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Geomagnetic Service of Canada

A Review of Large Scale Magnetic Anomalies Over Canada and Arctic Regions

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A REVIEW OF LARGE SCALE MAGNETIC ANOMALIES OVER CANADA AND ARCTIC REGIONS

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ABSTRACT

Charts of magnetic field anomalies over western Canada and Arctic regions have been compiled from several three-component airborne magnetometer surveys. The approximate waveband lies between 30 and 5000 km. A magnetic feature of several thousand kilometres wavelength dominates the region, and is probably due in major part to sources in the earth's core. Superimposed on this feature are several groups of anomalies containing wavelengths of the order of a thousand kilometres. These can be related to crustal features, and to major tectonic provinces. Two techniques to enhance the longer wavelength anomalies have been applied. Polynomials fitted to survey data sets describe the long wavelength end of the waveband. Upward continuations to altitudes 50, 100, 300 and 500 km demonstrate the relations between short wavelength anomalies (of crustal origin) and the longer wavelength anomalies.

INTRODUCTION

Several large scale magnetic surveys have now covered western Canada and Arctic regions with sufficient density of data that a study of the long-wavelength structure in the magnetic field is possible.

The waveband of interest ranges from the order of 100 km to several thousand kilometres - the 'intermediate' waveband. This waveband has in the past received relatively little study, on the one hand, by main field geomagneticians, because the wavelengths are small compared with the larger wavelength global anomalies, and require high orders of harmonic coefficients, with uniformly good data coverage, for description by spherical harmonic expansions. On the other hand, exploration geophysicists, even those concerned with regional studies, have, for the most part, been restricted by small survey *data sets and by the presence of more intense short-wavelength anomalies - and by the immediate geologic/economic importance of these latter anomalies.*

This 'intermediate' waveband is important, because many of the lithospheric features have dimensions which fall into this wavelength range. Some lithospheric plates, accretion regions, and subduction regions with associated tectonic belts, fall into this category. Continent-wide and global heat flow compilations indicate heat-flow variations - and thus probably crustal temperature variations - on this scale. Seismic studies indicate variations in crustal thickness over distances comparable with these wavelengths.

Recent satellite anomaly maps (Regan et al. 1975, Langel et al. 1975, and refined portions of these to be shown in this session), which have a waveband of about 400-3000 km, show some interesting correlations between magnetic anomalies and known geologic/tectonic provinces.

This paper attempts to review recent efforts to identify some intermediate wavelength anomalies over western Canada, to discuss some correlations with geologic/tectonic provinces, and to suggest some possible causes of the anomalies.

THE ANOMALY CHART

Figure 1 shows anomalies in the vertical component of the field, relative to the IGRF (from Coles et al. 1976). The contour interval is 200 gammas. The map was hand-contoured from data spaced at about 7 km along flight lines, approximately 40 km apart.

The patterns of short-wavelength anomalies show several distinct characteristic styles or signatures. Dominant trends and regions of suppressed or enhanced anomaly amplitudes can be seen in the map. These can be correlated with some major tectonic provinces.

Figure 2 shows a summary of the shorter wavelength character of the field (yellow shading represents higher field), along with indications of the major tectonic provinces. We see a good correlation. Over the western Cordillera, the field trends northwest and is subdued in intensity. Over the exposed and buried Shield, complex patterns of north and northeast trending anomaly belts, often of high intensity, are characteristic. Over the southern Canada Basin and Arctic Islands the field is very smooth with few major anomalies. The Alpha Ridge and adjacent ocean floor are characterized by high relief sublinear anomalies.

Thus, we can divide the short-wavelength anomalies into several distinct magnetic provinces which do, broadly speaking, correspond with tectonic provinces. Looking at this gross picture, we realize that we have here a longer wavelength character present in the field, which could be construed as a modulation impressed on the shorter wavelengths - a modulation in two dimensions, affecting trends and amplitudes. This 'modulation signal' carries the information which allows the field to be subdivided regionally.

REFERENCE FIELDS AND VERY LONG WAVELENGTHS

Apart from the short-wavelength patterns, a dominant feature of the map in Figure 1 is the long-wavelength anomaly of about 400 gammas amplitude, seen as a broad north - south trend. The wavelength of this feature is of the order of 4000 km, and it has a distorting effect when considering the shorter wavelengths. It results from the use of a degree 8 reference field, the IGRF, with cut-off wavelength about 5000 km.

Figure 3 shows several airborne survey areas, with contours in each area representing the difference field between a degree 3 polynomial fitted to the data set and the IGRF at the appropriate epoch. Again this representation displays the very long wavelength feature, but suffers from problems near the *boundaries of the polynomial areas and from secular change misfits.*

The several surveys of EPB were conducted over a span of several years. During this time secular changes in the main field occurred, meaning that individual survey data sets cannot always be simply merged at their overlap or boundary regions, if the reference field time terms are defective.

Ideally, one wants to separate completely the main field from the data, leaving the 'supposed' static lithospheric anomaly field. However, as is well known, the definition of the main field is not a simple matter. A number of models have been produced for the geomagnetic field, for various harmonic degrees. Recent work by Cain, Regan, Davis and others indicates that the lithospheric field becomes dominant at about degree 13 or 14. They found a distinct change of slope of the log power spectrum of the field in that region.

However, for studies of the long-wavelength lithospheric field in the vicinity of this spectral crossover, the problem of the degree of the reference field is more subtle. ---- If we are concerned primarily with identifying anomalies within a given waveband, then the use of a model of particular n_{max} *as a reference field is justified provided that it is as good as representation as is possible up to the wavelengths carried by degree* n_{max}*. ----- If, on the other hand, we are concerned primarily with the sources of long-wavelength lithospheric anomalies, then we must accept that a particular class of sources may have a considerable range in dimensions --- with consequent range in dominant wavelength content in the anomalies produced. Therefore, the arbitrary cut-off resulting from the use of a particular reference field degree may distort the desired anomaly field. ---- The optimum reference in one region may not be optimum elsewhere.*

At this point, it has not been possible to investigate this further. In practical terms at the present, we have a limited number of usable models, *and we are restricted to studying particular wavebands.*

One such model has been derived by J.C. Cain from POGO satellite data, POGO 6/71 of order 13. Figure 4 shows the difference field in the vertical component between the POGO model and the IGRF, over Canada and environs. We see the long-wavelength anomaly found in Figure 1 in a broader context, using an independent data set, and thus confirming its reality.

We have now considered anomalies in the waveband between about 5000 km (limit of IGRF) and about 3000 km(limit of POGO6/71). The anomalies seen in Figure 4 do not show any obvious correlations with tectonics. If one attempts to model these anomalies with lithospheric magnetostatic sources, one needs unrealistically high magnetizations in seemingly unreasonable structural forms. It is far more likely that these features are simply remnants of the much broader 'regional' (in the global sense) anomalies characterized by lower degree harmonics, and that they originate from the core or lowermost mantle.

THE LONG-WAVELENGTH LITHOSPHERIC FIELD

Using the POGO 6/71 model, we are able to consider anomalies in the waveband 3000 km downward.

Two separate, and perhaps complementary, approaches have been used. The one approach - least-squares fitting of polynomial surfaces of particular degree to the data -- starts essentially at the long-wavelength end of the spectrum, polynomials of increasing degree describing progressively shorter wavelengths. The other approach -- upward continuation -- could be considered as starting at the short-wavelength end of the spectrum --- with continuation to increasing altitudes progressively restricting the field to longer and longer wavelengths.

The polynomial representation (Haines 1967, 1968) describes the field at 0 km altitude but suffers from the problems of decreasing accuracy of fit *near the boundaries of the data sets. The upward continuation method describes the field at some altitude greater than 0 km, with consequent reduction in anomaly amplitude, but with better continuity between data sets; however, the finiteness of the data sets causes large-scale false trends to be present in the upward continued field. Nevertheless, both techniques have a place in the study of the long-wavelength field.*

Figure 5 shows the difference field between the 3rd degree polynomials fitted to the airborne data sets and the POGO 6/71 model. Note that the major high over western Canada has now largely disappeared, and that the residual long-wavelength field has a better correlation with major tectonics as shown in Figure 2. There are some mismatches at boundaries between survey areas, although in general the large-scale features are consistent. These mismatches are due in part to inadequacies which may be present in the description of secular change by the POGO 6/71 model and also in part to the decrease in the goodness of fit of polynomial surfaces near the boundaries. The degree of a polynomial governs the minimum wavelength which can be represented, and if a magnetic feature is only partly covered by a data set, it is possible that a polynomial fit of a particular degree may not adequately describe the field in that region. Such an effect may be the cause of mismatches near 60°N 12°W.

