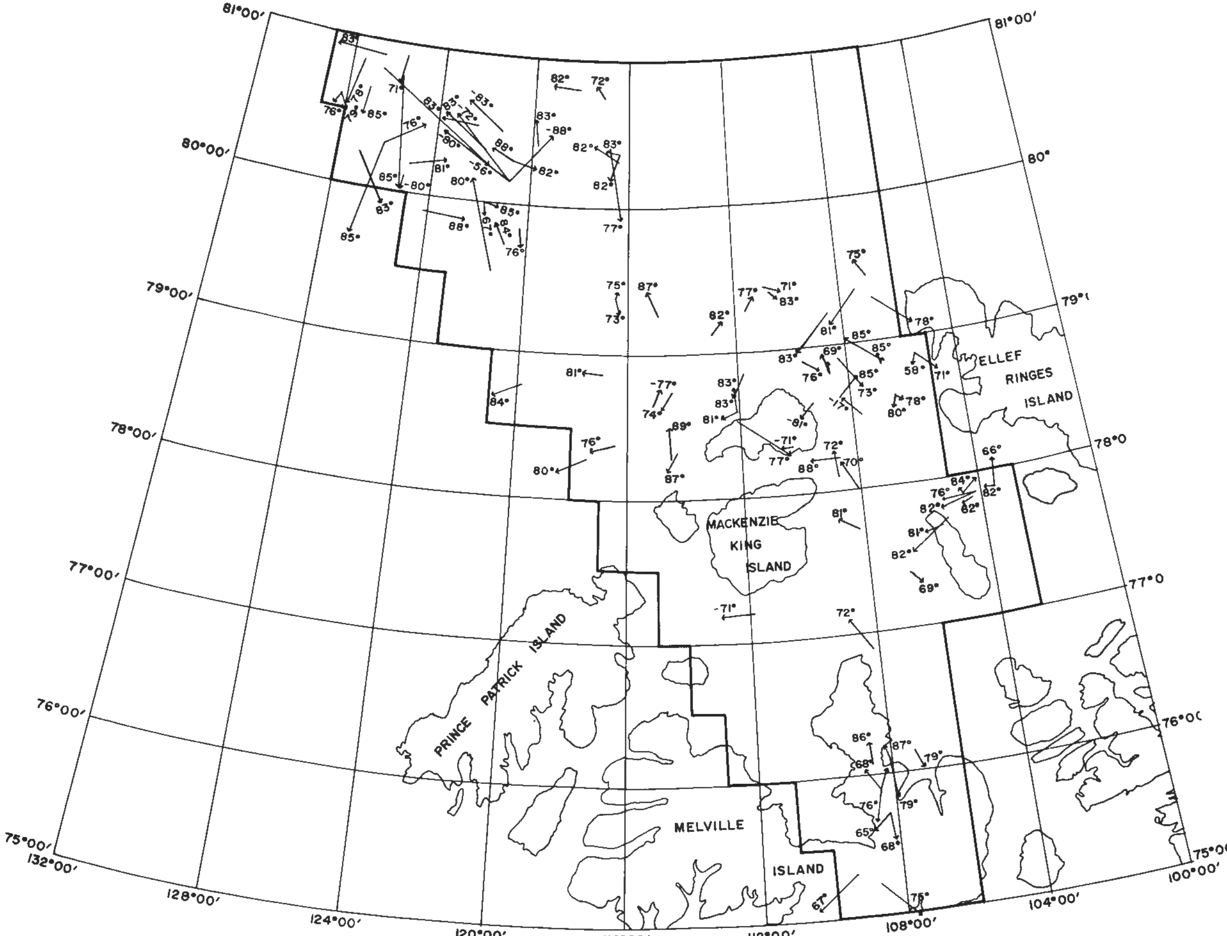

Figure 6. Plot of the polarization vectors associated with the different rock masses, showing the intensity, declination and inclination of each of the vectors.

Figure 5 presents the contour diagram of the depths to the bottom of the magnetic bodies. It may be noted here that the anomalies suitable for this type of analysis are not large in number. However, some extrapolation of the contours has been ventured upon because of marked similarity of this diagram to Figure 4. The extrapolated parts of the curves have been indicated by dashed lines. On the average the magnetic crust in this area seems to be about 3 to 5 km in thickness. No appreciable decrease in this thickness has been noticed in the oceanic part of this area.

The intensity and direction-cosines of the polarization vectors were also determined. They are shown in Figure 6. The magnitude and declination were used to plot the vectors. The dip angle has been written by the side of each vector. The marked differences in the intensity of magnetization at different places are probably due to gross petrographic differences of rocks. The intensity lies within a wide range from .003 to .267 cgs emu.

From Figure 6 it appears that the horizontal vectors can be grouped in three ways. Firstly, the group associated with the subcrop of the Canadian Shield has, on the average, a north-south trend. Secondly, the group over the northern part of the Sverdrup Basin and the Continental Shelf has a predominant east-west trend. Finally the group over the oceanic part is characterized by abrupt changes in orientation from point to point and by a marked increase in intensity. This last group suggests that this area has experienced widespread folding and faulting, as noted before.

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