Magnetic Survey Over the Ice-shelf Around the Indian Permanent Station in Antarctica

S.K. Verma, G.S. Mital, H.V. Rambabu, M. Venkatarayadu and K.N. Srinathareddy

National Geophysical Research Institute, Hyderabad

ABSTRACT

The results presented here relate to the magnetic investigations carried out around the Indian permanent station on the ice-shelf during the Fourth Indian Antarctic Expedition. Magnetic measurements were made along a 33 km long N-S traverse starting right from the northern edge of shelf to the region where deep water channels were encountered. The observed profile was interpreted using a number of geophysical methods. Utilizing the magnetic data obtained in earlier surveys it has been possible to delineate sub-shelf trends in the graben or rift-zone like structure of the basement. This structural pattern is supported by the marine seismic and magnetic work carried out in Lazarev sea during the first Indian expedition and by the geological studies hypothesizing the existence of extensive grabens.

INTRODUCTION

Antarctica provides a unique setting to earth scientists to carry out a number of exciting scientific experiments. As more than 98% of the continent is under a cover of ice/snow, geophysics assumes great significance by providing the most effective means to study various interesting aspects of Antarctica. One of the most popular tools employed by geophysicists in the subglacial geology has been the magnetic method. Some significant studies in this regard are due to Behrendt and Wold (1963), Hill (1979), Wellman (1982) and Bentley (1983).

The magnetic study under the Indian Antarctic research programme was initiated during the second expedition and the results of this survey, covering seven profiles and a total of 65 line km, over the iceshelf north of the Runway Hut (70°02'00"S, 12°00'00"E), are presented by Mittal and Mishra (1985). They observed a consistent magnetic anomaly of the order of 180-200 nT approximately 5-6 km south of the coast which they ascribed to a 3 km wide source lying at a depth of 2.5 km. The source, magnetised with a feeble intensity of 80-100 nT, could either be a metamorphosed basic intrusion extending deep into the crust or a depression in the bedrock. A few of the profiles reported by Mittal and Mishra (1985) were extended further south during the third expedition (Gupta and Varma; 1986) covering a total of 60 line km of observations distributed over four profiles. The longest of three profiles extended 28 km south of the Indian permanent station (70°05'37"S, 12° 00'00"E). The salient features of these profiles are the low amplitude, short wavelength magnetic anomalies superimposed over a broad anomaly. Gupta and Varma (1986) have interpreted the broad anomaly as being caused by an about 12 km thick body with its top at a depth of about 3.5 km and a polarization angle of about 60°.

The results presented in this paper pertain to a NS magnetic profile lying 3 km east of the Indian permanent station. The profile covered a region starting from the coast in the northern extreme to the deep un-negotiable water channels encountered 33 km south of the coast. The location of this profile as well as of those measured during the second and the third Indian Expeditions are shown in Fig. 1. In Fig. 1, the present profile is shown as A-B (no. 4) while the magnetic investigations carried out during the second and the third Indian Antarctic expeditions are marked as 2 and 3 respectively.

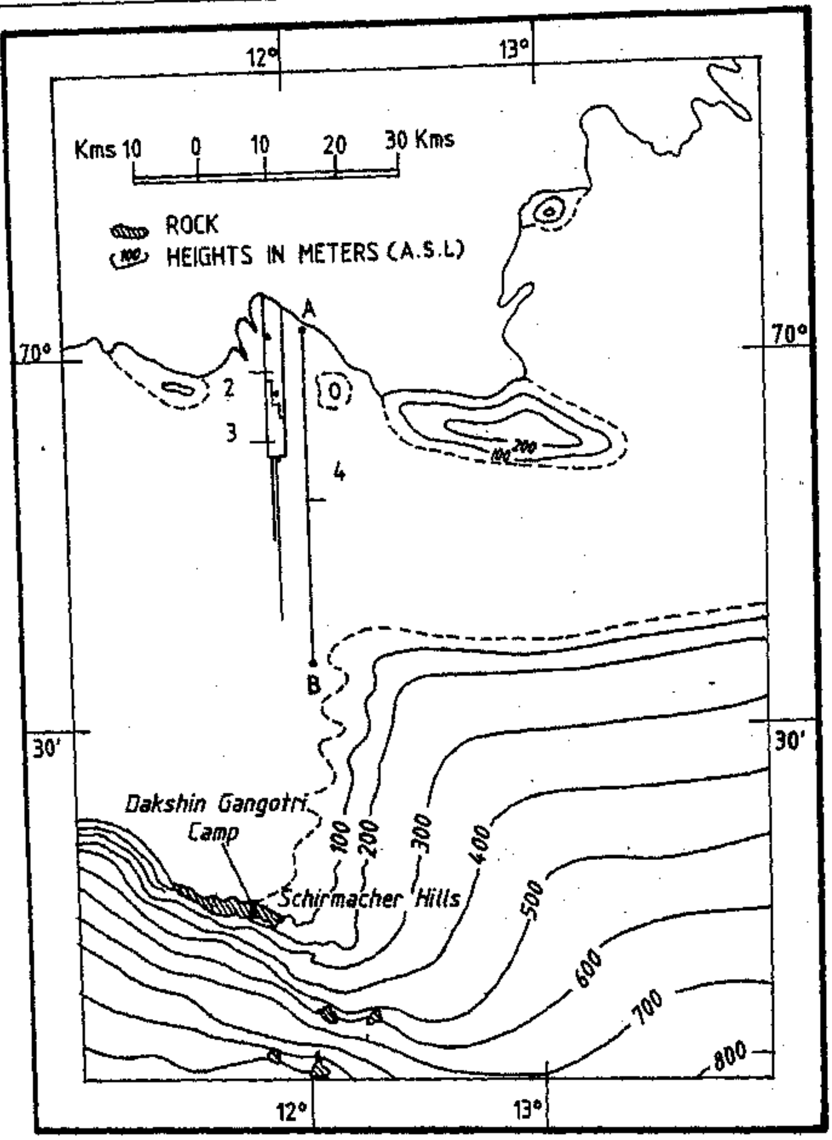

Fig.1. Location of the magnetic profiles obtained during the second and third expeditions.