Figure 6 shows the shorter wavelength anomalies also, relative to POGO 6/71. Here some smoothing has been applied, by averaging the data over 35 km intervals along flight lines. Note again the several regions having different magnetic characters and their relation to tectonic provinces.

The data used in Figure 6 (5600 data points) were upward continued. The continuation assumed a spherical earth and assumed that the residual field outside the data area was zero. Each data value was assumed to be associated with an elemental area determined by the average data point spacing in its vicinity.

Figure 7 shows the field of Figure 6 upward continued to 100 km. This has the effect of smoothing out the anomalies somewhat, and reducing the amplitudes.

Figure 8 shows the field continued to 300 km, with further smoothing and reduction of amplitude. This field is similar to that described by the polynomial differences in Figure 5, except for the reduced amplitudes.

Thus, we have now some idea of the long-wavelength anomaly field relative to POGO 6/71. From what has been said earlier, we can presume that this is lithospheric in origin. What are the sources for this field? Do we envisage bodies of large dimensions at crustal depths, or do we look to a superposition effect from short-wavelength anomalies?

Consider the correlations between the upward continuation in Figure 8 and the low altitude map in Figure 6. Several high anomalies in Figure 8 correspond with regions of short-wavelength high anomalies --- over the Alpha Ridge, over the Yukon, over northern Greenland, over northern Alberta. This suggests that these long-wavelength anomalies might be superposition effects. The amplitude of the anomaly would depend in part on the spacing of the short-wavelength anomalies. If they are close together, the long-wavelength component may be high, as over the Alpha Ridge and the Yukon. Over northern Alberta and Greenland, the anomalies are more widely spaced, resulting in a lower long-wavelength component.

Where the short-wavelength field is weak, such as over the southern Canada Basin and the western Cordillera, the long-wavelength field tends to be negative.

Consider Figure 9, which shows a histogram of residual anomalies in the vertical component for the three main airborne surveys under discussion. The distribution of anomalies has positive skewness. Relatively few, but high, positive anomalies contrast with a larger number of weak negative residuals.

If clusters of high positive short-wavelength anomalies generate long-wavelength positive anomalies, the effect on the regions of subdued anomaly relief is to make them negative relative to a least-squares or best-fit reference field. Thus, regions of different local anomaly amplitude characteristics can produce a long-wavelength anomaly field --- where regions of high magnetic activity (high positive anomalies in close proximity predominant) produce long-wavelength positive anomalies and regions of subdued magnetic relief produce long-wavelength negative anomalies.

Is this the only source of long-wavelength anomalies?

Consider the anomaly over Victoria Island; it does not overlie a region of intense short-wavelength anomalies such as those noted earlier. It is apparent in both the low and high altitude fields. Is it evidence of a thickened magnetic crust, or of higher magnetization? Is it possible that parts of the other highs noted earlier are caused in the same way?

NATURE OF SOURCES

What is the nature of the source bodies for the long-wavelength anomalies?

A detailed modelling of one particular shorter wavelength anomaly which contributes by way of superposition has been made. The anomaly, Figure 10, near Fort Nelson in British Columbia contributes to the broad ridge of relatively high field near 60°N 120°W. An interpretation, Figure 11, suggests a body between 7 and 25 km below sealevel and 100 by 200 km in extent, with a normal magnetization of about 5 amp/metre. This is but one of several broad high anomalies in this particular region.

Rock samples from the bottoms of deep drill holes under some of these anomalies show high magnetizations. Long-term measurements on some of these samples show that at elevated temperatures -- 100° to 300°C --- viscous magnetization builds up over a few months to values comparable with the induced *magnetizations, 3 amp/metre, typically, (Figure 12). These temperatures are typical of those expected in the crust. Viscous enhancement of magnetization may be a source of long-wavelength anomalies if significant lateral variations of temperature do in fact exist on a scale of order of a thousand kilometers.*

RECAPITULATION

Three long-wavelength magnetostatic effects need to be considered. There is the 'modulation' effect, where distinct regions, with dimensions hundreds to perhaps thousands of kilometres, having different characteristic magnetic field signatures, constitute a large-scale, long-wavelength pattern. Strictly, this is not a 'modulation' of the magnetic field, but rather of the source body structure. In the resultant magnetic field, there are, one, a 'modulation' effect and, two, a superposition effect. The long-wavelength modulation field signal(carrying trend and anomaly pattern information) cannot be separated from the short-wavelength field by simple isotropic (non-directional) filtering , but can by directional filtering and pattern recognition procedures. The superposition effect, from the coalescing of adjacent anomalies in a region, and which may or may not correspond identically in location with the modulation effect, can be separated from the short-wavelengths by isotropic filtering. Thirdly, there is the simple effect of large-dimensioned sources producing a long-wavelength anomaly field. These latter two effects are indistinguishable on the basis of filtering.

The long-wavelength anomalies delineated over parts of Canada and environs and the correlations with known lithospheric features indicate that all of these effects are operative in producing the observed anomalies. The amplitudes of the anomalies do not appear to be inconsistent with recent estimates of the thicknesses of the magnetic crust in various regions and of probable magnetizations in the crust (Hall 1974, and others, and this session).

The possibility of non-magnetostatic sources for some of these anomalies cannot be ruled out, but further discussion is beyond the scope of this paper.

Long-wavelength lithospheric anomalies can be detected from extensive airborne surveys, but the secular changes in the main field cause major problems when merging surveys. The data from satellites have greatly improved the modelling of the main field and have reduced considerably the secular change problems. The use of low-level satellite data to map the long-wavelength lithospheric field is a logical extension and data from the POGO satellites will be discussed in subsequent papers.

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Haines, G.V., 1968. Polynomial estimation of certain geomagnetic quantities, applied to a survey of Scandinavia. Pub. Dom. Obs. Ottawa, 37, 75-112.

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Regan, R.D., Cain, J.C. and Davis, W.M., 1975. A global magnetic anomaly map. J. Geophys. Res. 80, 794-802.

FIGURE CAPTIONS

Figure 1	*IGRF Z residual map*
Figure 2	*Summary of anomalies and tectonics; 1. areas of magnetic 'highs'; 2. axes of magnetic 'lows'; 3. boundaries of magnetic regions, as discussed in the text and indicated by Roman numerals; 4. edge of exposed Precambrian Shield and Precambrian province boundaries; 5. eastern limit of Cordilleran deformation; 6. northern edge of stable Precambrian platform; 7. some major faults; RMTS - Richardson Mountains.*
Figure 3	*3rd degree Polynomials-IGRF (1961,1963,1965,1969,1970,1972).*
Figure 4	*POGO 6/71 - IGRF over Canada*
Figure 5	*3rd degree Polynomials-POGO 6/71 (1961,1969,1970,1972)*
Figure 6	*POGO 6/71 Z residual map.*
Figure 7	*Upward continuation to 100 km.*
Figure 8	*Upward continuation to 300 km.*
Figure 9	*Histogram of 5 min. residuals relative to POGO 6/71*
Figure 10	*Fort Nelson anomaly map*
Figure 11	*Fort Nelson interpretation*
Figure 12	*Viscous magnetization build-up versus log. time.*

Fig. 1

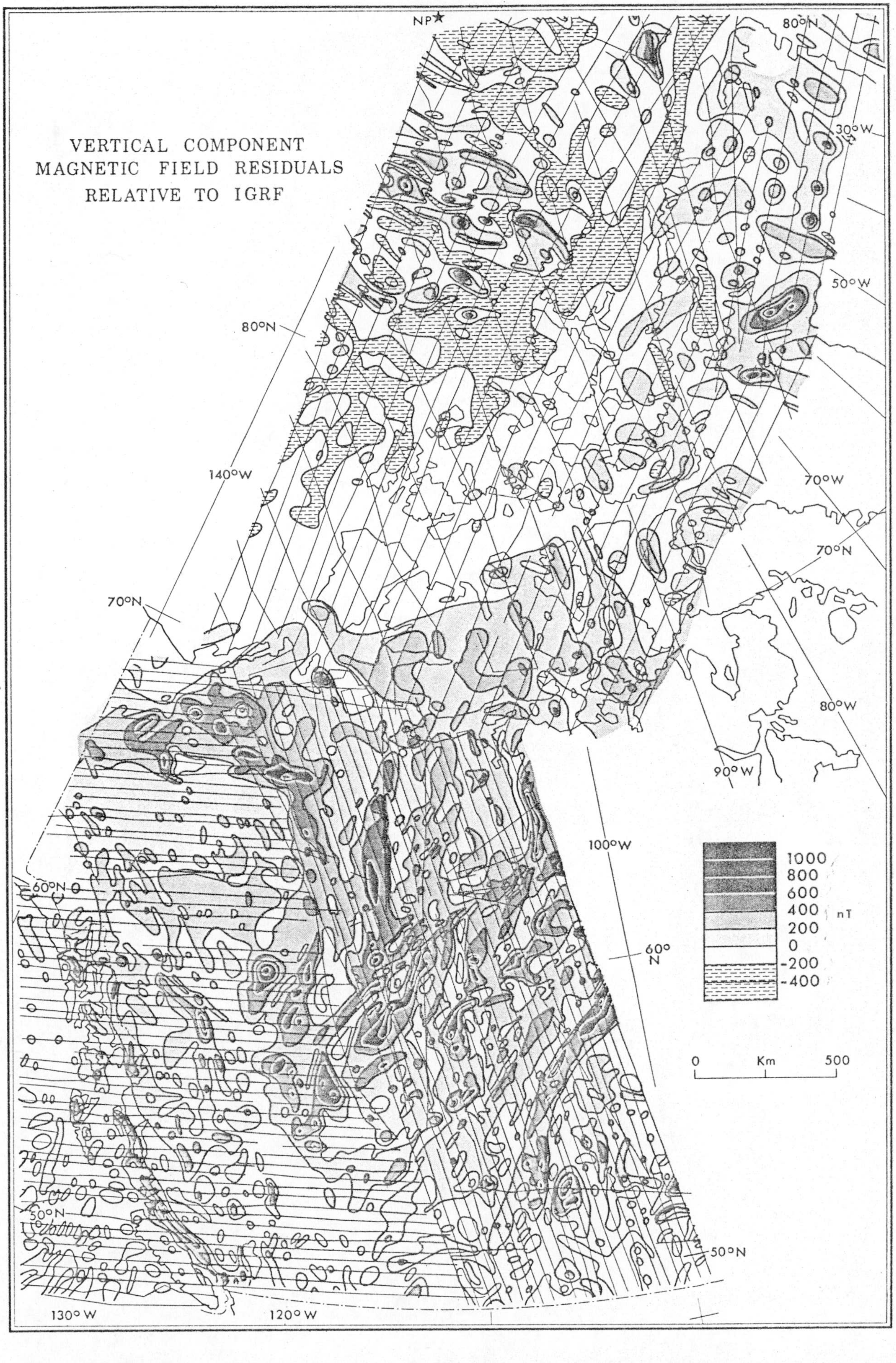
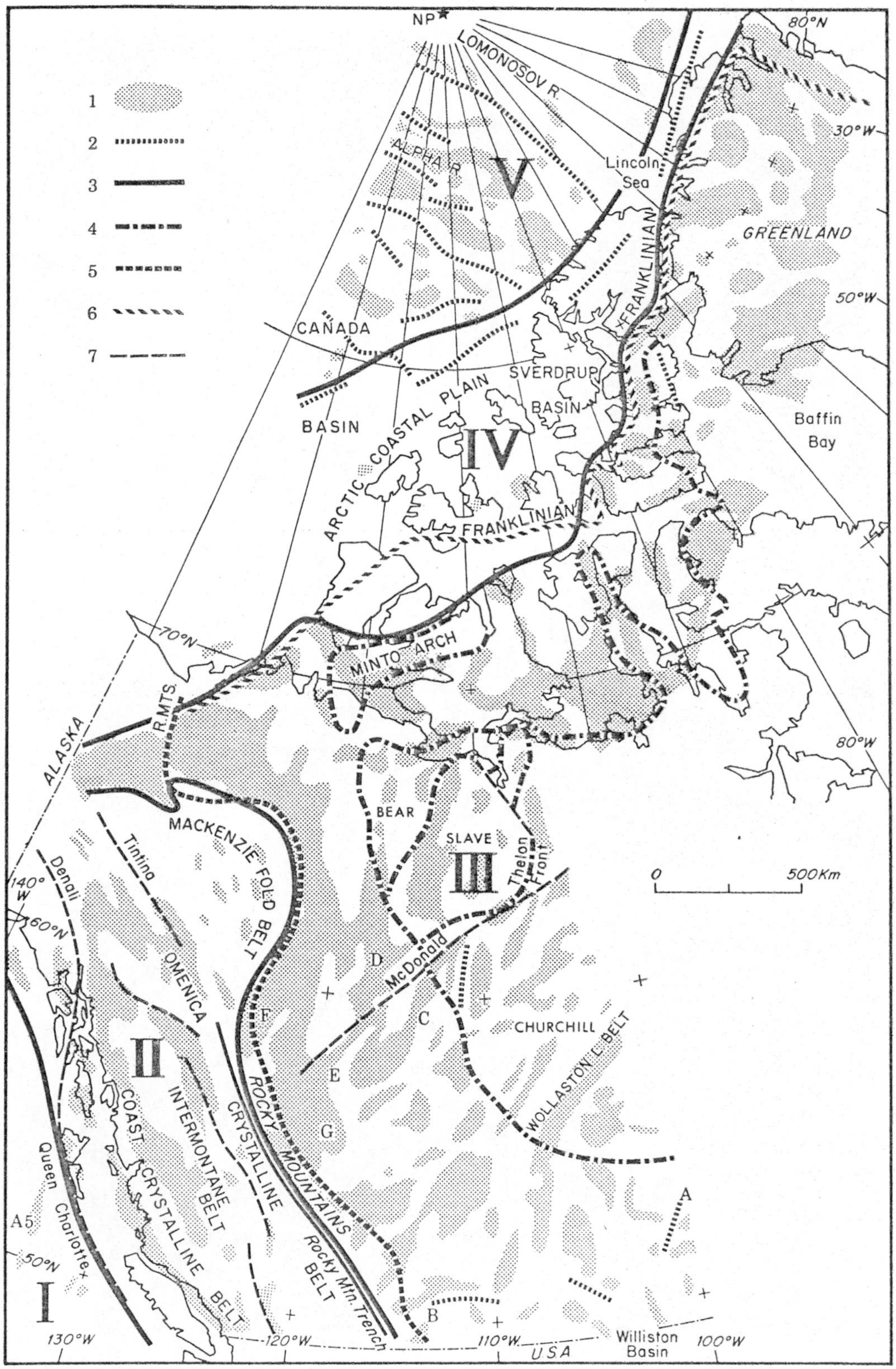
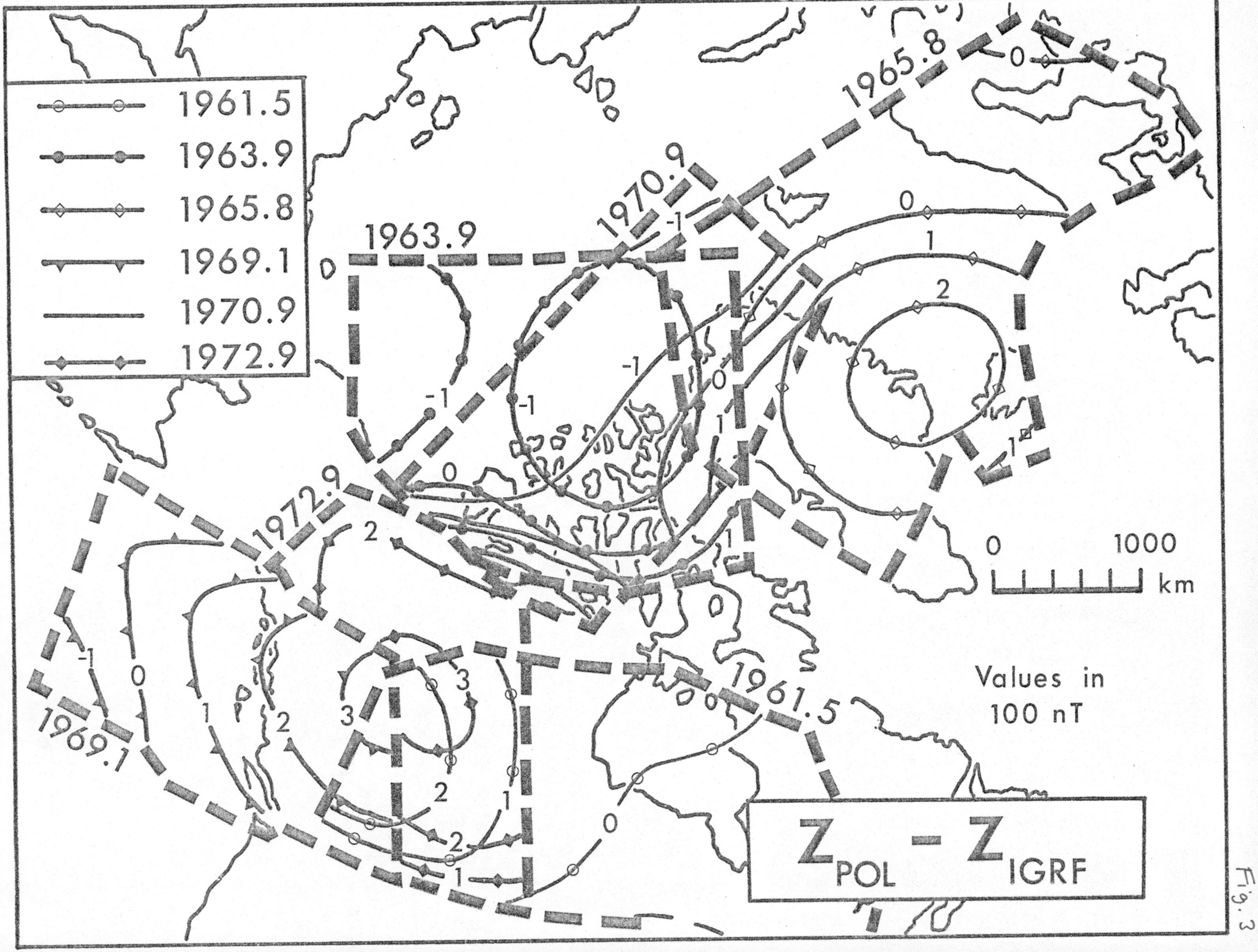