SURVEY STRATEGY DATA COLLECTION

The laying of the traverse line was greatly simplified because of the availability of a Magnavox system with the Pisten Bulley (snow mobile) that was used for the survey. The Magnavox system uses satellite data for the purpose of accurate navigation in an unknown territory. First we took a few good satellite fixes near the Runway Hut to check whether the Magnavox system is displaying correct position. After ensuring the accuracy (within ± 05") we proceeded 3 km due east from where the Pisten Bulley was driven due north towards the edge of the shelf (Point A, Fig. 1). From this point the Pisten Bulley was driven due south and poles with colour flags were put at every kilometre. While the N-S direction of the profile was maintained accurately with the help of the continuous digi-

tal navigational display of position in the Magnavox panel, distances were measured accurately (within ± 10 m) with the help of a Ski-doo (snow-scooter fitted with an accurate distance and speed meter).

The total intensity of the earth's magnetic field was recorded at 250 m intervals using a G816/826 Proton precession magnetometer having a sensitivity of 1 nT. To record the diurnal variations in the magnetic field, a base station was set up about 2 km NE of the Indian permanent station and a Proton precession magnetometer built by NGRI was used to record the diurnal variations on an automatic chart recorder. Because we used two different makes of magnetometers for the survey and for the diurnal measurements, it was necessary to check their performance with respect to each other before starting the survey. It was found that the two magnetometers yielded identical results (within a tolerance of ±2 nT) and thus were found to be suitable for their intended work. The magnetic intensity at the base station was checked by the field magnetometer (G816/826) twice daily at the start and at the end of the day's survey.

DATA PROCESSING AND INTERPRETATION

An examination of the diurnal chart records revealed that magnetic storm like conditions prevailed on several days during the periods when the survey was conducted. This is also well reflected in the three-hourly magnetic activity index Kp during the period Jan. 24,1985 to Feb. 9,1985 (Table I). In the Table I the values of Kp-Sum (last column) below 16 indicate a magnetically quiet day, those between 16 to 24 as magnetically disturbed day and values greater than that 24 indicate mag-

TABLE I

Three-hourly magnetic activity index Kp for the duration Jan. 24, 1985 to Feb. 9,1985.

(Note: times are in UT; 1 indicates the period 0-3 UT while 8 indicates 21-24 UT)

S.No.	Date	Kp 1	2	3	4	5	6	7	8	Kp-sum
1.	24 January 1985	1	2	2	1	1	1	1	1	14+
2.	25 January 1985	3	3	3	2	1	1	1	1	16-
3.	26 January 1985	1	1	1	2	1	3	2	2	13-
4.	27 January 1985	2	3	1	1	1	2	3	4	18-
5.	28 January 1985	6	5	5	5	6	6	5	6	43-
6.	29 January 1985	5	4	1	2	2	2	4	6	26
7.	30 January 1985	4	3	3	3	2	4	3	3	25
8.	31 January 1985	3	2	2	4	4	3	2	3	24-
9.	1 February 1985	3	3	3	3	3	4	3	2	23+
10.	2 February 1985	1	4	3	2	2	2	3	2	20-
11.	3 February 1985	2	2	1	1	3	3	3	0	14+
12.	4 February 1985	1	1	0	0	0	0	1	1	5
13.	5 February 1985	1	3	4	3	5	4	3	4	27+
14.	6 February 1985	5	4	5	5	5	5	6	4	39
15.	7 February 1985	3	3	4	4	4	3	2	4	27+
16.	8 February 1985	4	2	2	4	3	4	4	5	29-
17.	9 February 1985	3	3	5	3	4	3	2	3	27-

netic storms. Because of the disturbed magnetic conditions it was necessary to repeat a number of observations to get meaningful data.

The diurnal variation plots for a quiet day and a disturbed day are shown in Fig. 2 (a & b).

The total intensity values collected during the quiet period were corrected for the diurnal variations and the magnetic profile thus obtained is shown in Fig. 3. It is apparent from the figure that the normal intensity of the earth's magnetic field is approximately equal to 41,000 nT in the region. The profile shows a general trend of increasing magnetic intensity towards south. Towards the southern extreme of the profile a sharp drop in the intensity from 560 nT to 382 nT was observed (the normal value, i.e. 41000 nT, is omitted here). Towards the northem side, before the coast, the minimum intensity of 48 nT was observed which showed an increasing trend towards the sea.

Qualitative interpretation

In the analysis of a long magnetic traverse, it is normally assumed that the strike of various geological structures are perpendicular to the profile and the structures are assumed to be two-dimensional.

A close look at the magnetic profile reveals five magnetic anomalies marked as A1 to A5 in the Fig. 3. Since at higher magnetic latitudes, for normal induction, the magnetic high represents a basement high and vice versa, the basement at anomalies A1, A2 and A3 appears to be shallower than that near A4 and A5.