VERTICAL COMPONENT
MAGNETIC FIELD RESIDUALS
RELATIVE TO IGRF
NP
80°N
30°W
50°W
80°N
140°W
70°W
70°N
70°N
80°W
90°W
100°W
60°N
60° N
50°N
50°N
130° W
120° W
1000
800
600
400
200
0
-200
-400
nT
0
Km
500

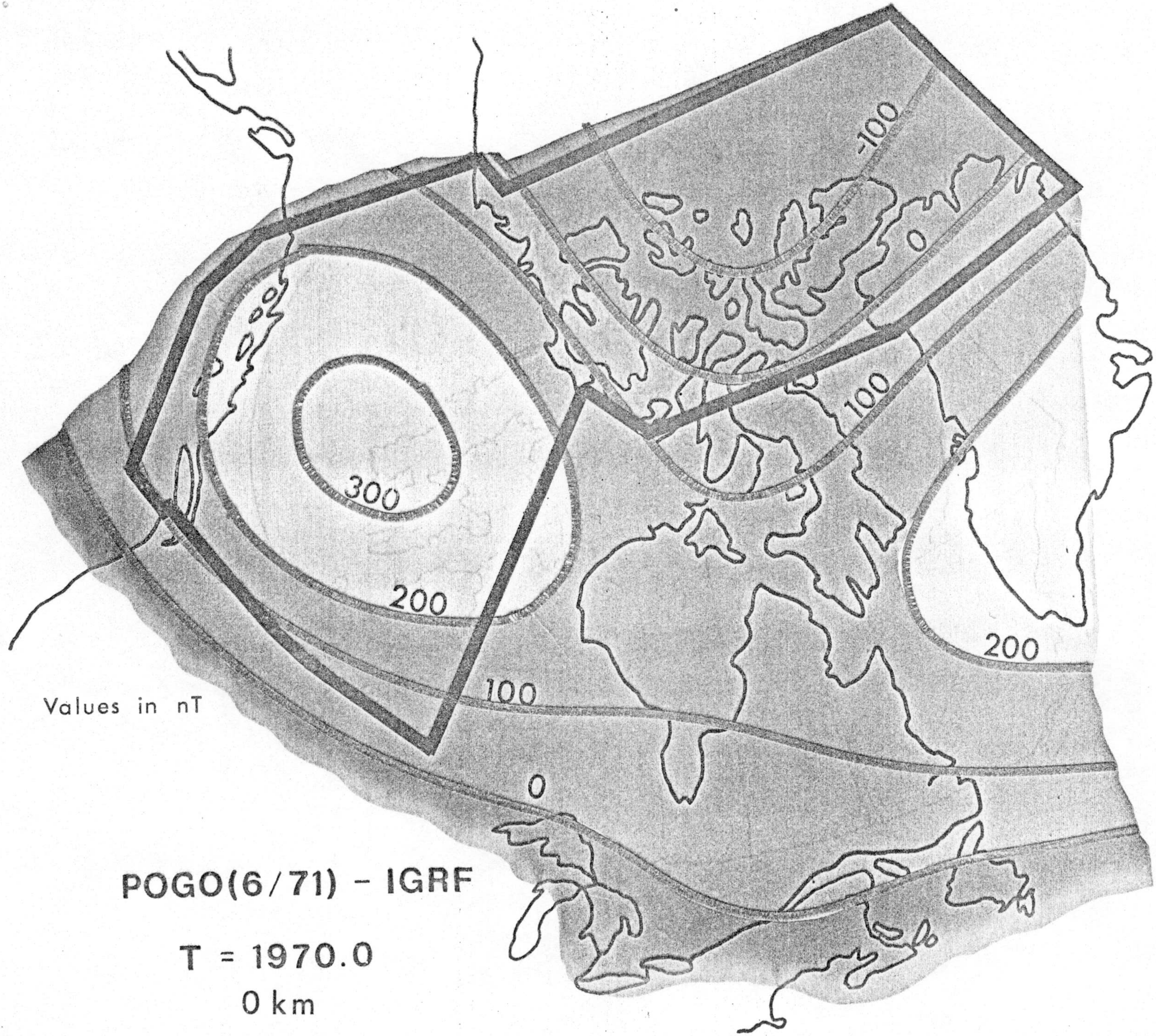
Fig. 2


NP
LOMONOSOV R.
ALPHA R.
V
Lincoln Sea
GREENLAND
80°N
30°W
50°W
FRANKLINIAN
CANADA
BASIN
SVERDRUP BASIN
ARCTIC COASTAL PLAIN
IV
FRANKLINIAN
Baffin Bay
70°N
MINTO ARCH
R. MTS.
ALASKA
80°W
MACKENZIE FOLD BELT
BEAR
SLAVE
III
Thelon Front
0
500Km
Tintina
Denali
140° W
60°N
OMENICA
McDonald
D
F
C
CHURCHILL
WOLLASTON L. BELT
II
E
COAST CRYSTALLINE BELT
INTERMONTANE BELT
CRYSTALLINE
ROCKY MOUNTAINS
G
Queen Charlotte
A5
Rocky Mtn. Trench
BELT
A
50°N
I
B
130°W
120°W
110°W
USA
Williston Basin
100°W
1
2
3
4
5
6
7



1961.5
1963.9
1965.8
1969.1
1970.9
1972.9
1963.9
1970.9
1965.8
1972.9
1961.5
1969.1
0
1000
km
Values in
100 nT
$Z_{POL} - Z_{IGRF}$

Fig. 3

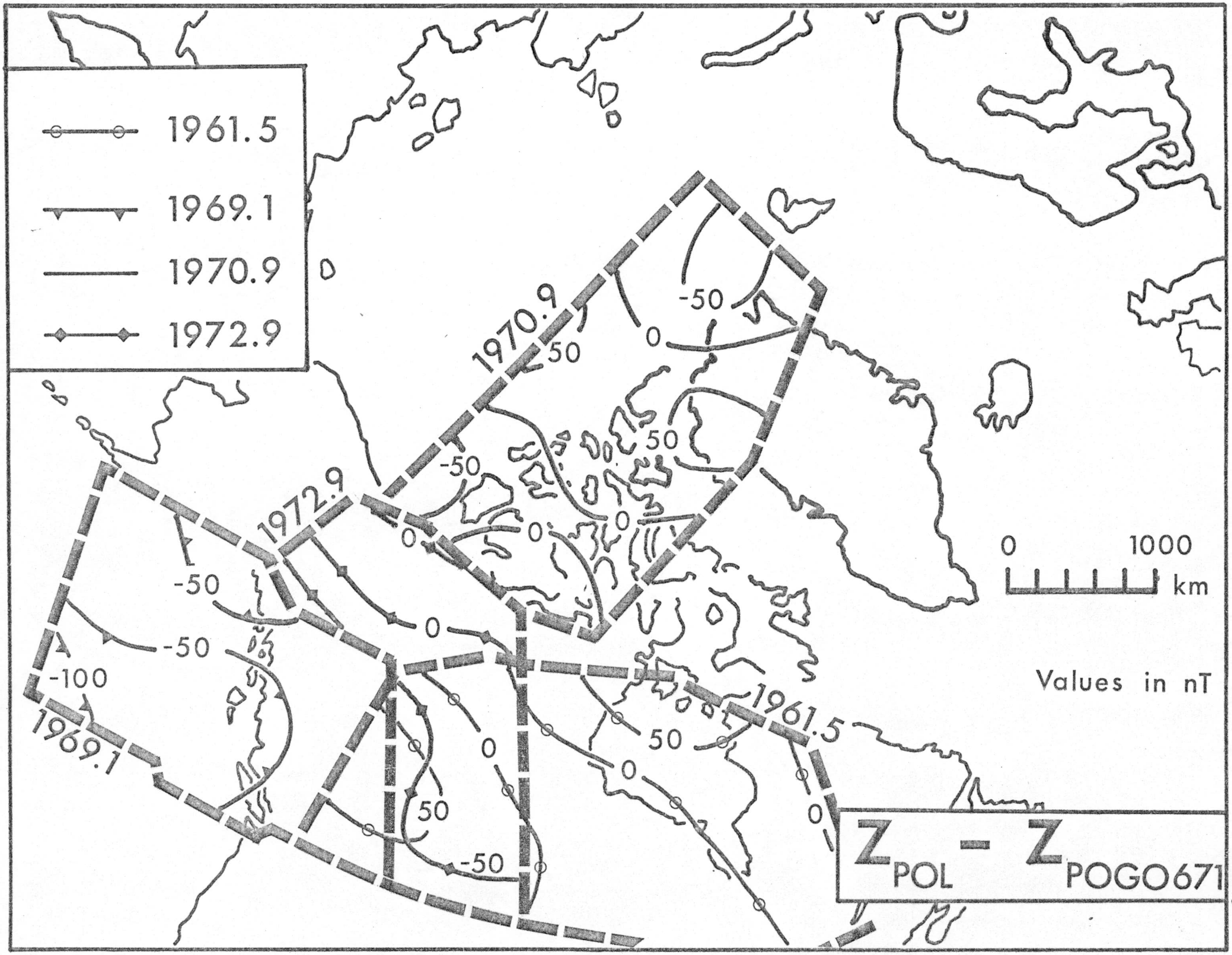


POGO(6/71) - IGRF

T = 1970.0

0 km

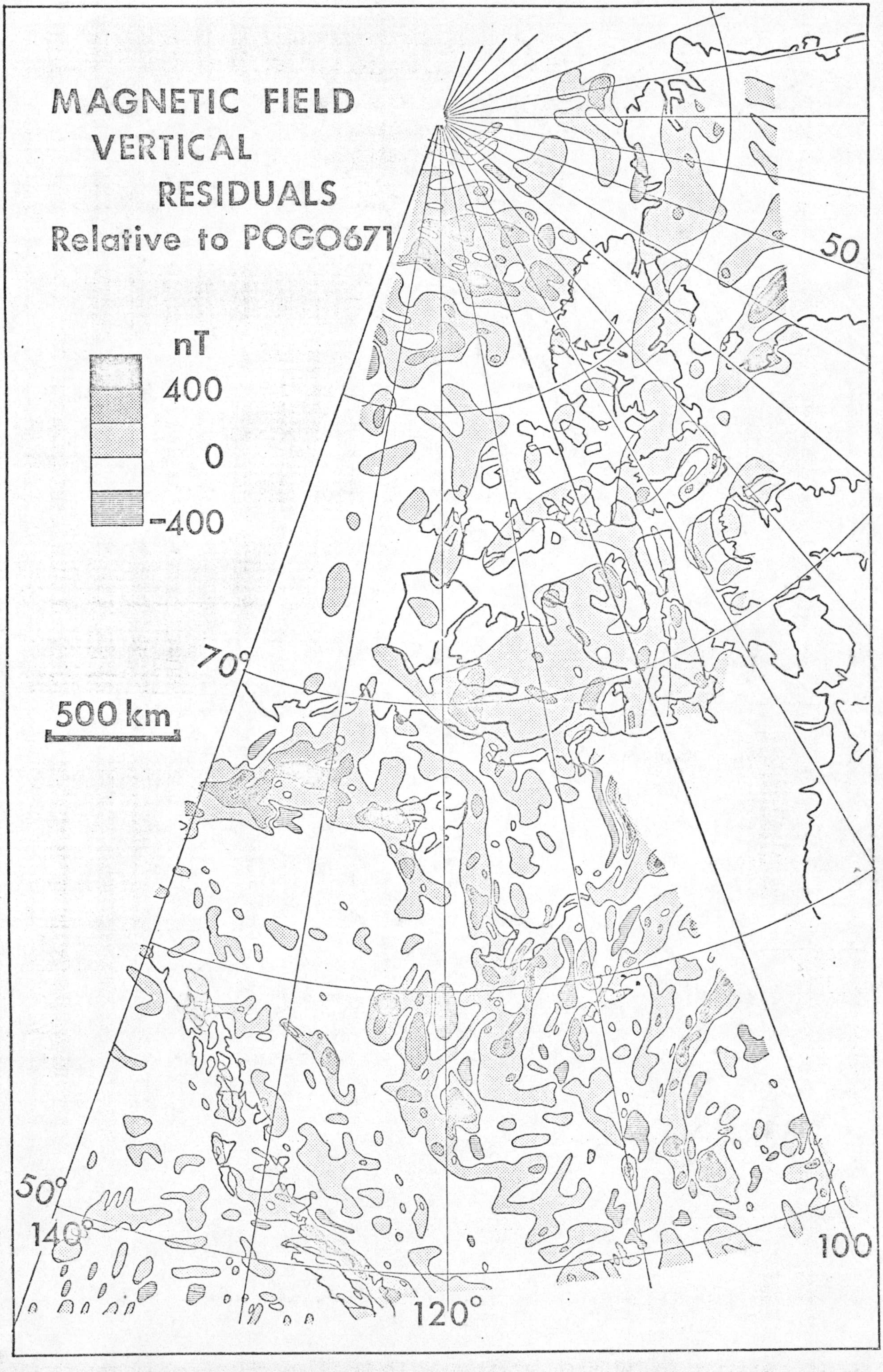
Fig. 4



1961.5
1969.1
1970.9
1972.9
1970.9
1972.9
1969.1
1961.5
-50
0
50
-100
0 1000
km
Values in nT
$Z_{POL} - Z_{POGO671}$