Quantitative interpretation

Several approaches were followed to interpret the observed magnetic profile. To get an idea about the average depth of a magnetic layer that would cause the observed response, the spectral study and the downward continuation techniques were used. The observed data was also used to obtain a pseudo-gravity anomaly. The pseudo-gravity response then yielded a continuous depth pro-

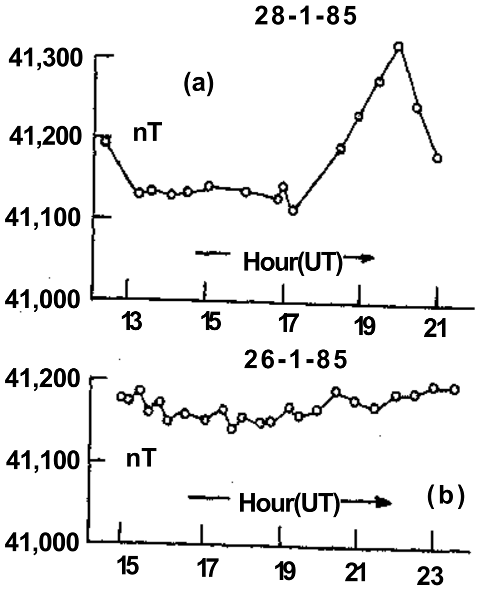

Fig. 2.(a&b). Diurnal variation plots for a quiet day (a) and a disturbed day (b).

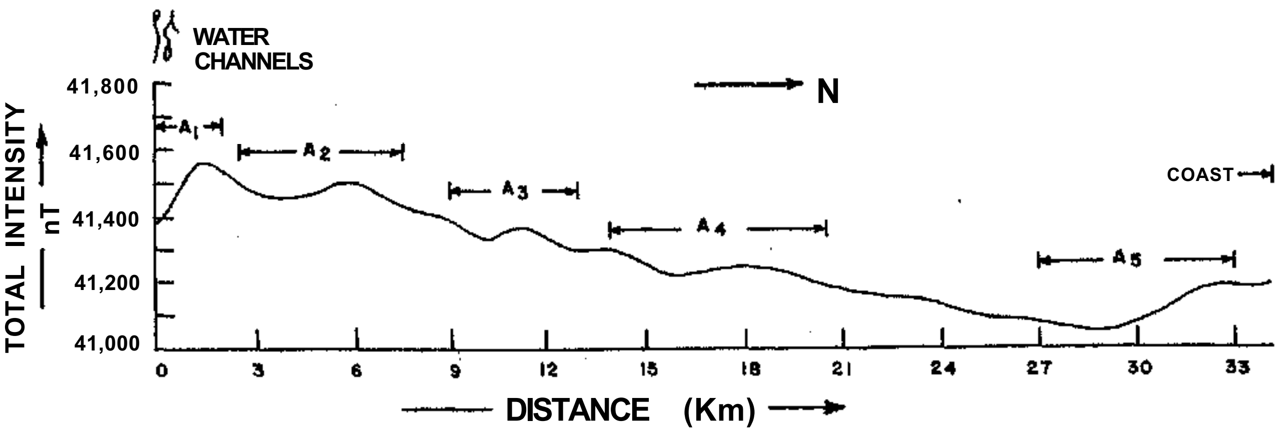

Fig.3. Magnetic profile obtained after correcting diurnal variations.

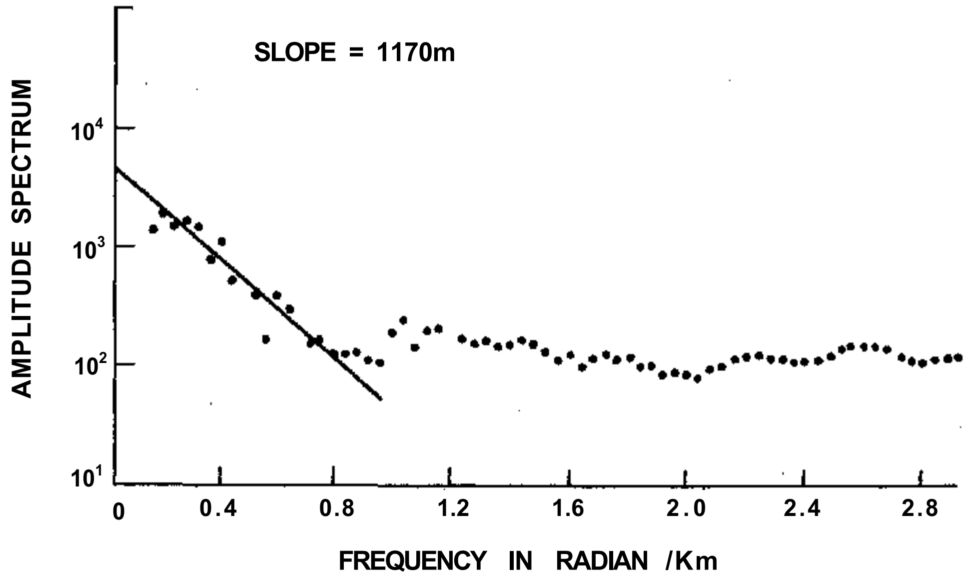

Fig. 4. Fourier amplitude spectrum of the magnetic profile.

file for the basement. The individual magnetic anomalies marked A1 to A5 were interpreted using an automatic inversion programme MAGMOD which is based on a computer curve fitting method. An additional check to the interpreted parameters was provided by the downward continuation of the individual anomalies (A1 to A5). The details of all these interpretations are presented below:

(a) Spectral analysis

The Fourier amplitude spectrum of the magnetic profile, shown in Fig. 4 was computed using an FFT algorithm to infer the average depth of the basement in this region. The slope of the straight line fitted to the amplitude spectrum gave the average depth of the source equal to 1170 metres in this region.