Fig. 5

Fig. 6



MAGNETIC FIELD
VERTICAL
RESIDUALS
Relative to POGO671
nT
400
0
-400
500 km
50
70°
50°
140°
120°
100

Fig. 7

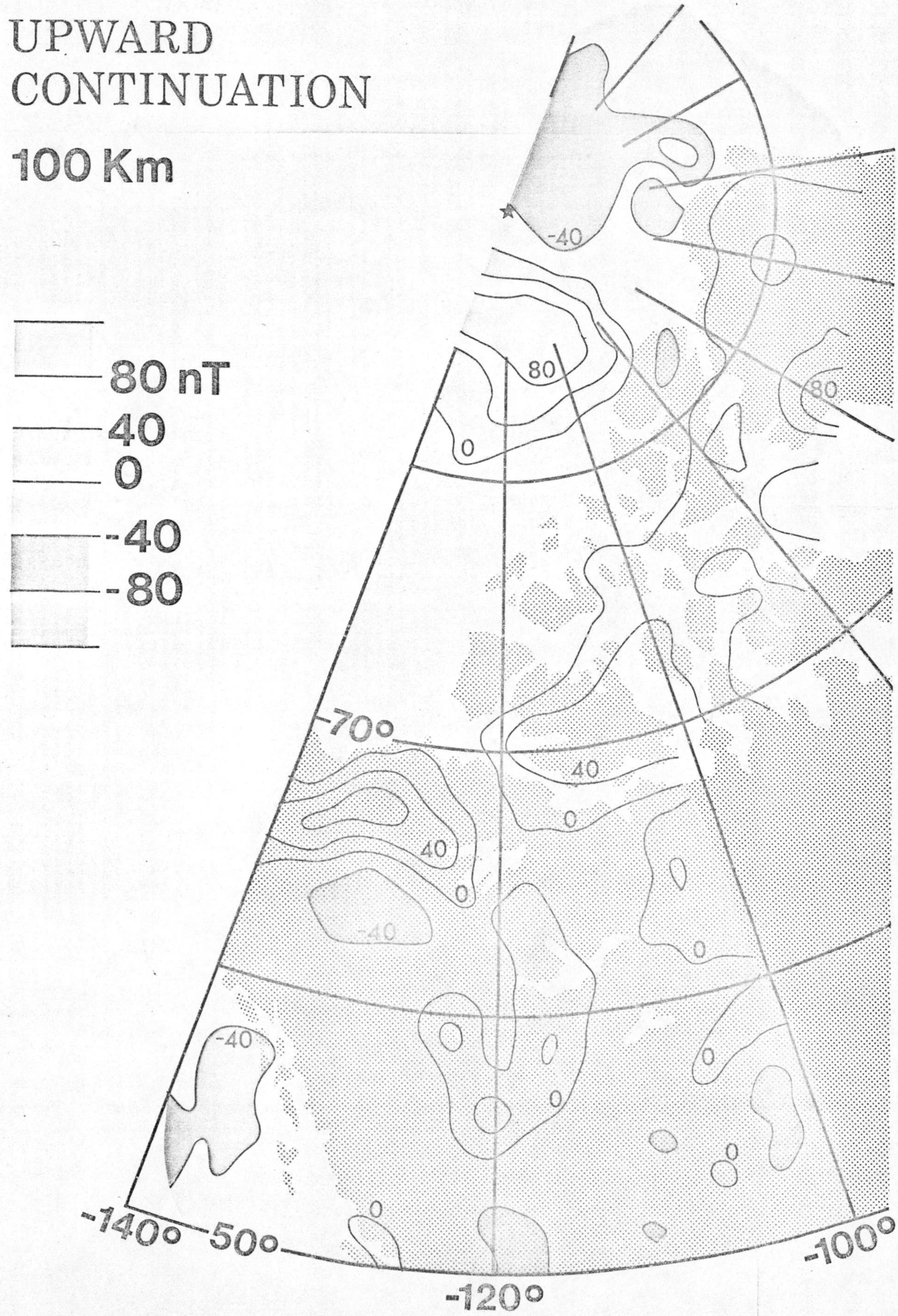
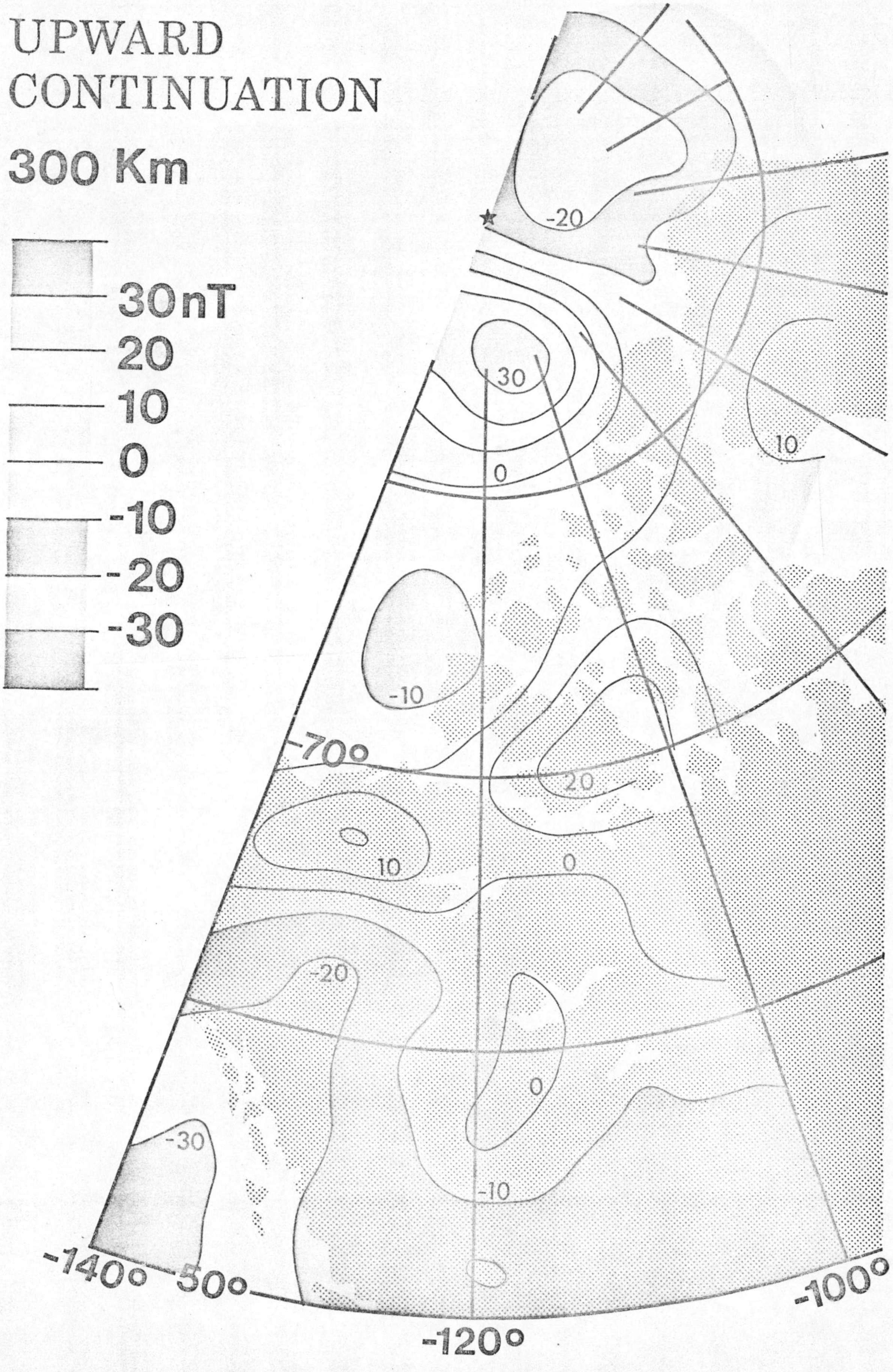

UPWARD
CONTINUATION
100 Km
80 nT
40
0
-40
-80
-40
80
80
0
-70°
40
0
40
0
-40
0
-40
0
0
0
0
0
-140°
-50°
-100°
-120°

Fig. 8


UPWARD
CONTINUATION
300 Km
30nT
20
10
0
-10
-20
-30
-20
30
0
10
-10
-70°
20
10
0
-20
0
-30
-10
-140°
50°
-120°
-100°

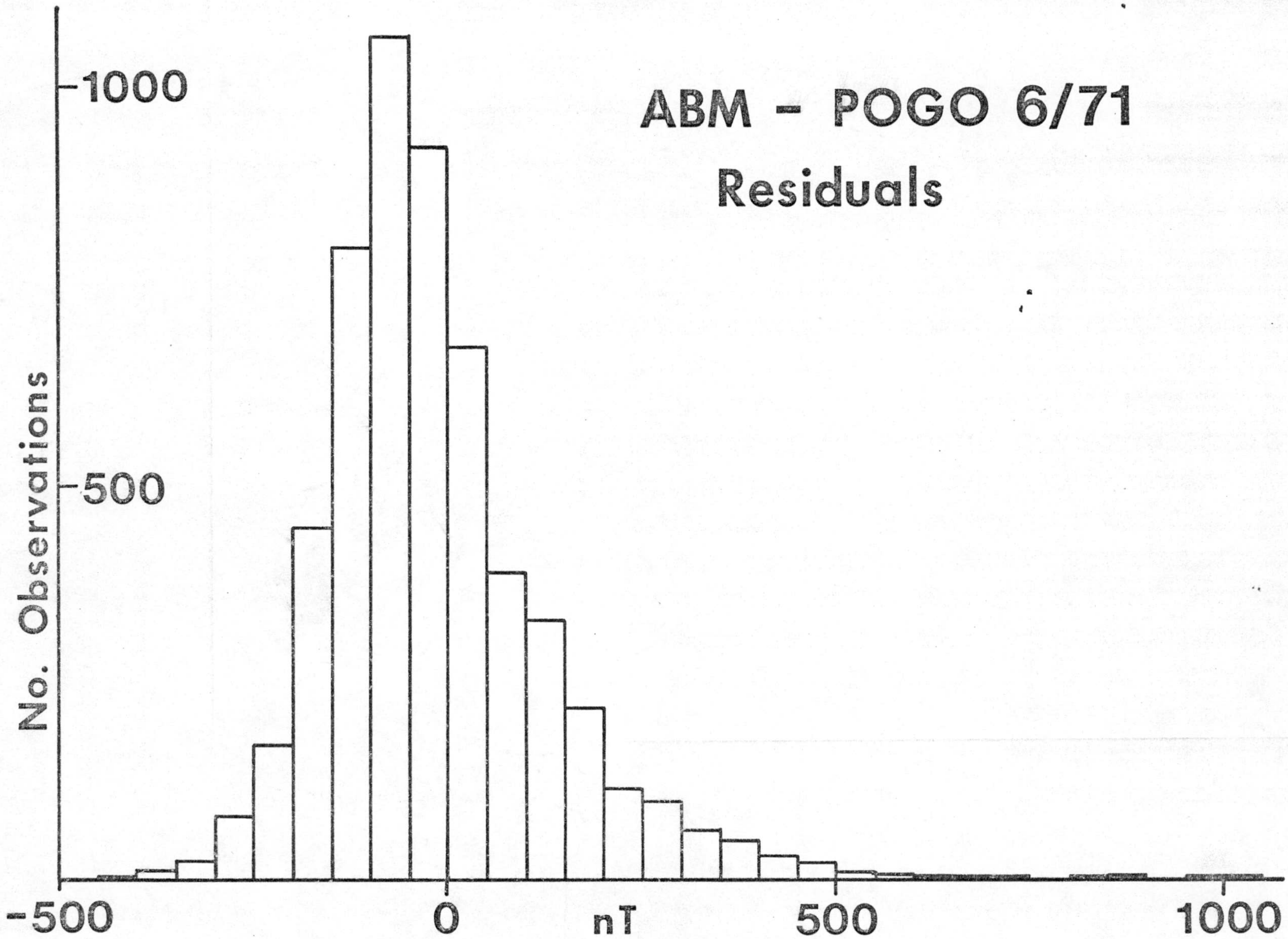
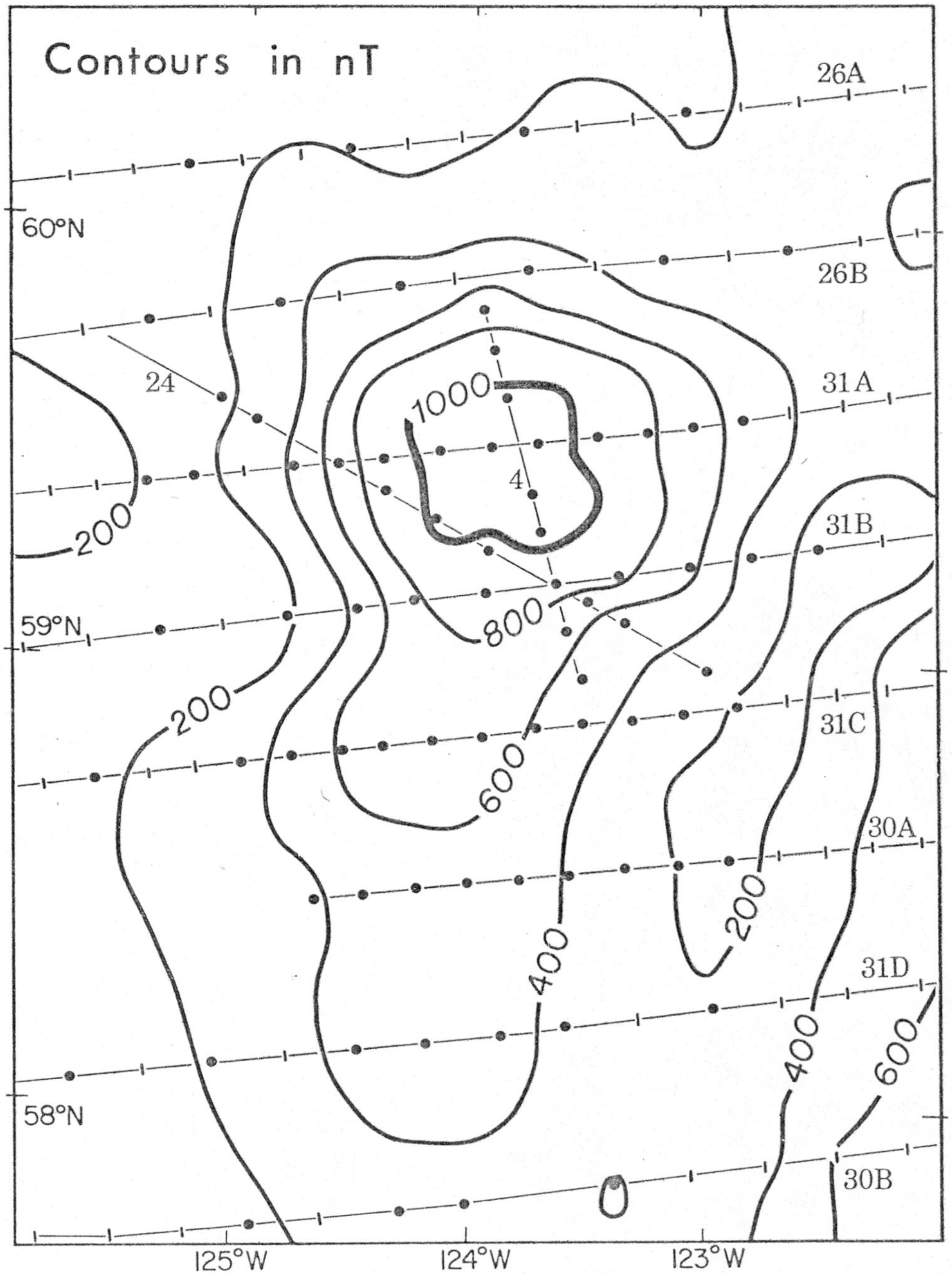
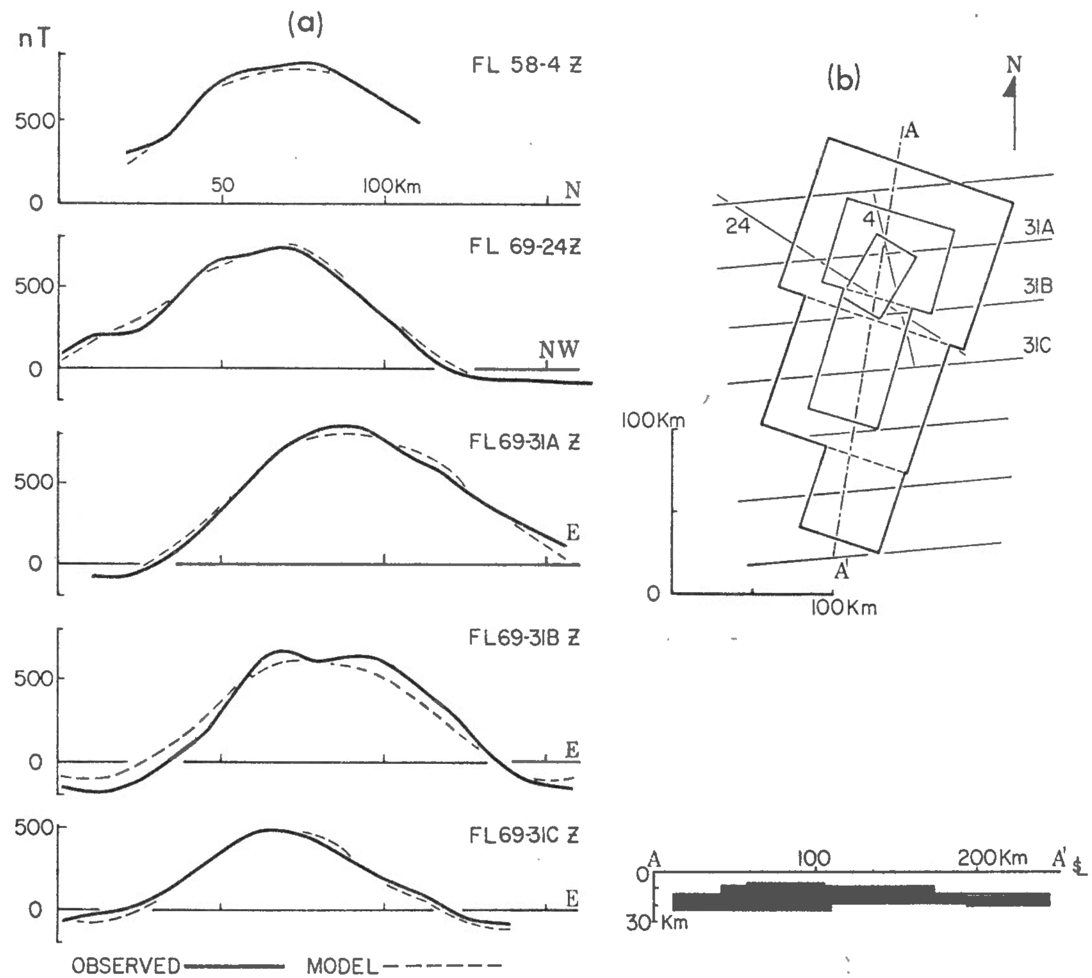