(b) Continuation

The upward and downward continuation results of the observed magnetic profile (Fig. 3) are shown in Fig. 5. For this purpose, the technique proposed by Roy (1976) was followed. As expected the upward continuation of the values yielded smoother profiles while the downward continuation yielded profiles with increasing unevenness with depth. In the figure, the continued profiles upto 4

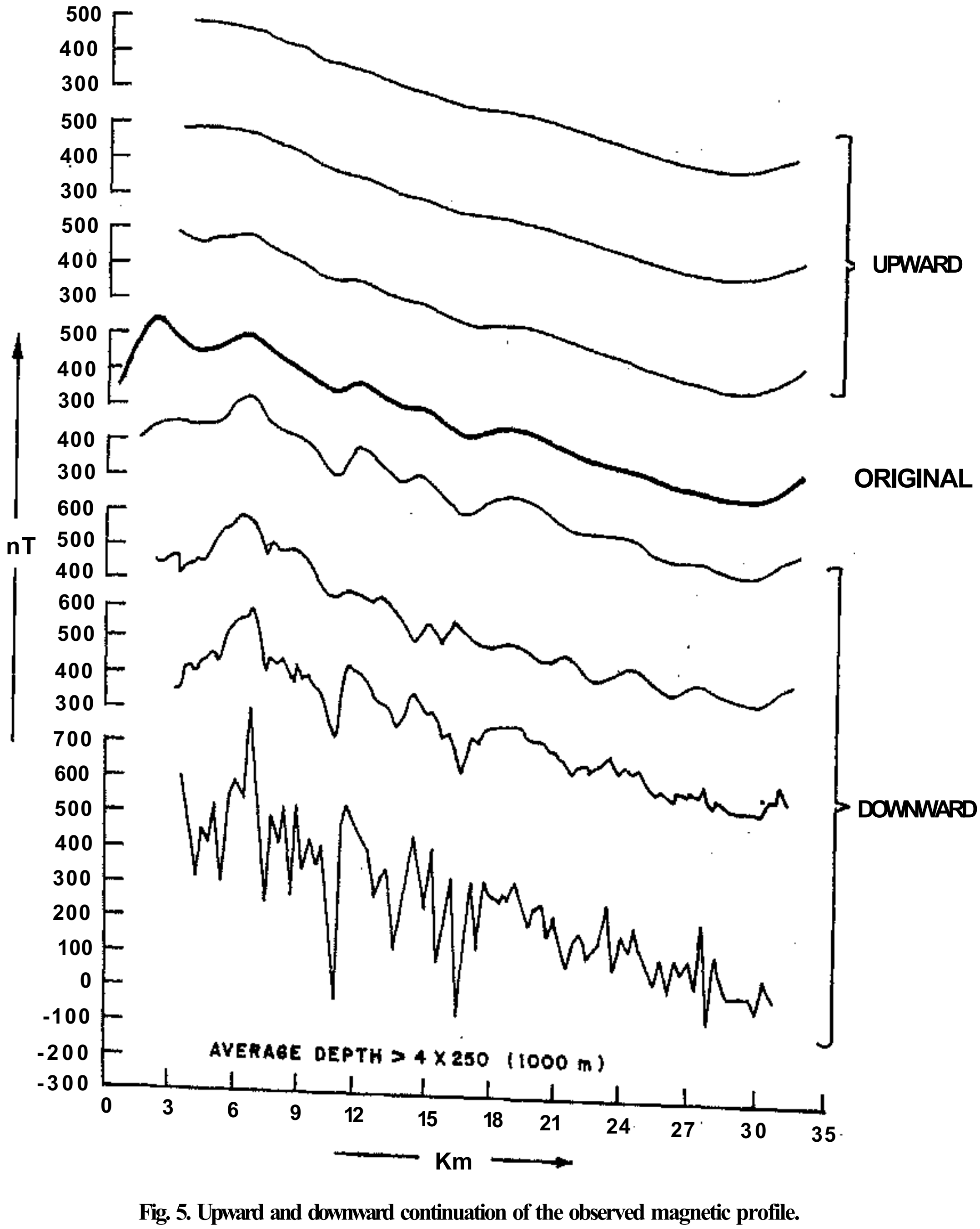

Fig. 5. Upward and downward continuation of the observed magnetic profile.

units of continuation depth are shown. The downward continuation to the fifth unit yielded highly oscillating curve of high positive and negative magnitudes. Thus, it could be inferred that the average depth to the magnetic basement, as obtained by the continuation technique, should be between 4 to 5 units of continuation depth. As the unit of continuation is 250 m, the average depth is inferred to be between 1000 m and 1250 m.

(c) Pseudo-gravity analysis

The pseudo-gravity anomaly was computed from the observed magnetic anomaly using the Hilbert transform technique described by Shuey (1972). This anomaly alongwith the observed data and the total field reduced to pole is shown in Fig. 6. The basement topography along the traverse was computed from the pseudo-gravity anomaly using Sazhina and Grushinsky (1971) method described below:

The depth of a density interface (Fig. 7) is related to the gravity anomaly by the approximate relationship (Sazhina and Grushinsky, 1971):

$$h = h_0 + \frac{\Delta g' - \Delta g_0}{2 \pi G (\sigma_2 - \sigma_1)} \qquad ...(1)$$

where G is the gravitational constant, σ_1 and σ_2 are the densities, Δg_0 is the anomaly at a point where the depth h_0 to the discontinuity is known and g is the anomaly where depth is to be determined. The above equation can be used to obtain the depth at a point from the known values of the gravity anomaly and the depth h_0 at a neighbouring point. For this purpose, the equation (1) can be rewritten as:

$$h = \left(h_0 - \frac{\Delta g_0}{2 \pi G\sigma} \right) + \frac{\Delta g}{2 \pi G\sigma}$$

or $$h \doteq C + m\Delta g \qquad ...(2)$$

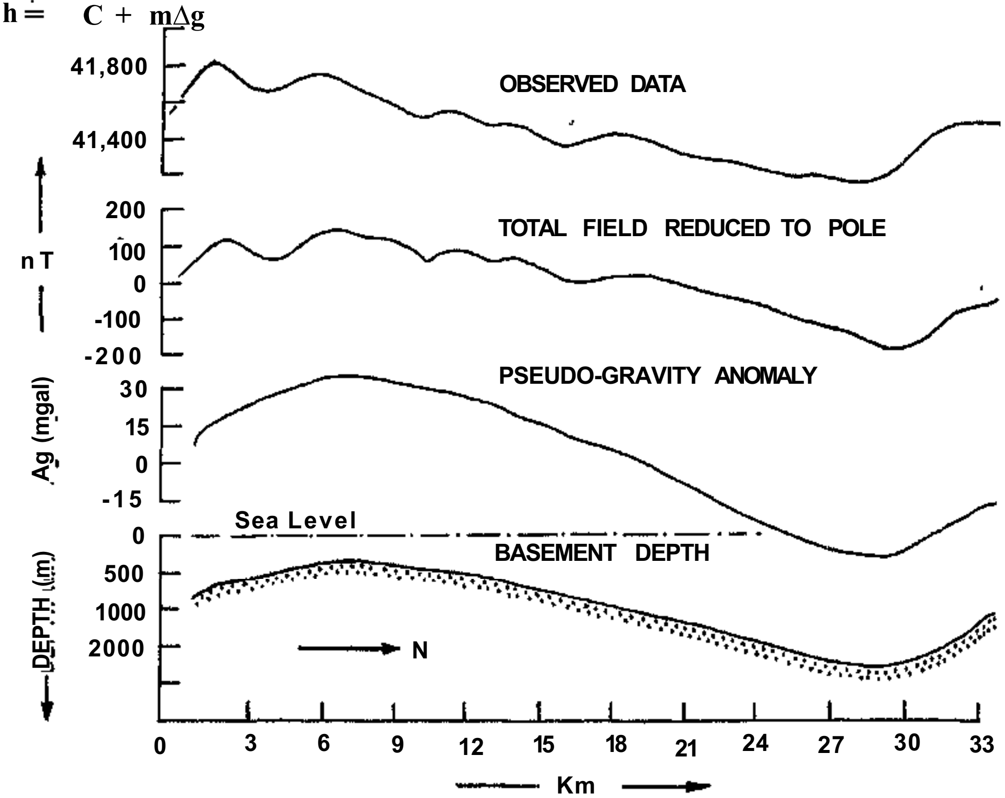

Fig. 6. Plot showing computed pseudo-gravity anomaly along with the observed data.

which is a straight line whose inverse slope is equal to 2 GσΔ (σΔ being the density contrast σ_2-σ_1).

A plot of the interpreted depth (*h*) values obtained for the magnetic anomalies A1,A2,....A5, against their corresponding pseudo-gravity anomalies is shown in Fig. 8. It may be seen from Fig. 8 that the plot is a straight line whose slope and intercepts are 1875 m/mgal and 1025 m respectively. Substituting these values in equation (2), we obtain

$$h = 1025 + 18.75 \quad \Delta g \tag{3}$$

The significance of obtaining a straight line is that all along the traverse there is no significant variation in the density contrast (i.e. o is a constant). From equation (2) it is clear that if σ is varying for different values of *h*, we shall not get a single straight line passing through all the points. Thus from Fig. 8 it is clear that the basement consists of rocks which show similar densities. In lack of any other control, it may be surmised that this inferred constancy in the density contrast implies that the composition of the basement below the traverse line is uniform. Various depths at different locations thus indicate first order variations in the basement topography only.

Using equation (3) a continuous depth section corresponding to the pseudo-gravity anomaly was computed. It is also shown in Fig. 6.

(d) Computer curve matching

The anomalies A1 to A5 (Fig. 3) were interpreted using the MAGMOD programme available at NGRI. For a prescribed model (such as dyke, prism, step etc.) this programme computes the forward response, compares it with the observed data, and then iteractively adjusts the parameters of the prescribed model until an acceptable match between the observed and the computer response is obtained. The anomalies A1 to A5 override a regional anomaly and thus indicate shallower features caused either by local variations in the depth of the magnetic basement or by contacts of different geological units. The results obtained by MAGMOD for a tabular model are given in Table II.

For the purpose of illustration the fits obtained between the computed and the observed curves using MAGMOD for the anomalies A2 and A3 are shown in Fig. 9(a) and (b).

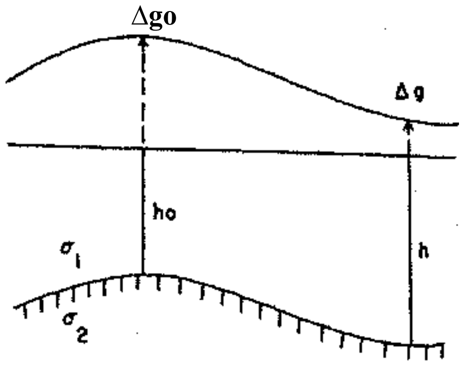

Fig. 7. Relationship between the depth of a density interface and the gravity anomaly.

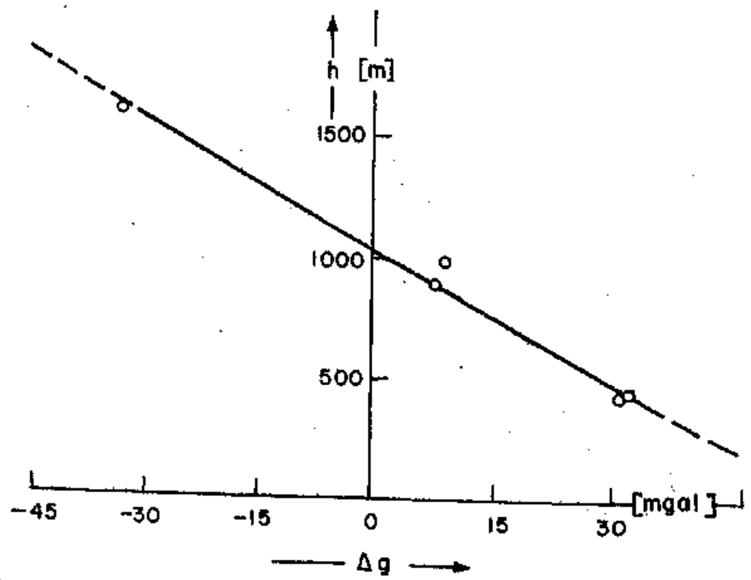

Fig. 8. Plot of interpreted depth versus pseudo-gravity anomaly.

(e) Continuation of individual anomalies

The individual anomalies A1 to A5 were continued downward using the method described by Roy (1967) to get an extra check on the results obtained by the programme MAGMOD. It was found that in general the continuation results yielded depths which were close to the top of the tabular model shown in Fig. 10(a) and (b). It can be seen that the depths obtained compare reasonably well with those given in Table II.

STRUCTURAL TREND AROUND THE INDIAN STATION ON ICE-SHELF

To get an idea about the trend of the basement below the shelf region around the Indian station, we have also utilized the magnetic data collected during the second expedition (Mittal and Mishra, 1985). A contour plot of the total magnetic intensity anomalies for the profiles collected during the second expedition and for the (8th) profile collected during the 4th expedition is shown in Fig. 11. From Fig. 11, it is apparent that the magnetic contours show two definite patterns, the first a N-S trend passing through the location of the Runway Hut, and the second a NNE-SSW trend that starts from the northernmost part of the profile 8 and shows a maximum south of the Runway Hut. According to Mittal and Mishra, 1985, the southern part of the profiles 4, 5 and 6 showed a 2.5 to 3.5 km wide basin like structure of depth 2.5 km. The results of the present analysis indicate a valley like structure (Anomaly A5, Fig. 3) towards the northernmost part of profile 8 having a depth of about

Depth to the Top : 464:0 m   Dip : 38°

Depth to the Bottom : 00   Susceptibility : 0.0006 cgs units

1/2 Width / Thickness : 976.0   Degree of Fit : 0.090

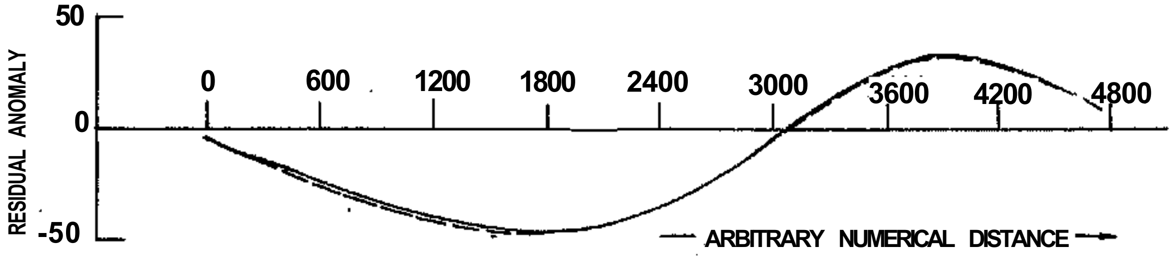

Fig.9(a)

Depth to the Top : 451.0 m   Dip : 30°

Depth to the Bottom : 00   Susceptibility : 0.0033 cgs units

1/2 Width / Thickness : 509.0   Degree of Fit : 0.033

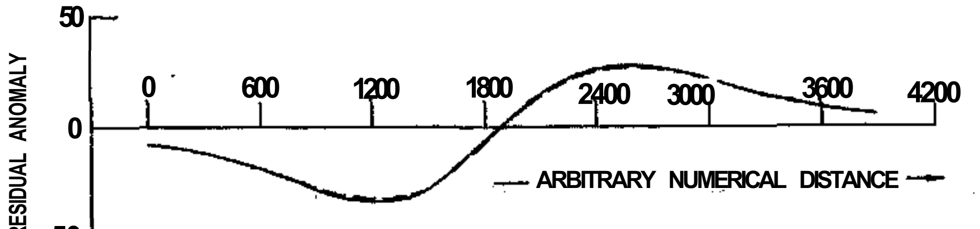

Fig.9(b)

Fig. 9(a&b). **Fits obtained between the computed and the observed curves for anomalies A_2 and A_3. (a) Anomaly A_2 tabular model, and (b) Anomaly A_3 tabular model.**