ABM - POGO 6/71
Residuals
No. Observations
1000
500
-500
0
nT
500
1000

Fig. 9

Fig. 10



Contours in nT
26A
26B
31A
31B
31C
30A
31D
30B
24
4
1000
800
600
400
200
200
200
200
400
600
60°N
59°N
58°N
125°W
124°W
123°W



(a)
nT
FL 58-4 Z
500
0
50
100Km
N
FL 69-24Z
500
0
NW
FL69-31A Z
500
0
E
FL69-31B Z
500
0
E
500
FL69-31C Z
0
E
OBSERVED
MODEL
(b)
N
A
4
24
31A
31B
31C
100Km
0
100Km
A'
A
100
200Km
A'
0
30 Km

Fig. 11

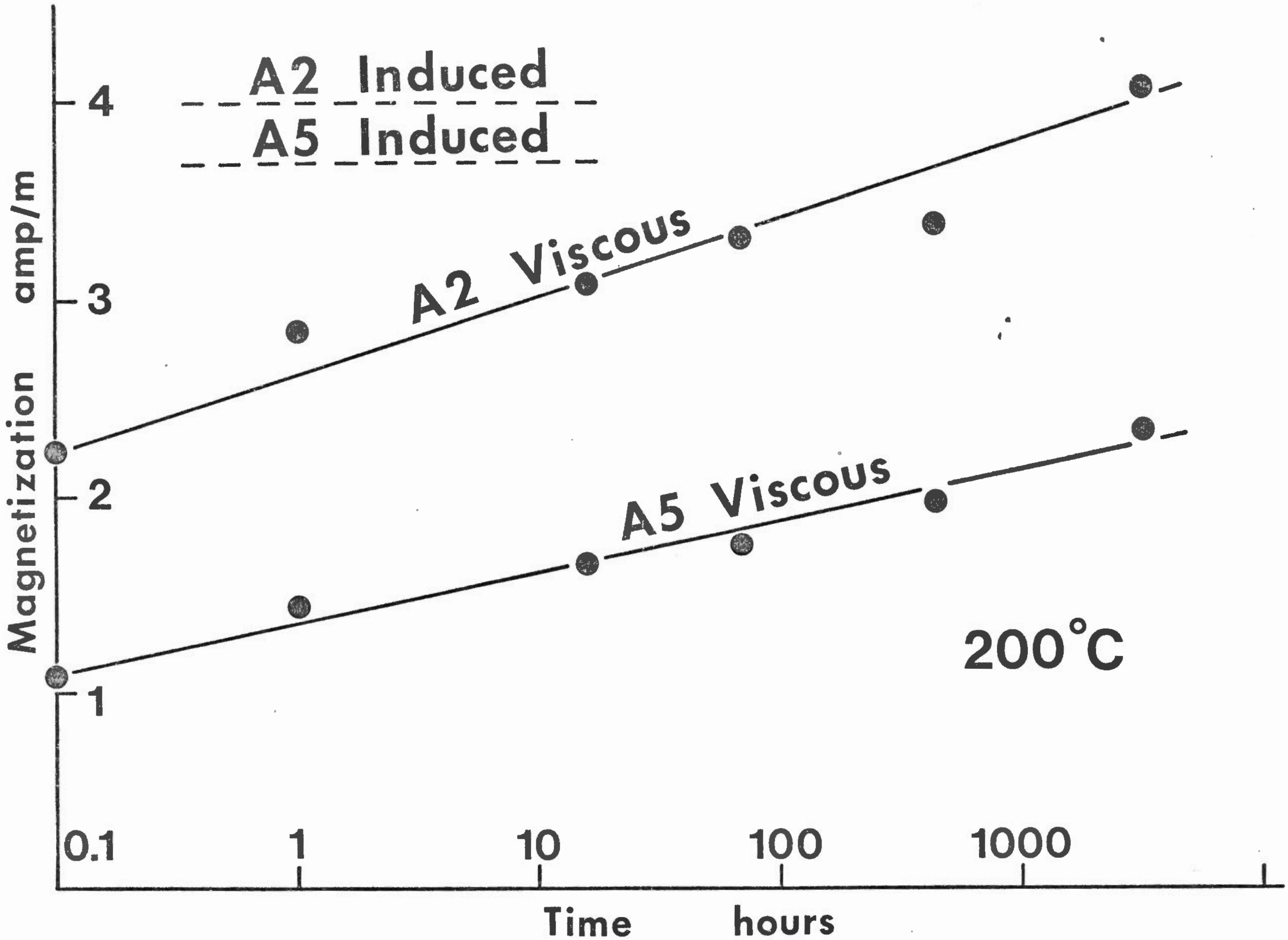

A2 Induced
A5 Induced
A2 Viscous
A5 Viscous
200°C
Magnetization amp/m
4
3
2
1
0.1
1
10
100
1000
Time hours

Fig. 12