DOWNWARD CONTINUATION OF ANOMALY A2

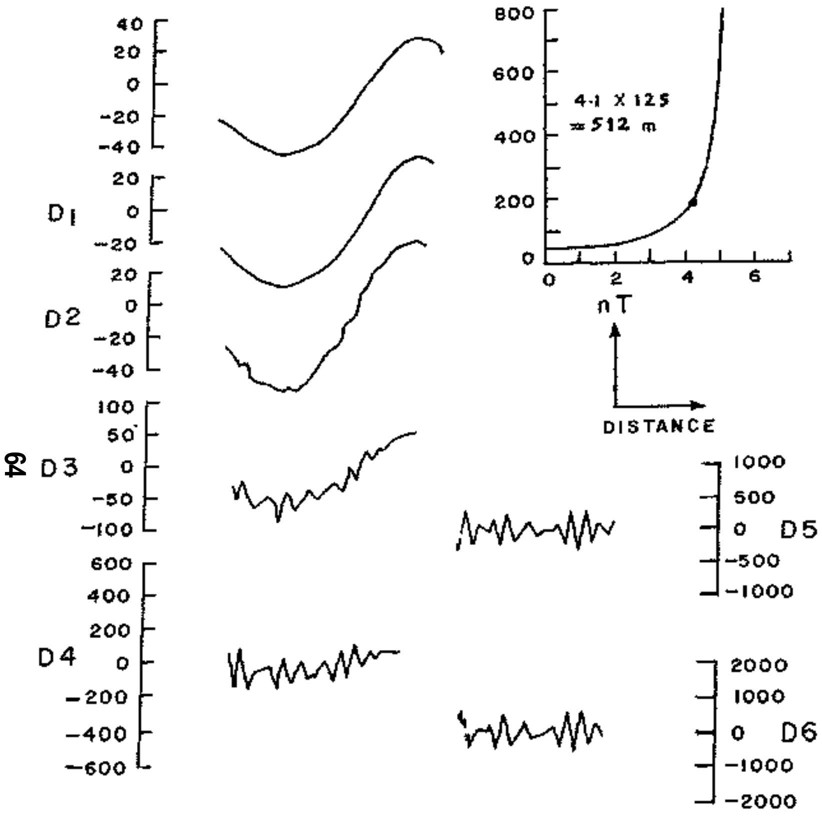

Fig.10(a)

DOWNWARD CONTINUATION OF ANOMALY A3

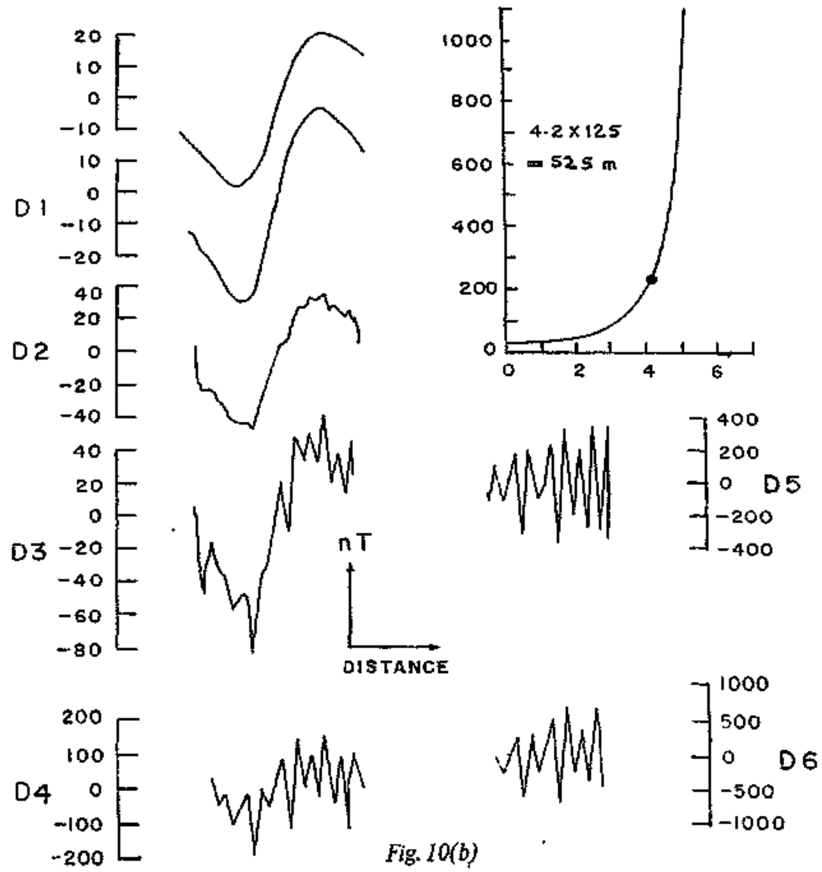

Fig. 10(b)

***Fig. 10 (a&b)*. Plots showing the continuation of anomalies A_2 and A_3.**

1600 m. The trend of the contour indicates a probable continuation of the valley from the northern end of the profile 8 to the south of the Runway Hut showing a NNE-SSW trend.

It may be interesting to note here that a large extensive graben extending southward from the coast for almost 700 km has been reported by Bentley (1983). Further, the existence of several rift zones that may exist around Antarctica has been postulated by other workers. The observed magnetic anomaly map of the region (Fig. 11) could well reflect the magnetic signatures of one of these rift zones or the graben structure suggested by Bentley (1983). The magnetic investigations carried out during the third Indian expedition (Gupta and Varma, 1986) indicate the existence of a valley like structure of width 12 km and depth 3.6 km further south of the Indian permanent station. This structure could again be surmised as an extension of the structure found in the present study.

The northward extension of the rift zones in the region is also evident in the marine seismic and magnetic investigations carried out during the First Indian expedition by Siddiquie et al. (1983).

TABLE II

The depths for anomalies A1 to A5 obtained for a tabular model using the Programme MAGMOD

Anomaly No.	Results	
A1	Depth to the top	800 m
	Half-Width	
	Dip	50
	Susceptibility	0.004 cgs units
	Degree of fit	0.048
A2	Depth to the top	464.0 m
	Depth to the bottom	
	Half width	
	Dip	38
	Susceptibility	0.006 cgs units
	Degree of fit	0.090
A3	Depth to the top	451.0 m
	Depth to the botton	
	Half width	
	Half width	509.0
	Dip	30
	Susceptibility	0.0008 cgs units
	Degree of fit	0.040
A4	Degree of fit	0.040
	Depth to the top	972.0 m
	Depth to the bottom	
	Half width	960.0
	Dip	10
	Susceptibility	0.0033 cgs units
	Degree of fit	0.060
A5	Depth to the top	1628.0 m
	Depth to the bottom	
	Half width	1216.0
	Dip	58
	Susceptibility	0.0015 cgs units
	Degree of fit	0.033

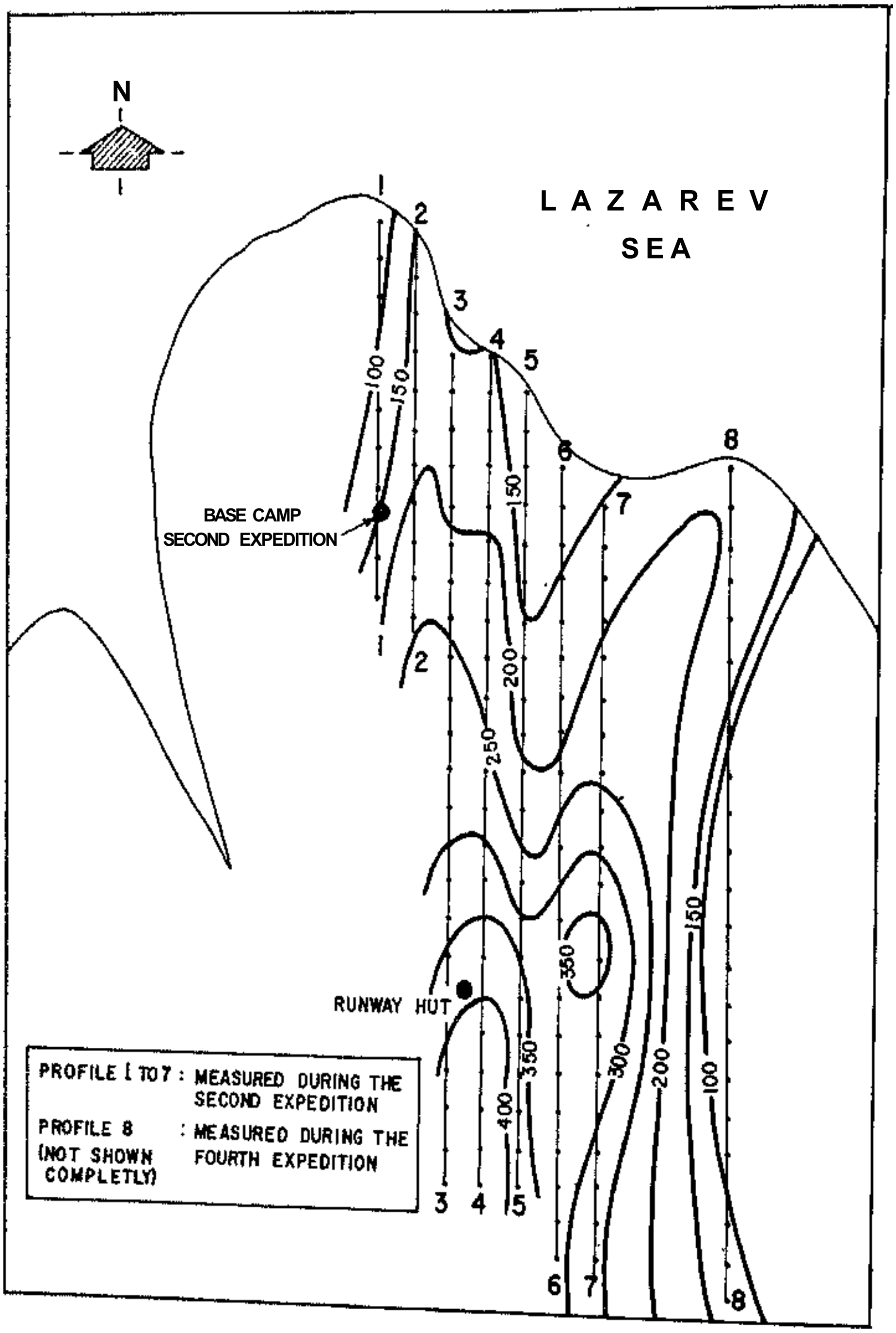

Fig. 11. **Magnetic contours for the profiles 1 to 8.**

This survey was done very close to the coast (Lat. 10°00'00" to 12°30'00"E and Long. 67°30'00" to 69°00'00"S) and the results clearly show the existence of a graben or rift zone structure.

CONCLUDING REMARKS

The investigations reported in this paper clearly establish the efficacy of the magnetic methods in delineating the basement structure under ice-shelf regions. While attempting to interpret a magnetic profile it is desirable to take into account the data already available in order to achieve a realistic interpretation.

The results indicate that the Indian Station on the ice-shelf is located above a NEE-SSW (or N-S) trending rift zone (graben) which continues northwards into the Lazarev Sea and may have a considerable southward extension (Bentley, 1983).

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